2022 Scientific Consensus Statement | Summary

Land-based impacts on Great Barrier Reef water quality and ecosystem condition

Waterhouse J, Pineda M-C, Sambrook K, Newlands M, McKenzie L, Davies A, Pearson R, Fabricius K, Lewis S, Uthicke S, Bainbridge Z, Collier C, Adame F, Prosser I, Wilkinson S, Bartley R, Brooks A, Robson B, Diaz-Pulido G, Reyes C, Caballes C, Burford M, Thorburn P, Weber T, Waltham N, Star M, Negri A, Warne M St J, Templeman S, Silburn M, Chariton A, Coggan A, Murray-Prior R, Schultz T, Espinoza T, Burns C, Gordon I, Devlin M

Citation

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(Authors ordered based on Question number within the 2022 Scientific Consensus Statement)

The 2022 Scientific Consensus Statement was led and coordinated by C₂O Consulting coasts | climate | oceans.

Report design: Katie Sambrook

Cover image: Mulgrave-Russell, Wet Tropics, Queensland.
Photo credit: Dieter Tracey


Branching corals
Photo: Kanenori

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Acknowledgements

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We are also thankful to the guidance and support provided by the Consensus Process Working Group (Andrew Ash, John Cook, Daniel Druckman, Roger Shaw, Trevor Ward and Kerrie Wilson [to July 2023]), the Reef Water Quality Independent Science Panel (ISP), the Reef 2050 Independent Expert Panel (IEP), and Contract Managers (Australian Government's Department of Climate Change, Energy, the Environment and Water, DCCEEW; and Queensland Government's Department of Environment, Science and Innovation, DESI). The conceptual diagrams were prepared by Kate Hodge (Hodge Environmental).

The 30 individual syntheses of evidence that support this Summary document were peer reviewed by 63 independent reviewers, following a process similar to indexed scientific journals, with an Editorial Board managing the process (Editor-in-Chief: Russell Reichelt; Lead Editors: Stuart Bunn, Peter Doherty, Cameron Holley, Tony Jakeman, Geoff MacFarlane and John Rolfe). The ISP provided a technical review of this document, followed by external review by three eminent experts. Australia's Chief Scientist, Dr Cathy Foley, provided oversight and assurance for the 2022 Scientific Consensus Statement process.

For a complete list of individuals involved in the development of the 2022 Scientific Consensus Statement, see Appendix 2.

We would like to acknowledge the significant contribution to the 2022 Scientific Consensus Statement made by Professor Michael St J Warne who passed away before the project was completed. Professor Warne will be hugely missed by the Great Barrier Reef science community for his exceptional expertise in pesticides and other pollutants, and for the positive energy that he brought to every discussion.

We dedicate the 2022 Scientific Consensus Statement to the memory of Jon Brodie who led the previous Scientific Consensus Statements and made significant contributions over many decades to expand our scientific knowledge of the Great Barrier Reef and its catchments.

Mangroves, Goolboddi (Orpheus Island)
Photo: Matt Curnock

Australia’s Chief Scientist | Statement of Assurance

Dr Cathy Foley, Australia’s Chief Scientist, was tasked in 2021 by the Prime Minister to provide quality assurance and oversight for the development of the *2022 Scientific Consensus Statement on Land-Based Impacts on Great Barrier Reef Water Quality and Ecosystem Condition* (2021–2024).

The role of the Chief Scientist was to identify, recommend and support process enhancements that would increase transparency, accountability and confidence in the findings and conclusions of the 2022 Scientific Consensus Statement, to build on the continuous improvements applied to successive Scientific Consensus Statements since their commencement in 2002.

Australia’s Chief Scientist provided advice and made several recommendations to enhance the 2022 Scientific Consensus Statement process, through strengthened processes to manage conflicts of interest through the engagement of an external probity advisor and providing guidance on the development of the peer review process including appointment of Editorial Board members and eminent reviewers. For the five major process steps in the development of the 2022 Scientific Consensus Statement, Australia’s Chief Scientist concluded:

- **Question Setting:** The approach to question-setting was iterative and inclusive. The consultation process involved more than 70 stakeholders, Traditional Owner groups and end users from a range of organisations and industries. This ensured the final list of questions was broadly supported and as a result was relevant to non-government stakeholders, experts, policy makers and managers.
- **Author Selection:** The approach to author selection was transparent and robust and achieved the objectives of minimising bias and avoiding real or perceived conflicts of interest.
- **Methods Development:** The approach to the methods development was objective and transparent and took account of multiple lines of evidence and the best available science. There was adequate oversight to evaluate and review the validity and quality of the methods for all stages of the process.
- **Peer Review:** The peer review process was comprehensive and fully transparent, including the process for managing conflicts of interest. An Editorial Board was established to manage the review process. The editorial process involved contributions from 69 external reviewers from Australia and overseas to ensure the outputs were rigorous and credible.
- **Consensus Process:** Best practice methods were used for the consensus process and developed in an objective and transparent manner, taking account of multiple lines of evidence and including the best available science which contributed to the quality and integrity of the process. There was adequate oversight to evaluate and review the validity and quality of the 2022 Scientific Consensus Statement.

The *2022 Scientific Consensus Statement on Land-Based impacts on Great Barrier Reef Water Quality and Ecosystem Condition* is an exemplar of the academic methods for reaching scientific consensus. The public can trust the processes used to develop the 2022 Scientific Consensus Statement, and the conclusions can be relied upon and trusted to inform decision-making.

Reef Water Quality Independent Science Panel Remarks

The Independent Science Panel was established in 2009 to provide multidisciplinary scientific advice to the Australian and Queensland governments on the implementation of the Reef Water Quality Protection Plan. In this role, the Independent Science Panel has reviewed the 2013, 2017 and 2022 Scientific Consensus Statements.

The 2022 Scientific Consensus Statement is currently the best and most authoritative source of information to support evidence-based decisions for better water quality in the Great Barrier Reef World Heritage Area. The Independent Science Panel endorses the process, findings and conclusions of the updated statement.

The process used to develop the 2022 Scientific Consensus Statement was much more formalised compared to previous iterations. To meet the needs of end users, issues were categorised into 30 questions across eight major themes, with teams of expert authors enlisted to address each question. Structured templates, formal evidence appraisal methods and multiple review processes were used to ensure rigour, quality, transparency, independence and convergence in the outputs. The systematic approach used to assess the literature is novel in the field of environmental management and has proved to be a very effective strategy.

The results show that there is considerable and strong foundational evidence that has not changed since the previous Scientific Consensus Statement, including clear evidence of the impact of anthropogenic land-based runoff on water quality and freshwater, estuarine, coastal and inshore marine ecosystems. This provides greater confidence for managers in the strength of the evidence that underpins the Reef 2050 Water Quality Improvement Plan.

Notable advances from previous Scientific Consensus Statements are greater emphasis on climate change as a pressure and threat, increased analysis of management actions and their potential impacts, and much more focus on social and economic aspects of management as well as factors of success for engaging Traditional Owners in water quality issues. Improving water quality will bolster the resilience of ecosystems against climate change pressures, but scaling up remediation actions and implementing changes to management practices remains challenging.

Knowledge gaps still exist, in particular around potential co-benefits, the economics of changing different management practices, the social drivers that will help adoption of practice changes to improve water quality, and the role that wetlands can play as both an ecosystem asset and a regulating mechanism. While there has been more emphasis on the role of non-agricultural contaminants this is still a notable data gap.

In summary, the use of a systematic approach to assess literature in the field of environmental management establishes new standards for knowledge synthesis and enhances confidence in the quality of the findings. This Scientific Consensus Statement updates the peer reviewed knowledge about water quality issues and management options in the Great Barrier Reef and establishes a new reference point for subsequent governance, program design and investment.

1. Introduction and Process Overview

The 2022 Scientific Consensus Statement brings together the latest scientific evidence to understand how land-based activities can influence water quality in the Great Barrier Reef, and how these influences can be managed to improve water quality outcomes for the Great Barrier Reef.

The Scientific Consensus Statement is updated periodically and is used by policymakers as a foundational evidence-based document for making decisions about managing Great Barrier Reef water quality. It is one of several projects that provides supporting information for the design, delivery and implementation of the Australian and Queensland government's Reef 2050 Water Quality Improvement Plan. The Plan defines objectives and targets related to water quality improvement, identifies spatial management priorities and describes actions for improving the quality of the water that enters the Great Barrier Reef from the adjacent catchment area.

The **primary outputs** of the 2022 Scientific Consensus Statement are shown in Figure 1 and include:

- The 2022 Scientific Consensus Statement Conclusions
- The 2022 Scientific Consensus Statement Summary – This document
- The 2022 Scientific Consensus Statement Synthesis of the Evidence and high-level Evidence Statements

These outputs follow an informal hierarchy in the level of detail presented, moving from the full details of the synthesis of the evidence to a summary of that material, and finally the highest-level conclusions.

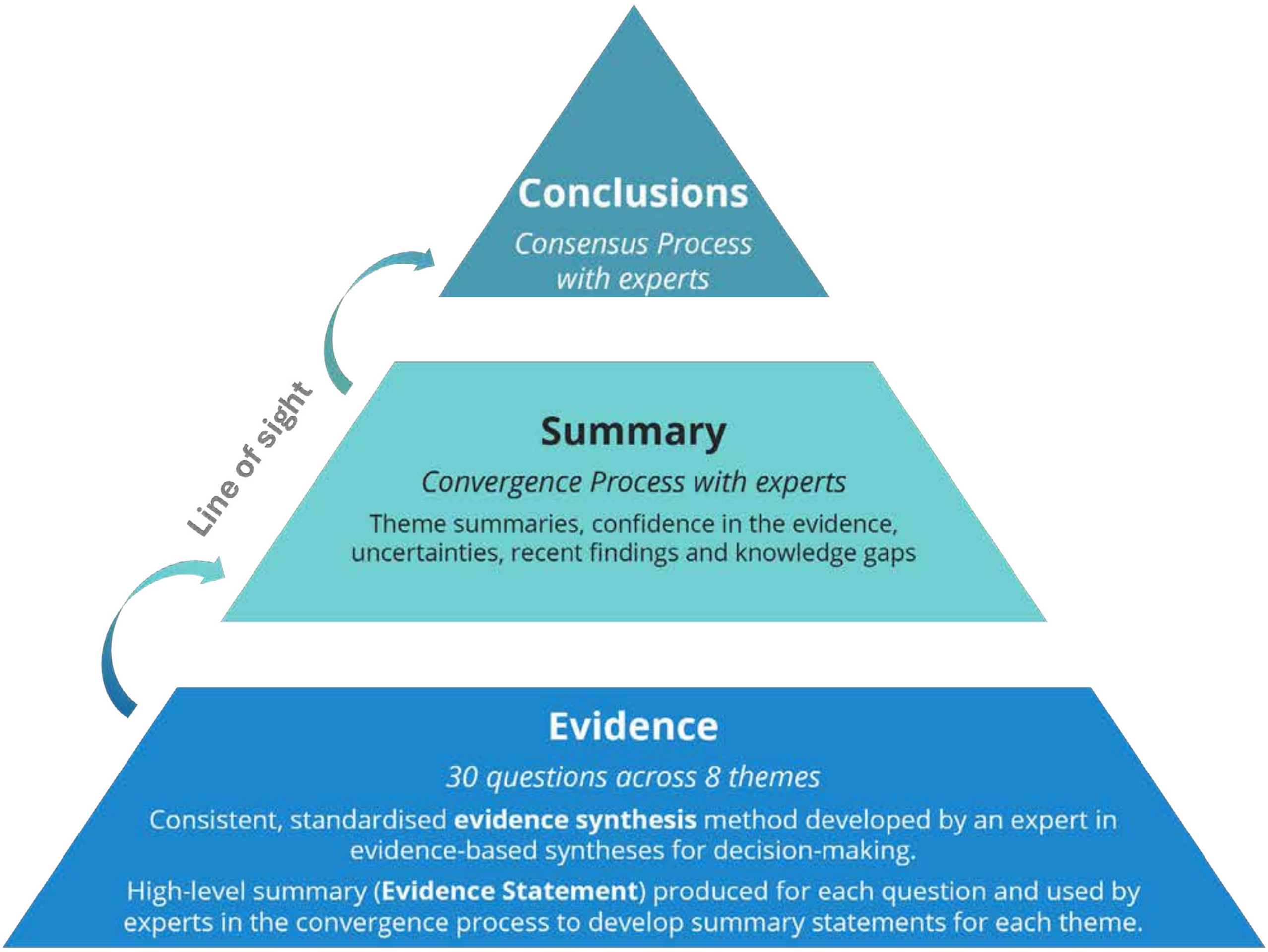

Figure 1. Main outputs and hierarchy of the 2022 Scientific Consensus Statement.

This document, the ‘2022 Scientific Consensus Statement Summary’, is structured into three sections. **Section 1** introduces the 2022 Scientific Consensus Statement and its main components, highlighting some of the differences between this and previous iterations (for more details see the Process section of the 2022 Scientific Consensus Statement website). **Section 2** contains the Overarching Conclusions resulting from the formal consensus process. **Section 3** contains the key findings for each Theme. This includes the Summary Statements developed with convergence among all experts within each Theme expert group, a summary of the results of the evidence appraisal for each Question (quantity, diversity, relevance, consistency and confidence)[1] and the supporting Evidence Statements for each question within a Theme, extracted from the syntheses of evidence.

1.1 Process overview

There are several changes to the way that the 2022 Scientific Consensus Statement has been developed, designed, and delivered compared to earlier iterations. These changes were introduced following stakeholder feedback which identified several areas for improvement including demonstrated independence from decision makers in the synthesis and review of the evidence, increased transparency and rigour in the approach to synthesise the evidence base, an assessment of the level of confidence in the findings, greater engagement with end users, stakeholders and other audiences, and more accessible outputs. To reinforce the commitment to these improvements, a set of guiding principles were developed that underpin the delivery and implementation of all aspects of the 2022 Scientific Consensus Statement process (Figure 2). These principles were supported and endorsed by a variety of audiences, stakeholders and end users including Australia’s Chief Scientist, the Reef Water Quality Independent Science Panel and the Reef 2050 Independent Expert Panel. C₂O Consulting coasts | climate | oceans was engaged by the Australian and Queensland governments to coordinate and deliver the 2022 Scientific Consensus Statement.

The scope of the 2022 Scientific Consensus Statement is underpinned by the conceptual framework in Figure 3 which was developed in consultation with the Reef Water Quality Independent Science Panel and a sub-group of scientific experts. This framework represents the breadth of scientific information needed to support the Reef 2050 Water Quality Improvement Plan. This is also illustrated in the map in Figure 4. The ecosystems within scope included coral reefs, seagrass meadows, mangroves, estuaries, saltmarshes, freshwater wetlands and the plankton, microbes, fish, megafauna, and other pelagic and benthic communities that inhabit them. The land uses of primary interest were grazing, sugarcane, horticulture and bananas, irrigated and dryland cropping (including grains) and urban land uses. Other non-agricultural land uses within scope included roads, sewage treatment plants, aquaculture and intensive industrial land uses. Conservation areas, forestry, mining and military land were out of scope.

The 2022 Scientific Consensus Statement has been developed over two years (2022–2024) and is the most comprehensive and rigorous assessment of land-based impacts on the water quality of the Great Barrier Reef to date. The major steps of the process are presented in Figure 2. The development of the 2022 Scientific Consensus Statement has involved almost 200 experts, researchers, scientists, policy and management teams, and other stakeholders and groups from Australia and overseas. It addresses 30 priority questions that were developed in consultation with scientific experts, policy and management teams and other key stakeholders including representatives from agricultural, tourism, conservation and research organisations, and Traditional Owner groups. The questions are organised into eight Themes: values, condition and drivers of health of the Great Barrier Reef, sediments and particulate nutrients, dissolved nutrients, pesticides, other pollutants, human dimensions of water quality improvements, and emerging science. For consistency, each pollutant Theme contains questions that cover ecological processes, delivery and source, and management options (Figure 5). The scope of each question was clarified with authors at the beginning of the process to minimise overlap between questions and ensure that they met end user expectations. The syntheses primarily focused on evidence from 1990 to December 2022.

To address the 30 questions, the 2022 Scientific Consensus Statement adopted a formal evidence review and synthesis method. Formal evidence review methods are increasingly being used where science is needed to inform decision making, and have become an internationally recognised standard for accessing, appraising and synthesising scientific information. More specifically, ‘evidence synthesis’ is the process of identifying, compiling and combining relevant knowledge from multiple

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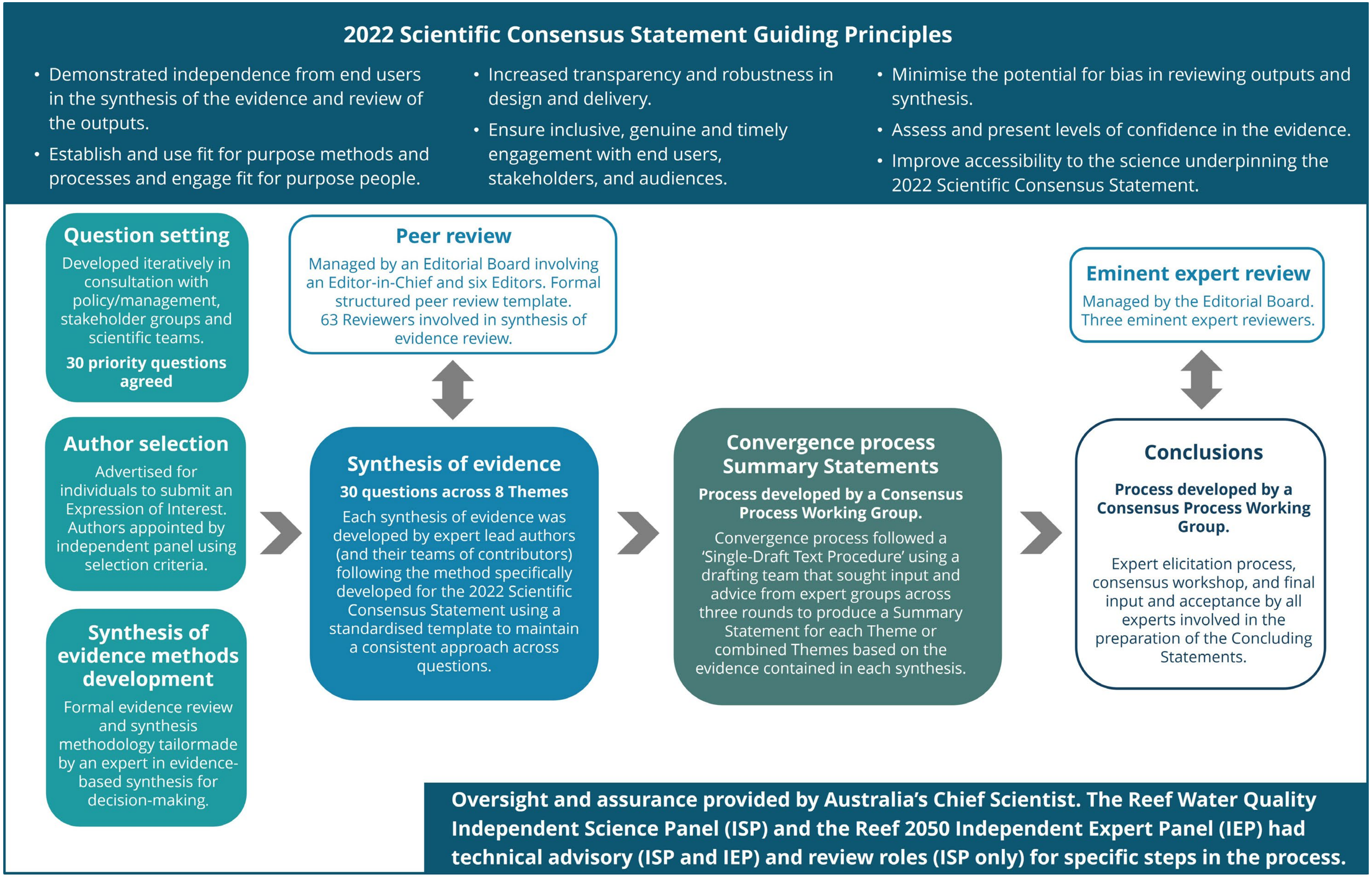
[1] Refer to the ‘2022 Scientific Consensus Statement Methods for the synthesis of evidence’ for additional information on the approach for the evidence appraisal.



2022 Scientific Consensus Statement Guiding Principles

- Demonstrated independence from end users in the synthesis of the evidence and review of the outputs.
- Establish and use fit for purpose methods and processes and engage fit for purpose people.
- Increased transparency and robustness in design and delivery.
- Ensure inclusive, genuine and timely engagement with end users, stakeholders, and audiences.
- Minimise the potential for bias in reviewing outputs and synthesis.
- Assess and present levels of confidence in the evidence.
- Improve accessibility to the science underpinning the 2022 Scientific Consensus Statement.

Question setting

Developed iteratively in consultation with policy/management, stakeholder groups and scientific teams.

30 priority questions agreed

Author selection

Advertised for individuals to submit an Expression of Interest. Authors appointed by independent panel using selection criteria.

Synthesis of evidence methods development

Formal evidence review and synthesis methodology tailormade by an expert in evidence-based synthesis for decision-making.

Peer review

Managed by an Editorial Board involving an Editor-in-Chief and six Editors. Formal structured peer review template. 63 Reviewers involved in synthesis of evidence review.

Synthesis of evidence

30 questions across 8 Themes

Each synthesis of evidence was developed by expert lead authors (and their teams of contributors) following the method specifically developed for the 2022 Scientific Consensus Statement using a standardised template to maintain a consistent approach across questions.

Convergence process Summary Statements

Process developed by a Consensus Process Working Group.

Convergence process followed a 'Single-Draft Text Procedure' using a drafting team that sought input and advice from expert groups across three rounds to produce a Summary Statement for each Theme or combined Themes based on the evidence contained in each synthesis.

Eminent expert review

Managed by the Editorial Board. Three eminent expert reviewers.

Conclusions

Process developed by a Consensus Process Working Group.

Expert elicitation process, consensus workshop, and final input and acceptance by all experts involved in the preparation of the Concluding Statements.

Oversight and assurance provided by Australia's Chief Scientist. The Reef Water Quality Independent Science Panel (ISP) and the Reef 2050 Independent Expert Panel (IEP) had technical advisory (ISP and IEP) and review roles (ISP only) for specific steps in the process.

Figure 2. Overview of the 2022 Scientific Consensus Statement process.

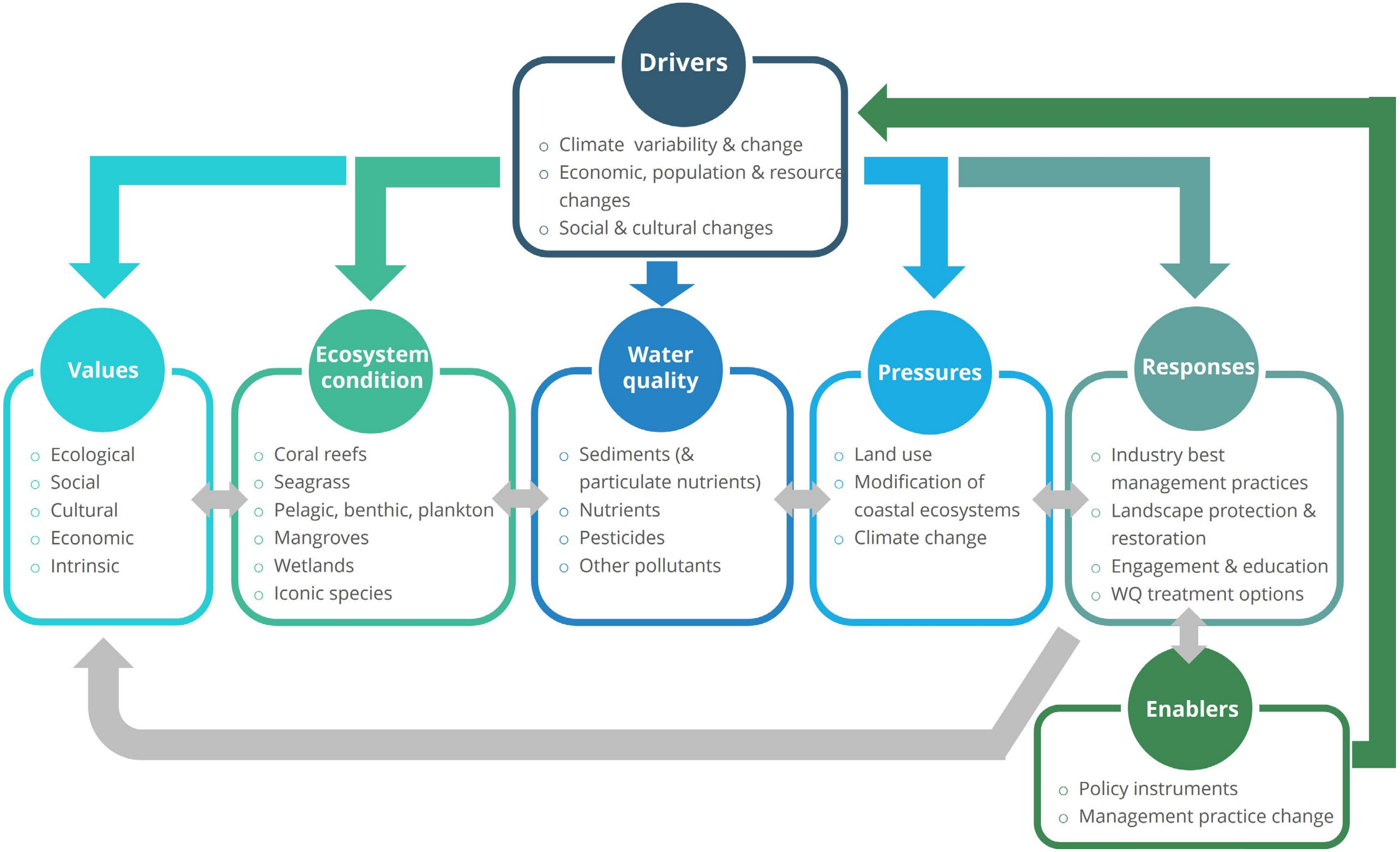
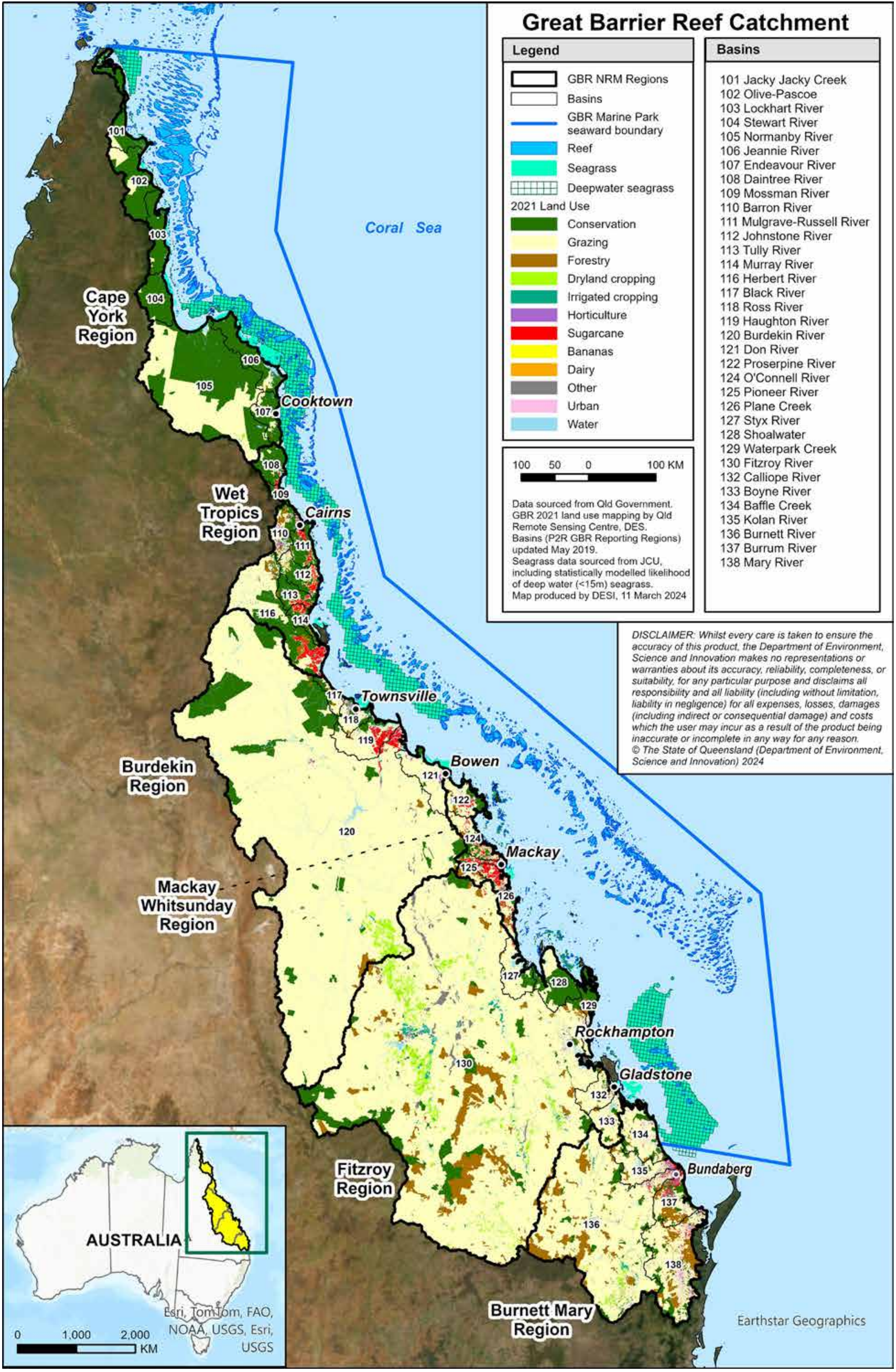


Figure 3. Overarching conceptual framework for the scope of the 2022 Scientific Consensus Statement.



Data sourced from Qld Government.
GBR 2021 land use mapping by Qld Remote Sensing Centre, DES.
Basins (P2R GBR Reporting Regions) updated May 2019.
Seagrass data sourced from JCU, including statistically modelled likelihood of deep water (<15m) seagrass.
Map produced by DESI, 11 March 2024

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Figure 4. Map illustrating the scope of the 2022 Scientific Consensus Statement including the 35 major basins in the adjacent catchment area, Natural Resource Management regions, major land uses, corals reefs and seagrass.

sources so it is readily available for decision makers[2]. Each synthesis included an appraisal of the evidence, which involved assessment of the relevance, quantity, diversity and consistency of the evidence base for answering the question. Importantly, this approach meant that for the first time, the Scientific Consensus Statement was able to formally assess the confidence in the scientific evidence for each question based on the overall relevance and consistency of the evidence base[3]. Each synthesis of evidence was peer reviewed by external and independent experts, following a similar process to indexed scientific journals. An Editorial Board, endorsed by Australia's Chief Scientist, managed the peer review process. All of the steps in the process have been documented and externally reviewed to provide assurance that the methods and approaches used are high-quality, transparent, reproducible and minimise bias. A high level of probity has been applied to all aspects of the project to ensure management of potential conflicts of interest for all participants in the process.

Oversight and assurance of the 2022 Scientific Consensus Statement process was provided by Australia's Chief Scientist. The Reef Water Quality Independent Science Panel (ISP) and the Reef 2050 Independent Expert Panel (IEP) had technical advisory (ISP and IEP) and review (ISP only) roles for specific steps in the process. Several expert working groups were established to support the development of methods to ensure best practice was followed for the synthesis of the evidence, peer review and consensus processes. Policy and management representatives and stakeholders, including the Reef 2050 Advisory Committee (RAC), were kept informed throughout the process.

1.2 The approach to scientific consensus

For the 2022 Scientific Consensus Statement, identifying the points of scientific consensus that are agreed by experts across multiple fields of research and disciplines is highly significant for policy makers, managers, delivery partners and broader audiences that all hold an interest in water quality outcomes for the Great Barrier Reef. The definition of consensus approved by the Reef Water Quality Independent Science Panel and applied for the 2022 Scientific Consensus Statement was: '*A public statement on scientific knowledge on Great Barrier Reef water quality and ecosystem condition, drawn from multiple lines of evidence, that is generally agreed by a representative group of experts. The consensus does not necessarily imply unanimity.*' The outputs of the consensus process also highlight the strength of the evidence, and areas where further knowledge is needed.

The steps where scientific consensus was sought from experts in the 2022 Scientific Consensus Statement were:

- **Evidence Statements** within the '2022 Scientific Consensus Statement Syntheses of Evidence': Agreement of the summary of findings relevant to policy or management action and supporting points was required among author teams for each of the 30 questions.
- **Summary Statements** within the '2022 Scientific Consensus Statement Summary' (this document): A formal convergence process using a 'Single-Draft Text Procedure' method[4] was used to produce a Summary Statement for each Theme. This involved a single drafting team who produced an initial draft based on the evidence contained in the syntheses. This draft was circulated to expert groups (all Lead Authors and several Contributors with specific expertise) and revised across three rounds until agreement was reached on the final Summary Statement for the Theme.
- **Concluding Statements** within the '2022 Scientific Consensus Statement Conclusions': The development of the Concluding Statements involved a formal expert elicitation process designed by an expert Consensus Process Working Group. A consensus workshop brought together the Lead Authors (and several Contributors with specific expertise) of the 30 questions to discuss and agree on a final set of Concluding Statements with a clear line of sight to the underpinning evidence base.

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[2] 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.

[3] Refer to the '2022 Scientific Consensus Statement Methods for the synthesis of evidence' for additional information on the approach for the evidence appraisal and the categories presented for each indicator (quantity, diversity, relevance, consistency and confidence).

[4] Single-text negotiation and One-text procedure

Themes 1 & 2

Values, condition and drivers of health of the Great Barrier Reef

Theme 3

Sediments and particulate nutrients

Theme 4

Dissolved nutrients

Themes 5 & 6

Pesticides and other pollutants

Themes 7 & 8

Human dimensions of water quality improvement and emerging science

Figure 5. Structure of the 2022 Scientific Consensus Statement.

2. Overarching Conclusions

This section is an excerpt from the *2022 Scientific Consensus Statement Conclusions*. These Overarching Conclusions were agreed by the 35 experts who were involved in the 2022 Scientific Consensus Statement Conclusions consensus process (listed in **Appendix 1**).

1 Historical and continuing land management and catchment modification impair Great Barrier Reef water quality through extensive vegetation degradation, changed hydrology, increased erosion, and expansion of fertilised land uses, urban centres and coastal developments.

2 Pollutant loads from the catchment area to the Great Barrier Reef have increased from pre-development loads by 1.4 to 5 times for fine sediments, and 1.5 to 3 times for dissolved inorganic nitrogen (with variations depending on basins).

3 Poor water quality, particularly elevated levels of fine sediments, nutrients and pesticides, continues to have detrimental impacts on Great Barrier Reef ecosystems. The greatest impacts are on freshwater, estuarine, coastal and inshore marine ecosystems.

4 Human-induced climate change is the primary threat to the Great Barrier Reef and poor water quality can exacerbate climate-related impacts. Good water quality is critical for healthy and resilient ecosystems and supports recovery from disturbances such as mass bleaching and extreme weather events. Meeting water quality improvement targets[5] within the next ten years is imperative.

5 While several land management practices and remediation actions are proven to be cost-effective in improving water quality, translating these into more substantial pollutant reductions will require significant scaling up of the adoption of these actions, prioritisation of pollutant hotspots, and greater knowledge of the costs and potential co-benefits of practice adoption.

6 Greater focus on locally effective management solutions can encourage faster adoption, especially when designed and delivered using collaborative approaches involving landholders, Indigenous communities, the broader community, policy makers and scientists.

7 World-leading monitoring, modelling and reporting programs underpin the Great Barrier Reef ecosystems and provide essential knowledge to inform water quality improvement strategies. These programs could be strengthened and refined by increasing their spatial and temporal coverage to capture regional and local differences, provide more balanced coverage across land uses and ecosystems, improve trend analysis and quantify uncertainties.

8 Expanded research effort and more consistent methods are urgently needed to adequately assess 1) the co-benefits and efficiency (including costs) of management solutions across different landscape and climate conditions, 2) the effectiveness of water quality improvement programs and instruments including assessment beyond the life of programs, and 3) ecosystem risks from a wider range of pollutants.

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[5] The 2025 targets defined in the Reef 2050 Water Quality Improvement Plan [currently under review] require a 25% reduction in the 2009 anthropogenic end-of-catchment fine sediment loads, 20% reduction of particulate nutrients, and a 60% reduction of dissolved inorganic nitrogen loads. The target for pesticides is to protect at least 99% of aquatic species at end-of-catchments by 2025.

3. Theme Summaries

Yunbenun (Magnetic Island)
Photo: Matt Curnock

Themes 1 and 2: Values, condition and drivers of health of the Great Barrier Reef

Themes 1 and 2: Values, condition and drivers of health of the Great Barrier Reef

Context

The Great Barrier Reef is one of the most complex natural systems on Earth and was listed as a UNESCO World Heritage Area in 1981 due to its Outstanding Universal Value. It spans 348,700 km² and encompasses multiple ecosystems across terrestrial and aquatic landscapes and is highly valued at local, national and international scales. However, the Great Barrier Reef is subject to a growing number of local and global pressures which can affect the health of its ecosystems, resulting in serious concerns for the long-term outlook of the Great Barrier Reef.

The synthesis of the evidence for **Themes 1 and 2** included a total of **1,023** studies extracted and synthesised for **6** questions (with some overlap in evidence between questions) (Figure 6). These combined Themes present the relevant background information for the 2022 Scientific Consensus Statement including evidence of the ecological, cultural, and socioeconomic assets and values for the Great Barrier Reef (Q1.1), and the current status, condition and key threats for selected ecosystems (Q1.2/1.3/2.1). Evidence about the impact of climate change, the primary threat to the health of the Great Barrier Reef (Q2.2), and the interaction between climate change and poor water quality (Q2.4) are examined in more detail. Connectivity between the Great Barrier Reef catchment, coastal and marine ecosystems, and the threats to those connections, are also described (Q1.4), as is evidence for changes in land-based runoff to the Great Barrier Reef since the arrival of Europeans (Q2.3).

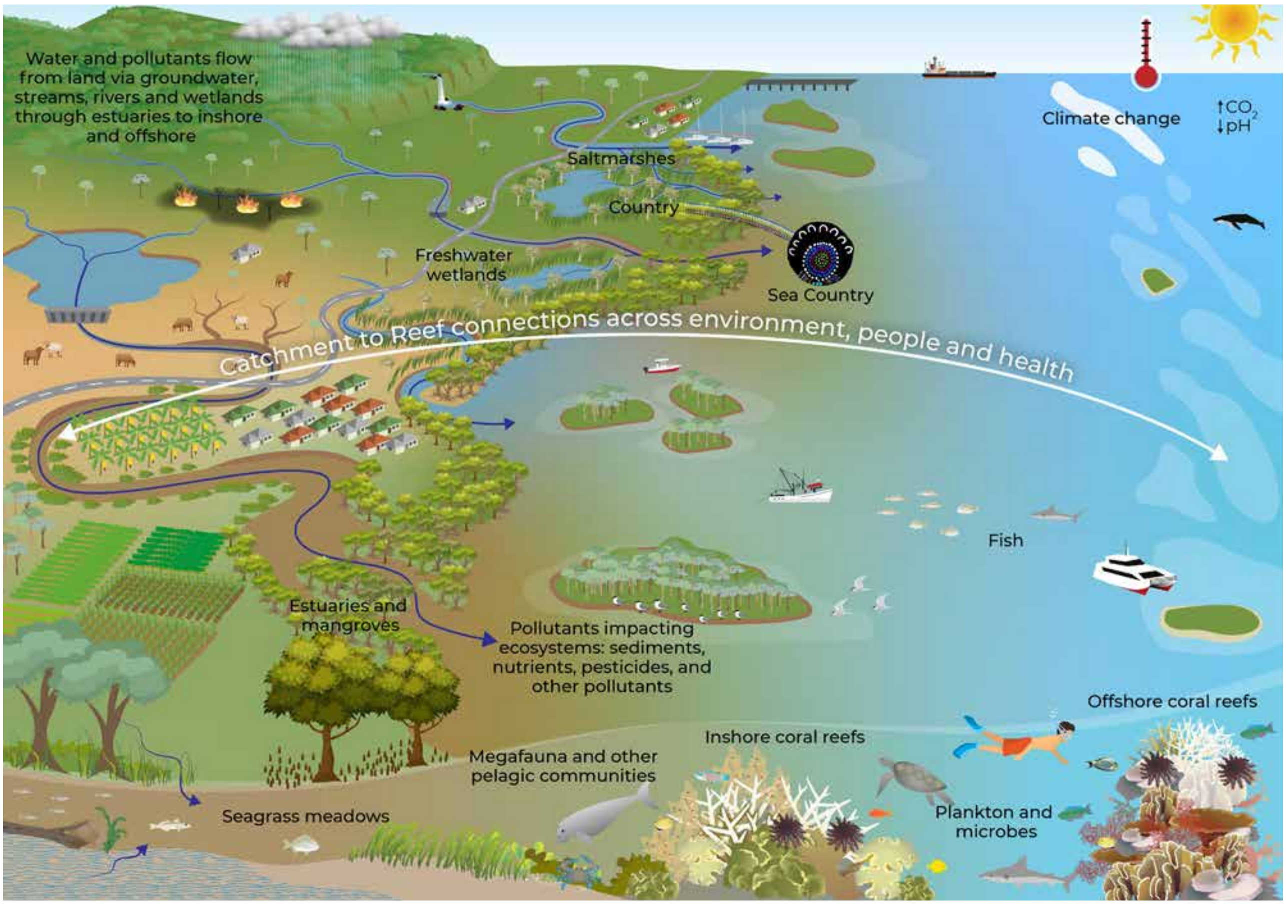

Figure 6. This diagram is a pictorial representation of the scope of Themes 1 & 2. It represents a section of the Great Barrier Reef catchment and marine environment, including the main ecosystems covered in the 2022 Scientific Consensus Statement (inshore and offshore coral reefs, seagrass meadows, mangroves, estuaries, saltmarshes, freshwater wetlands, plankton and microbes, fish, megafauna, and other pelagic and benthic communities) and the ecosystem connections, main values (ecological, cultural, economic and social) and main drivers of health (such as climate change, poor water quality - including increased sediments, nutrients, pesticides and other pollutants, coastal development, invasive species, outbreaks of crown-of-thorns starfish, and other pressures related to direct use).

Summary Statement for Themes 1 and 2

Convergence was reached for this Summary Statement among all authors within the Expert Group for Themes 1 and 2 (listed in **Appendix 1**).

The synthesis of the evidence for **Themes 1 and 2** included a total of **1,023** studies extracted and synthesised for **6** questions (with some overlap in evidence between questions).

The **summary of findings** relevant to policy or management action for **Themes 1 and 2** are:

- The Great Barrier Reef covers an area of 348,700 km² from the tip of Cape York to Bundaberg (including 24,094 km² of coral reefs, 35,679 km² of seagrass meadows, 2,188 km² of mangroves, 1,757 km² of salt flats and saltmarshes, and 15,556 km² of wetlands). It has high connectivity to the adjacent catchment area (424,000 km²), as demonstrated by input of land-based materials (especially sediments, organic material, nutrients and pesticides), movements in the life histories of many species and the dispersal of plankton and movement of larger organisms. Connections across the catchment to reef landscape are diverse and essential to many biogeochemical and ecological processes, plants and animals, and may be modified or interrupted by some natural and, increasingly, anthropogenic processes and drivers such as floodplain drainage, artificial structures for water management, stretches of poor water quality, and dense plant growth. [Q1.2/1.3/2.1, Q1.4]
- The Great Barrier Reef encompasses ecological, social, economic, and culturally diverse (including Indigenous heritage) values which are also interconnected. Any decline in the condition of ecosystems, including disruption of ecological processes, can also have a direct impact on connected socio-ecological services and other Great Barrier Reef values. [Q1.1, Q1.4]
- The current condition of the Great Barrier Reef varies between ecosystems and locations. Observational studies report that the condition of Great Barrier Reef inshore coral reef ecosystems from the Wet Tropics to the Fitzroy region has declined marginally since 2017 and was categorised as ‘Poor’ condition in 2020 to 2021[6] (based on a multi-indicator resilience index) with regional differences. Hard coral cover on shallow mid- and outer shelf reefs has increased overall since 2017, showing fast recovery from Cooktown to Bundaberg after experiencing losses from repeated mass coral bleaching and/or crown-of-thorns starfish between 2016 and 2019[7]. Inshore seagrass meadows across the Great Barrier Reef declined from ‘Moderate’ abundance and resilience in 2017 to ‘Poor’ in 2020[6], and while overall condition improved in 2021 (to Moderate), there were continuing declines in the Fitzroy and Burnett Mary regions. These declines were primarily a consequence of above-average discharges from some rivers and disturbance from tropical cyclones. Mangroves and saltmarsh ecosystems are considered stable and in Good condition[8], and wetlands are considered stable but in Moderate condition[6], however, historical loss of wetland extent has been significant for some wetland types in some regions. [Q1.2/1.3/2.1]
- Although the overall primary threat to Great Barrier Reef ecosystems is climate change, poor water quality from land-based delivery of fine sediments, nutrients, pesticides and other pollutants is also a major threat, especially for freshwater, coastal and inshore marine ecosystems. Other threats including tropical cyclones and storms, crown-of-thorns starfish and, to a lesser extent, direct use, can impact certain ecosystems at different levels. Multiple stressors acting in a cumulative manner are also becoming increasingly important. [Q1.2/1.3/2.1]
- Studies over the last three decades confirm that the climate of the Great Barrier Reef is changing rapidly and in multiple ways, with some changes already significantly impacting Great Barrier Reef ecosystems, organisms and water quality. These impacts are occurring through rising temperature, increasing frequencies of marine heatwaves, increasing ocean acidification, sea level rise, and more extreme rainfall events. Additional regionally specific predictions include increasing frequency of droughts and drought-breaking floods in the southern Great Barrier Reef (south of Bowen), and a potential reduction in the frequency but increasing intensity of tropical cyclones in the northern Great Barrier Reef (north of Bowen). [Q2.2]
- There is consistent evidence that periods of extreme sea surface temperature are causing mass coral bleaching and mortality. Thermal extremes also cause stress and damage to numerous other marine organisms including

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[6] Reef Water Quality Report Card 2020

[7] AIMS Long Term Monitoring Program

[8] Great Barrier Reef Outlook Report 2019

some species of fish, sponges, and seagrasses. There is limited information on the impacts of climate change on Great Barrier Reef wetlands. [Q2.2]

- There are multiple lines of evidence demonstrating that the volume of river discharge and loads of suspended sediment, dissolved and particulate nutrients (nitrogen and phosphorus), and pesticides have increased for most river basins of the Great Barrier Reef catchment area since the arrival of Europeans c. 1850. The increases in loads have largely occurred because catchments have been modified for the major land uses of livestock grazing (73% of catchment area), irrigated and dryland cropping (2.8%), sugarcane (1.2%), horticulture and bananas (0.2%), urban development (0.7%) and mining (0.3%), in combination with long-term climate variability. Evidence of increases in catchment loads comes from fluvial proxy records, coral-reef proxies (including coral and reef sediment cores), water quality monitoring and subcatchment and catchment-scale modelling. [Q2.3]
- The footprint of increased land-based runoff and pollutant loads within the Great Barrier Reef is most pronounced in estuarine, coastal and inshore environments but can be evident more than 100 kilometres alongshore from the river mouth of influence. Those ecosystems nearest to the mainland are at greatest risk from exposure to chronic poor water quality associated with land-based runoff. While these areas generally represent a relatively small proportion of the Great Barrier Reef, they provide critical ecosystem services and maintain high tourism, aesthetic, spiritual and recreational values. [Q1.1, Q1.2/1.3/2.1, Q2.3]
- There is consistent evidence that climate change factors (including temperature and ocean acidification) and water quality characteristics (including nutrients, light/sediments and pesticides) have interactive effects on a variety of organisms in coral reef ecosystems of the Great Barrier Reef. In the majority of cases, the outcome for the organism is worse under these combined stressors. Improved water quality indirectly benefits coral reef ecosystems by increasing resilience of organisms and reducing recovery time following acute disturbances such as bleaching, crown-of-thorns starfish outbreaks and cyclones. Resilience will become increasingly important as climate pressures continue to grow. [Q2.4]
- The evidence confirms the urgency of meeting all Great Barrier Reef water quality targets within the next ten years before impacts exceed the capacity for Great Barrier Reef ecosystems to persist. [Q2.2]
- Current knowledge of the catchment to reef landscape is sufficient to provide a holistic framework for future policy and management, incorporating cross-disciplinary and cross-jurisdictional planning to the entire catchment to reef landscape. [Q1.4]

Bleached corals
Photo: J.Stella. © Commonwealth of Australia (Reef Authority)

The **confidence** rating of the questions in **Themes 1 and 2** was High with only Question 2.3 rating Moderate-High due to Moderate-High consistency in the results. The findings in these Themes are underpinned by a large body of evidence, including concepts that have been consistently repeated for more than three decades. The **strength of evidence** across these Themes, considering the confidence, quantity and diversity of study types is generally considered to be consistently High, with some exceptions related to the cumulative effects of different pressures, and the impacts of pressures on coastal ecosystems including estuaries, mangroves and freshwater wetlands.

The **key uncertainties** identified in these Themes were associated with the extrapolation of the key findings under different episodic climatic events or under changing climate conditions. Additionally, not all Great Barrier Reef ecosystems and habitats are equally assessed spatially or temporally, rendering overall condition assessments, and prediction of future responses to increasing threats, challenging.

Recent findings show the need for greater emphasis on social values, on the role of Indigenous knowledge in decision making for the Great Barrier Reef, further documentation of evidence of land use change in the catchment area, and a shift in the severity of climate-related impacts on Great Barrier Reef ecosystems and associated values. Climate-related impacts are predicted to intensify rapidly throughout this century, with severity depending on global carbon dioxide emission pathways. The importance of the role of improved water quality in the context of climate change has become clearer and the evidence of the combined effects of climate and different water quality conditions has strengthened.

Within **Themes 1 and 2**, the areas where further **knowledge is needed** that are most relevant to policy and management are: i) greater understanding of the interconnectivity between the socio-ecological, cultural, intrinsic and economic values of the Great Barrier Reef; ii) greater spatial and temporal assessment for wetlands and deep marine ecosystems within the Great Barrier Reef; iii) further development of new rare earth element and longer-term coral proxies to help reconstruct changes in sediment and particularly nutrient exposure in the Great Barrier Reef; iv) increased knowledge of the combined impact of multiple stressors on a range of ecosystems and species; and v) identifying whether water quality guidelines need to be adjusted under changing climatic conditions.

Aerial view of a coral reef
Photo: GeoNadir

Summary information for Questions in Themes 1 and 2

The Table below summarises the evidence appraisal indicators and confidence ratings in the evidence base for each of the Questions within these Themes. The Confidence rating was determined by the overall relevance of studies to the question and the consistency of the body of evidence (refer also to Appendix 3: Glossary for explanation of indicators). *Note: In Diversity of items: Experimental (E), Mixed (X), Modelling (M), Monitoring (N), Observational (O), Reviews (R), Theoretical or Conceptual (T), Proxy (P), Sediment Cores (C).*

Question	**Quantity of items**	**Diversity of items**	**Overall relevance**	**Consistency**	**Confidence**
What are the socio-ecological, cultural, economic and intrinsic values of the Great Barrier Reef? [1.1]	High (85)	High *(62% O, 19% R, 11% M, 5% E, 3% T)*	High	High	High
What is the extent and condition of Great Barrier Reef ecosystems and what are the primary threats to their health? [1.2/1.3/2.1]	High (100)	High *(52% O, 27% M, 19% R, 2% T)*	High	High	High
How are the Great Barrier Reef's key ecosystem processes connected from the catchment to the reef and what are the primary factors that influence these connections? [1.4]	High (276)	Moderate *(69% O, 15% R, 14% M, 2% E)*	High	High	High
What are the current and predicted impacts of climate change on Great Barrier Reef ecosystems (including spatial and temporal distribution of impacts)? [2.2]	High (317)	High *(37% O, 32% E, 22% M, 9% R)*	High	High	High
What evidence is there for changes in land-based runoff from pre-development estimates in the Great Barrier Reef? [2.3]	High (128)	High *(64% E-O including 44% P & 20% C; 15% N, 12% O, 9% M)*	High	Moderate-High	Moderate - High
How do water quality and climate change interact to influence the health and resilience of Great Barrier Reef ecosystems? [2.4]	High (117)	High *(61% E, 13% M, 13% R, 9% X, 4% O)*	High	High	High

Evidence Statements for Questions in Themes 1 and 2

What are the socio-ecological, cultural, economic and intrinsic values of the Great Barrier Reef? [1.1]

Maxine Newlands, Oluwatosin Olayioye

The synthesis of the evidence for **Question 1.1** was based on 85 studies undertaken predominantly within the Great Barrier Reef region and published between 1990 and 2023. The synthesis includes a *High* diversity of study types (62% observational, 11% modelled, 5% experimental, 3% theoretical and 19% reviews), and has a *High* confidence rating (based on *High* consistency and *High* overall relevance of studies).

Summary of findings relevant to policy or management action

The Great Barrier Reef embodies a diverse array of values including ecological (including biological), social, economic and cultural (including Indigenous and non-Indigenous) heritage values. Its outstanding universal value is formally recognised through the declaration of the Great Barrier Reef as a World Heritage Area in 1981. The values and benefits generated by the Great Barrier Reef are multifaceted and intertwined. Values range from tangible commercial benefits like tourism, recreation and commercial fishing, to cultural aspects, including Indigenous heritage and identity. Many benefits are enjoyed directly, including recreational activities such as snorkelling, diving, and boating, that enrich people's wellbeing and lifestyle. The Great Barrier Reef also generates a range of indirect and non-use benefits, including the intrinsic value of its existence, aesthetic, lifestyle, protection, educational and research outcomes. Quantifying the benefits of the Great Barrier Reef is complex given the large number of factors involved and diversity of stakeholders. Financial investments, regulatory instruments, policy and management decisions are typically informed through the assessment of values, and these values can vary across the Great Barrier Reef region depending on location, demographics and the benefits being assessed. A number of threats to the values of the Great Barrier Reef have been identified, though climate change is recognised as the most significant.

Supporting points

- The Great Barrier Reef is a complex and diverse ecosystem that supports a vast array of marine life including fish, corals, turtles, dugong, whales, and many other life forms. It encompasses 70 'bioregions' (30 reef bioregions and 40 non-reefal bioregions) and it is home to thousands of species, including many endangered and threatened species, making it important for ecosystem biodiversity. The Great Barrier Reef and its catchment area also provides many ecosystem services and related livelihoods for Great Barrier Reef communities.
- Different conceptual frameworks are available to depict the complex relationships between ecological and human systems which categorise the flow of uses, benefits and services in different ways, informing concepts of value. The Total Economic Value framework and Ecosystem Services framework are two of the main approaches that have been applied. More recent approaches place greater emphasis on the relationships between people and ecosystems and how the condition and perceptions of the Great Barrier Reef can impact on those.
- Previous (pre-pandemic) economic analyses show that the Great Barrier Reef generates billions of dollars annually through tourism, fishing, research and recreational activities. It supports approximately 64,000 direct and indirect jobs and attracts over two million visitors each year who contribute to the local and national economies through spending on accommodation, trips to the reef, and other services. However, there is a need for updated economic information that considers the economic, social and cultural implication of bleaching events and the economic effects of the COVID-19 pandemic on a larger scale.
- Australians, even those who do not use it directly, place great value on the Great Barrier Reef, and broadly support efforts to ensure the maintenance and continuation of its existence, aesthetic and other intrinsic benefits. Further loss of values may affect public trust in the government's ability to effectively manage the Great Barrier Reef.
- Cultural heritage values, particularly the Indigenous values of Aboriginal and Torres Strait Islander peoples and their connection with traditional lands and waters are significantly important. The Great Barrier Reef has deep spiritual, cultural, and historical significance to these communities, having been at the heart of their culture and way of life for thousands of years, supplying sustenance, cultural practices, and connections to ancestral lands.

- The low level of Indigenous participation in studies on the values of the Great Barrier Reef is identified as a gap, and there is a need for further research into methodologies that incorporate Indigenous values into established models.
- There are knowledge gaps in the understanding of value concepts, particularly how scientists and researchers define 'value.' The evidence suggests that the development of a typology of Great Barrier Reef values that considers different perspectives and cultures would be helpful to define those values.
- The health of the Great Barrier Reef has an important impact on people's economic security and sense of wellbeing, and the connection between value, health and wellbeing is critically important, particularly in the context of the threats impacting its Outstanding Universal Value.

What is the extent and condition of Great Barrier Reef ecosystems and what are the primary threats to their health? [1.2/1.3/2.1]

Len McKenzie, Mari-Carmen Pineda, Alana Grech, Angus Thompson

The synthesis of the evidence for **Question 1.2/1.3/2.1** was based on 100 studies undertaken within the Great Barrier Reef and published between 2017 and 2022 with this timeframe selected to reflect 'current' conditions. The synthesis includes a *High* diversity of study types (52% observational, 27% modelling, 19% reviews and 2% conceptual), and has a *High* confidence rating (based on *High* consistency and *High* overall relevance of studies).

Summary of findings relevant to policy or management action

Observational studies report that the condition of inshore Great Barrier Reef coral reef and seagrass ecosystems declined marginally from 2017 to 2019 (to Poor condition[9]) due to elevated sea temperatures and heatwaves, tropical cyclones and, additionally in the case of corals, crown-of-thorns starfish. Evidence from 2020 to 2021 has documented recovery of some, but not all, coral reef and inshore seagrass ecosystems. Recovery varied spatially and for coral reefs was less evident or did not occur on inshore reefs from the Burdekin region south or offshore in the Fitzroy region. Mangroves and saltmarsh ecosystems are considered stable and in Good condition[10]. Wetlands are considered stable but in Moderate condition[9] although this varies with wetland types. Based on multiple lines of evidence, the primary threats to Great Barrier Reef marine ecosystems (in order of relative importance) are human-induced climate change, including elevated sea surface temperatures, heatwaves and ocean acidification, and poor water quality from land-based delivery of fine sediments, nutrients, pesticides and other pollutants. For mangroves and saltmarshes, the primary threats are climate change related, including storms, extreme sea level variation and heatwaves. For wetlands, threats include landscape modification and vegetation clearing leading to wetland loss, poor water quality, invasive species, changes in hydrological connectivity, and increasing temperature and salinity from climate change. There is consistent evidence that the resilience of Great Barrier Reef ecosystems is affected by the cumulative impacts of climate change along with local acute stressors such as tropical cyclones and chronic stressors including poor water quality. For marine ecosystems, those nearest to the mainland are at greatest risk from exposure to chronic poor water quality associated with land-based runoff which can have a direct impact but can also impede the ability of these ecosystems to recover from acute pressures.

Supporting points

- Great Barrier Reef ecosystems are extensive and diverse; however, not all ecosystems and habitats are equally assessed spatially or temporally, rendering overall condition assessments challenging.
- There are 24,094 km² of coral reefs mapped within the Great Barrier Reef. The condition of inshore coral reefs from the Wet Tropics to the Fitzroy Natural Resource Management region has declined marginally since 2017 and was categorised as Poor[9] in 2020 to 2021 (based on a multi-indicator resilience index) with regional differences. Hard coral cover on shallow mid- and outer shelf reefs has increased overall since 2017, showing fast recovery from Cooktown to Bundaberg after experiencing losses from repeated

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[9] Reef Water Quality Report Card 2020

[10] Great Barrier Reef Outlook Report 2019

mass coral bleaching and/or crown-of-thorns starfish between 2016 and 2019[11].

- The primary threats to Great Barrier Reef coral reef ecosystems are rising sea surface temperature and heatwaves, tropical cyclones, outbreaks of crown-of-thorns starfish, and ocean acidification. For corals on inshore reefs, their ability to resist or recover from these threats is impeded by additional pressures imposed by land-based runoff and associated impacts such as reduced light, increased macroalgal growth and disease.
- Seagrass meadows are dynamic, changing seasonally in extent and condition, and cover an estimated 35,679 km². Inshore seagrass meadows across the Great Barrier Reef declined from Moderate abundance and resilience in 2017 to Poor in 2020[9], and while overall condition improved in 2021 (to Moderate), there were continuing declines in the Fitzroy and Burnett Mary regions. These continuing declines were primarily a consequence of above-average discharges from some rivers and disturbance from tropical cyclones.
- The primary threats to seagrass meadows in the Great Barrier Reef are tropical cyclones, land-based runoff (particularly fine sediments and pesticides), and thermal stress from rising sea surface temperatures.
- Other components of the Great Barrier Reef marine ecosystem (pelagic, benthic and planktonic communities) are not included in current monitoring programs and there is limited assessment, however, there are some individual studies that indicate long-term decline in ecosystem condition.
- Although some regional populations of dugongs and turtles are recovering (e.g., southern green turtle), populations of the Great Barrier Reef are in Poor condition and in decline[12]. The greatest threats to dugong and turtle populations are incidental catch (fishing) and loss of habitats (e.g., seagrass loss due to land-based runoff and floods); pollutants in land-based runoff such as trace elements and temperature related feminisation of turtle hatchlings are also important in some locations.
- In Great Barrier Reef estuaries, there are 2,188 km² of mangroves and 1,757 km² of salt flats and saltmarshes. Apart from minor localised losses, they are stable and in Good condition[12]. The primary threats to mangroves and saltmarshes are climate change-related including extreme events such as tropical cyclones and storms, extreme sea level variations, and heatwaves.
- In the Great Barrier Reef catchment area, the most recent assessment of wetland extent in 2017 reported 15,556 km² of mapped wetlands (artificial/highly modified, lacustrine, palustrine, riverine and estuarine), estimated at around 85% of pre-development extent, in stable and Moderate condition[9]. However, the extent varies between wetland types and regions with substantial declines in some areas (e.g., significant losses in extent of palustrine wetlands such as vegetated swamps in the Wet Tropics and Mackay Whitsunday regions of ~49% and ~44% respectively, compared to pre-development estimates).

How are the Great Barrier Reef's key ecosystem processes connected from the catchment to the reef and what are the primary factors that influence these connections? [1.4]

Aaron Davis, Richard Pearson

The synthesis of the evidence for **Question 1.4** was based on 276 studies undertaken mostly in the Great Barrier Reef and published between 1990 and 2022. The synthesis includes a *Moderate* diversity of study types (observational 69%, experimental 2%, modelling 14% and reviews 15%), and has a *High* confidence rating for both catchment and marine components (based on *High* consistency and *High* overall relevance of studies).

Summary of findings relevant to policy or management action

Evidence published over the last three decades for the Great Barrier Reef and its catchment universally indicates the importance of the biophysical, and particularly the hydrological, connections within and between freshwater and marine ecosystems. Connections across the catchment to reef landscape are diverse and essential to many biogeochemical and ecological processes, plants and animals. In the

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[11] AIMS Long Term Monitoring Program

[12] Great Barrier Reef Outlook Report 2019

catchment, there are important connections between land and waterways, and through the aquatic system, with transport of dissolved and suspended materials from land-based activities (e.g., agriculture, urban areas and coastal development), including sediments, organic material, nutrients and pesticides, plant propagules and animal larvae. Larger animals, especially fish, actively move between connected habitats for reproduction and dispersal. The strength of the catchment to reef connections typically diminishes from inshore to offshore, especially in the case of the transport of sediments and dissolved materials. However, some connections remain strong across an inshore to offshore gradient, for example, for animal species that migrate from streams to oceanic waters. Strong connections in marine systems are driven by prevailing water currents for planktonic organisms, and by migratory capabilities of others, especially vertebrates. Connectivity is strongly influenced by many spatial and temporal patterns and processes (e.g., biogeographic history, oceanographic and catchment hydrodynamics, flood plumes, tides, life history strategies), and may be interrupted by some natural and, increasingly, anthropogenic processes and drivers. Current knowledge is sufficient to provide a holistic framework for future policy and management, incorporating cross-disciplinary and cross-jurisdictional planning to the entire catchment to reef landscape.

Supporting points

- Demonstrated connections between the catchment and the reef include:
    - Input of land-based materials (especially sediments, organic material, nutrients and pesticides), with variable effects on downstream environments.
    - A range of interdependencies between catchments, estuaries and the Great Barrier Reef lagoon in the life histories of many species, especially crustaceans and fish, largely determined spatially and temporally by water connections and currents.
    - Passive dispersal of plankton, including animal larvae, and plant propagules, by marine currents.
    - Active dispersal and migration of larger organisms, including sharks, bony fish, turtles, birds, dugongs and whales.
- Coastal ecosystems provide a critical biogeochemical and hydrological connection between catchment and marine habitats. These ecosystems fix and transform materials (particularly carbon and nitrogen), and exchange gases and dissolved and particulate materials with adjacent coastal habitats, such as deeper seagrass communities and nearshore coral reefs. They also provide important habitat for many species that move between the catchment and the reef.
- Coastal ecosystems dominated by plants – such as mangroves, saltmarshes, and seagrasses –are increasingly appreciated for playing a large and critical role in the global sequestration of carbon that would otherwise remain as atmospheric CO_2 which can exacerbate climate change.
- Anthropogenic barriers to connectivity are created by artificial structures for water management in catchments, such as dams, weirs, other water control structures, and culverts; by stretches of poor water quality, especially discharges during critical periods of faunal movement; and dense plant growth (exacerbated by loss of riparian shade and input of nutrients from agricultural drainage). Marine dispersal may be interrupted or curtailed by natural temperature gradients, human-induced change to marine temperature regimes and input of poor water quality from catchments.

What are the current and predicted impacts of climate change on Great Barrier Reef ecosystems (including spatial and temporal distribution of impacts)? How is climate change currently influencing water quality in coastal and marine areas of the Great Barrier Reef, and how is this predicted to change over time? [2.2, 2.2.1]

Katharina Fabricius, Aimee Brown, Al Songcuan, Catherine Collier, Sven Uthicke, Barbara Robson

The summary of the evidence for **Question 2.2 and 2.2.1** was based on 317 studies, primarily undertaken in the Great Barrier Reef and published between 1990 and 2022. The synthesis includes a *High* diversity of study types (37% observational, 32% experimental, 22% modelled and 9% reviews), and has a *High* confidence rating (based on *High* consistency and *High* overall relevance of studies).

Summary of findings relevant to policy or management action

Studies over the last three decades confirm that the climate of the Great Barrier Reef is changing rapidly and in multiple ways, with some changes already significantly impacting Great Barrier Reef ecosystems and selected organisms. These studies also clearly show that impacts are predicted to intensify rapidly throughout this century, with severity depending on CO_2 emissions pathways. Climate change is now widely accepted as the most significant threat to the long-term outlook of Great Barrier Reef coral reef ecosystems. The main climate change agents known to affect coastal and marine ecosystems include: warming temperatures, increasing frequencies of marine heatwaves, increasing ocean acidification, extreme rainfall events, changes to the frequency and intensity of droughts and drought-breaking floods, sea level rise, and a potential reduction in the frequency but increasing intensity of tropical cyclones. Of great concern is the prediction that conditions that lead to heat-induced coral bleaching will become almost annual by 2040, depleting sensitive species and severely threatening the ecosystem integrity of coral reefs. By 2030, the evidence consistently indicates that some reefs will already start experiencing a seawater carbonate saturation state below ecologically critical levels, diminishing reef accretion and reef recovery rates. The strong link between rainfall extremes and terrestrial runoff of pollutants into the Great Barrier Reef show that climate change is already impacting Great Barrier Reef water quality, and these impacts will continue to intensify. The evidence also demonstrates the cumulative impacts from climate change and water quality, with the latter adversely affecting recovery times and community composition as climate disturbances are becoming more frequent and intense. The evidence confirms the urgency of meeting all Great Barrier Reef ecologically relevant water quality targets within the next decade, before climate impacts exceed the capacity for reef ecosystems to persist.

Supporting points

- Studies verify that periods of extreme sea surface temperatures (exceeding the long-term maximum summer monthly means by six or more ‘degree heating weeks’ i.e., the product of temperature exceedance and duration) are causing mass coral bleaching and can lead to mortality.
- Thermal extremes also cause stress and damage to numerous other marine organisms including some species of fish, sponges, and seagrasses.
- Effects of ocean acidification on reefs (proliferation of fleshy macroalgae, greater bioerosion, negative effects on coral recruitment, negative effects on crustose coralline algae) are similar in their direction to the effects of poor water quality, suggesting water quality improvement may mitigate some of the effects of ocean acidification on inshore reefs.
- Modelling studies attribute substantial loss of reef performance to local stressors, in addition to the losses from climate change. They conclude that management strategies to alleviate cumulative impacts have the potential to reduce the vulnerability of some reefs, but only if combined with strong emissions mitigation.
- During extreme heatwaves, and once bleaching conditions occur near-annually (predicted to be around 2040), water quality management in conjunction with other local management are insufficient tools for coral reef protection. However, they will remain relevant for other Great Barrier Reef ecosystems and functions that are less immediately threatened by climate change.
- Increasingly extreme rainfall events along the whole Great Barrier Reef suggests significantly greater challenges to meet Great Barrier Reef water quality targets, as severe rainfall leads to more severe terrestrial runoff of sediments, nutrients and pesticides.
- The review demonstrated regional differences in exposure and vulnerability to climate change:
    - Climate models predict overall greater regional warming, reduced cloud cover and more frequent bleaching events in the Southern and Central Great Barrier Reef Marine Park zones compared to the Northern and Far Northern zones where cloud cover may increase.
    - Predictions of reduced cyclone frequency and increasing intensity applies to the Great Barrier Reef north of about Latitude 20°S (Bowen), not to the southern Great Barrier Reef.
    - More severe episodic runoff from intensifying rainfall extremes will predominantly affect the inshore Great Barrier Reef, although the offshore may also be affected due to the links between floods and outbreaks of crown-of-thorns starfish, and offshore transport of pollutants in the narrower Great Barrier Reef north of about Latitude 18°S.
    - Predictions about increasing drought intensity mostly relate to the Great Barrier Reef south of about Latitude 20°S.

  - Frequency of droughts may increase during this century in southern Great Barrier Reef basins, adding to challenges to meet water quality targets, as sediment loads tend to be highest in drought-breaking floods.
  - Predicted increase in upwelling due to a strengthening East Australian Current (EAC) would increase offshore nutrient supply in the central Great Barrier Reef.
  - Ocean acidification is affecting the whole Great Barrier Reef, however, carbonate saturation state is temperature dependent (increases with warmer temperatures) and there are indications of coastal acidification, making the southern inshore reefs potentially the most vulnerable to ocean acidification.

These points suggest region-specific differences in management responses to changing climate, including greater challenges to meet Great Barrier Reef water quality targets in some locations.

- Altered sensitivity of some organisms to pollutants under warming temperatures highlights that water quality guideline values may need to be adjusted as the climate changes.
- Some threatened species may become critically endangered due to additional pressure from climate change (e.g., sea turtles due to their temperature-controlled hatchling sex determination), confirming the need for climate change specific threatened species management plans.

What evidence is there for changes in land-based runoff from pre-development estimates in the Great Barrier Reef? [2.3]

Stephen Lewis, Zoe Bainbridge, Scott Smithers

The synthesis of the evidence for **Question 2.3** was based on 128 studies undertaken in the Great Barrier Reef published between 1990 and 2022. The synthesis includes a *High* diversity of study types (44% proxy, 20% marine sediment cores, 15% monitoring, 12% observational and 9% modelling type studies), and has a *Moderate-High* confidence rating (based on *Moderate-High* consistency and *High* overall relevance of studies).

Summary findings relevant to policy or management action

There are multiple lines of evidence demonstrating that the loads of suspended sediment, dissolved and particulate nutrients (nitrogen and phosphorus), and pesticides have increased for most river basins of the Great Barrier Reef catchment area since the arrival of Europeans c. 1850. Evidence of increases in catchment loads comes from fluvial proxy records, coral core proxies, water quality monitoring and subcatchment and catchment-scale modelling exercises. The increases in loads have largely occurred because catchments have been modified for the major land uses of livestock grazing (73% of catchment area), irrigated and dryland cropping (2.8%), sugarcane (1.2%), horticulture and bananas (0.2%), urban development (0.7%) and mining (0.3%). These modifications, combined with climate variability, result in more frequent, larger-volume river discharge events interspersed with drought periods that reduce ground cover, which then leads to higher sediment yields during 'drought-breaking' rainfall events. The footprint of increased land-based runoff and pollutant loads within the Great Barrier Reef is most pronounced in estuarine and nearshore environments, but based on coral cores and other proxy records can be seen on the inner Great Barrier Reef shelf over 100 km alongshore from the river mouth of influence. However, proxy records derived from reefs in some parts of the inner shelf, but particularly for the middle and outer shelfs[13], are more subtle and variable in showing direct association with land-based sediments than those derived from the nearshore settings. This variability will reflect the spatial differences of exposure to land-based runoff but also the complex bio-geochemical processes that are active within flood plumes during the transport of materials over greater distances.

Supporting points

- Time series data of land use change in the Great Barrier Reef catchment area from 1860 to 2019 show extensive modification of most river basins for livestock grazing, cropping and urban developments.
- A range of fluvial proxy records - including Beryllium-10 isotopes, sediment deposition records from

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[13] In terms of bathymetry, which is linked to sediment characteristics, the Great Barrier Reef is defined as inner shelf (up to 20 metres depth), middle shelf (20 to 40 metres depth) and outer shelf (more than 40 metres depth).

lakes, floodplains and river benches, water quality and observational measurements from different land uses - almost universally indicates increased sediment erosion since European arrival.

- Catchment modelling of river basin loads of fine sediment and nutrients identify substantial increases during the post-European arrival period for most Great Barrier Reef basins. Exceptions include basins that have relatively low areas of intensive land use modification, which are mainly situated within the Cape York Natural Resource Management region.
- The latest Source Catchments modelling suggests that sediment loads have more than tripled for most basins within the Burdekin, Mackay Whitsunday, Fitzroy, and Burnett Mary regions (exceptions include the Black, Proserpine, Shoalwater, and Waterpark Basins). The basins of the Cape York region have modelled load increases of 1.3-fold or less except for the Normanby Basin where projected loads have increased 5-fold. These increases are validated by multiple lines of independent evidence including a number of catchment proxy studies, land use-focused water quality monitoring data and coral core proxy data.
- Based on the latest Source Catchments modelling, dissolved inorganic nitrogen loads from basins with intensive cropping, such as sugarcane areas in the Wet Tropics region, have increased by 1.5 to 3-fold from pre-development loads. Evidence of these increases is supported by land use-focused water quality monitoring data.
- Luminescent lines in corals (proxy for river discharge) from various locations on the Great Barrier Reef show a marked increase in the frequency and size of river discharge events from the 1850s, and again from the 1950s, when compared to a long-term background dataset extending over the past 400 years. This increase is correlated with changes in the frequency and intensity of El Niño Southern Oscillation (ENSO) events and the behaviour of the Indo-Australian monsoon across northern Australia, as well as from increased runoff likely due to widespread land clearing (and resulting catchment hardening).
- Chemical elements incorporated within coral cores highlight increased land-based runoff (i.e., freshwater discharge and sediment) at a multitude of inshore sites within the Great Barrier Reef following the arrival of Europeans. Evidence of increased nitrogen loads using coral core proxies is less conclusive.
- New coral proxies to help reconstruct changes in sediment and nutrient exposure, including rare earth elements and nitrogen isotopes respectively, are under development for application in the Great Barrier Reef.

How do water quality and climate change interact to influence the health and resilience of Great Barrier Reef ecosystems? How are the combined impacts of multiple stressors (including water quality) affecting the health and resilience of Great Barrier Reef coastal and inshore ecosystems? Would improved water quality help ecosystems cope with multiple stressors including climate change impacts, and if so, in what way? [2.4, 2.4.1, 2.4.2]

Sven Uthicke, Katharina Fabricius, Aimee Brown, Bianca Molinari, Barbara Robson

The synthesis of the evidence for **Question 2.4** was based on 117 studies undertaken mostly in the Great Barrier Reef and published between 1990 and 2022, including a *High* diversity of study types (61% experimental, 13% modelling, 13% reviews, 9% mixed methods, and 4% observational) 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 consistent evidence that climate change factors (including temperature and ocean acidification) and water quality characteristics (including nutrients, light/sediments and pesticides) have combined effects on a variety of organisms in coral reef ecosystems of the Great Barrier Reef. In the majority of cases, the outcome for the organism is worse under combined effects. These combined effects have mainly been studied on coral reefs, with far fewer studies on seagrass meadows (often associated with coral reef studies) and very limited information on coastal wetlands. For corals, the most detrimental effects documented are the combined effects of climate change and herbicides, and there is also evidence that climate change can interact with both nutrients and light reduction/sedimentation to cause additional stress, including reduced thermal tolerance. Several interactions between climate change and water quality have also been detected in seagrass ecosystems, with the possible exception of ocean acidification which can stimulate plant growth. Although mechanisms are not always fully understood and quantified, there is high confidence (from the Great Barrier Reef and elsewhere) that improving water quality will to some extent ameliorate climate change impacts ('buy time') for coral reef and seagrass ecosystems. The strength and length of this reprieve cannot yet be quantified. Improved water quality also indirectly benefits coral reef ecosystems by increasing resilience of organisms and reducing recovery time following acute disturbances such as bleaching, crown-of-thorns starfish outbreaks and cyclones. These benefits will become increasingly important as climate pressures continue to grow.

Supporting points

- Simultaneous exposure of climate change and water quality stressors can have detrimental impacts on coral reef ecosystems. The combinations of these stressors are often additive and pose a greater (aggravating) threat to organisms than single stressors (e.g., temperature or nutrient exposure in isolation).
- From this review, most stressors showed aggravating impacts (i.e., combined stressors had a greater impact than individual stressors) on at least one physiological or life history trait such as growth, mortality or photosynthesis.
- The combinations of climate change and herbicides can have a negative impact particularly for corals and algae. Data on this combination are sufficient to model species sensitivity distributions and define climate-adjusted thresholds for individual herbicides. From the studies that examined how climate change and herbicides interact, 89% showed additive/aggravating effects across a range of organisms.
- The combined effects of climate change and increased nutrients have been well studied, primarily in corals and foraminifera, with 77% of studies finding that nutrients impose an additional stress when combined with climate change factors such as temperature and ocean acidification.
- Corals and seagrass are negatively impacted by the interactive effects of climate change, primarily temperature, and light reduction from turbidity or sedimentation, with 70% of studies indicating aggravating effects. There is evidence to suggest the combination of climate change stressors also results in negative interactive effects on coral reef ecosystems and organisms. The most studied combination was between temperature and ocean acidification, whereby 56% of studies identified aggravative effects on a wide range of organisms.
- There has been limited research on some combinations of water quality and climate change stressors in the Great Barrier Reef including salinity, and heatwaves and the frequency and intensity of runoff events.
- To reduce the cumulative pressures and the associated detrimental outcomes on coral reef ecosystems and organisms, improved water quality throughout the Great Barrier Reef is essential, together with national and global reductions in carbon emissions to reduce the rate of warming and ocean acidification.

Burdekin Bridge
Photo: Matt Curnock

Theme 3: Sediments and Particulate Nutrients – Catchment to Reef

Theme 3: Sediments and Particulate Nutrients – Catchment to Reef

Context

Fine sediment inputs to the Great Barrier Reef can cause important ecological impacts such as reduction in benthic light, smothering of benthic organisms, direct disturbance by suspended particles or increased loads of particulate and potentially bioavailable nutrients. Across the Great Barrier Reef, a 25% reduction in the 2009 anthropogenic end-of-catchment fine sediment loads and a 20% reduction of particulate nutrients, is required to meet the 2025 targets defined in the Reef 2050 Water Quality Improvement Plan. Substantial effort is required to meet these targets, especially in the basins delivering the largest fine sediment and particulate nutrient loads to the Great Barrier Reef, and particularly in the context of other stressors including climate change.

The synthesis of the evidence for **Theme 3** included a total of **850** studies extracted and synthesised for **6** questions (with some overlap in evidence between questions) (Figure 7). This Theme reviews the evidence of the causal relationships between the impacts, sources and management of sediments and particulate nutrients influencing the Great Barrier Reef. It starts with the evidence of the ecological processes within the Great Barrier Reef including the spatial and temporal distributions of terrigenous sediments and associated

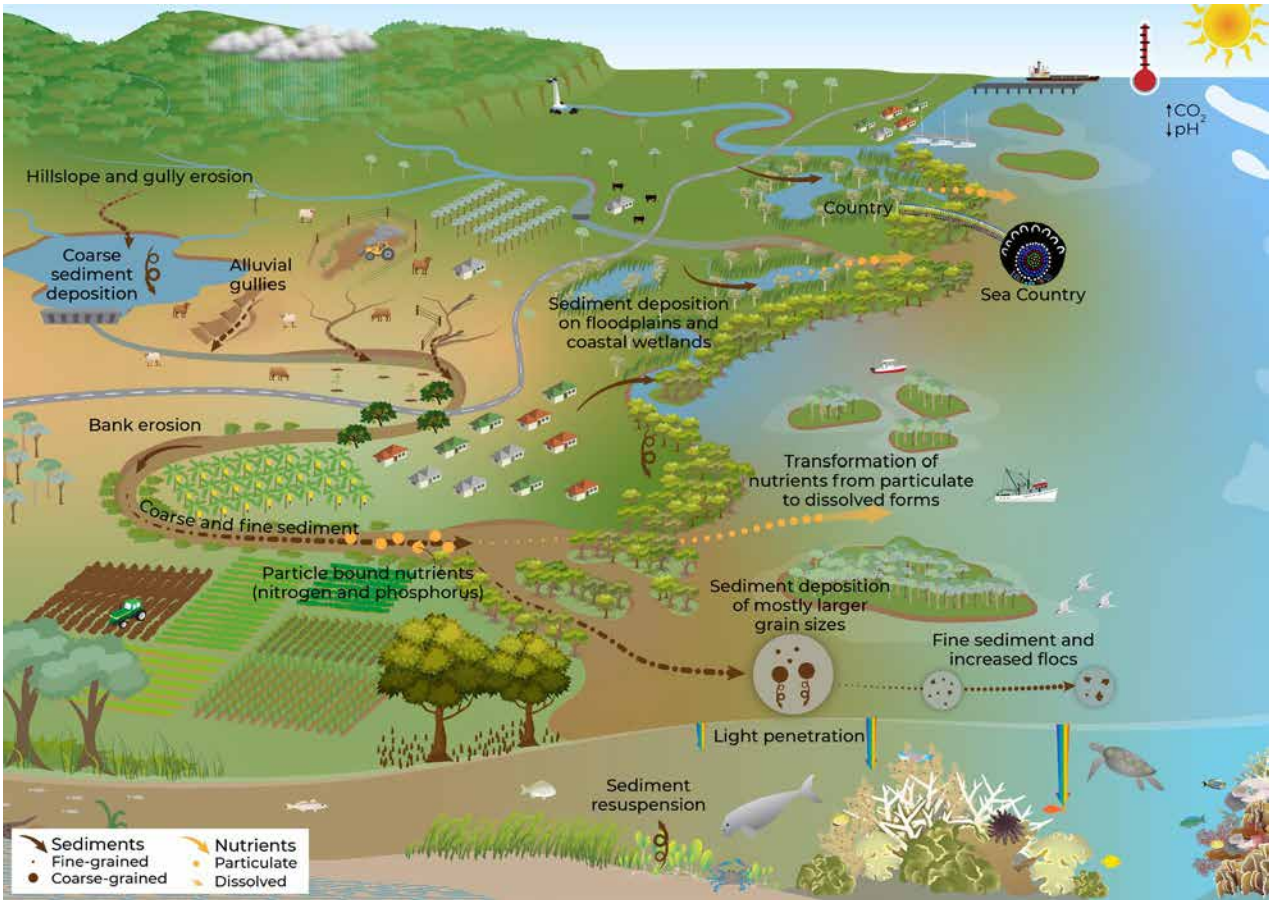


Figure 7. This diagram is a pictorial representation of the scope of Theme 3. It represents the Great Barrier Reef catchment and marine environment and shows the ecological impacts of fine sediment and particulate nutrients on aquatic ecosystems and biota including the influence of flood plumes which mostly affect inshore and midshelf areas. The primary sources are shown, of which grazing is the largest contributor, followed by cropping and other land uses, along with the transport pathways for fine sediments and particulate nutrients from the catchment to the Great Barrier Reef. Transport is heavily driven by vegetation degradation and surface disturbance which contribute to accelerated hillslope, gully and streambank erosion. Examples of potential management measures to minimise runoff are illustrated including the need to maintain ground cover and riparian vegetation, and gully and streambank restoration. Climate change is also identified as affecting the frequency and severity of droughts and floods, both of which are likely to exacerbate vegetation degradation, surface disturbance and soil degradation.

indicators (Q3.1), and the measured impacts of those sediments and particulate nutrient loads on Great Barrier Reef ecosystems (Q3.2). The primary sources are presented (Q3.3), with expansion of the evidence of the biophysical drivers, transport and delivery processes of fine sediment and particulate nutrient export from the catchment area to the Great Barrier Reef (Q3.4). Synthesis of the most effective management practices for reducing sediment and particulate nutrient export from the Great Barrier Reef catchment area provides insights for policy and management (Q3.5), with specific review of the effectiveness of gully remediation and streambank rehabilitation actions (Q3.6).

Summary Statement for Theme 3

Convergence was reached for this Summary Statement among all authors within the Expert Group for Theme 3 (listed in **Appendix 1**).

The synthesis of the evidence for **Theme 3** included a total of **850** studies extracted and synthesised for **6** questions (with some overlap in evidence between questions).

The **summary of findings** relevant to policy or management action for **Theme 3** are:

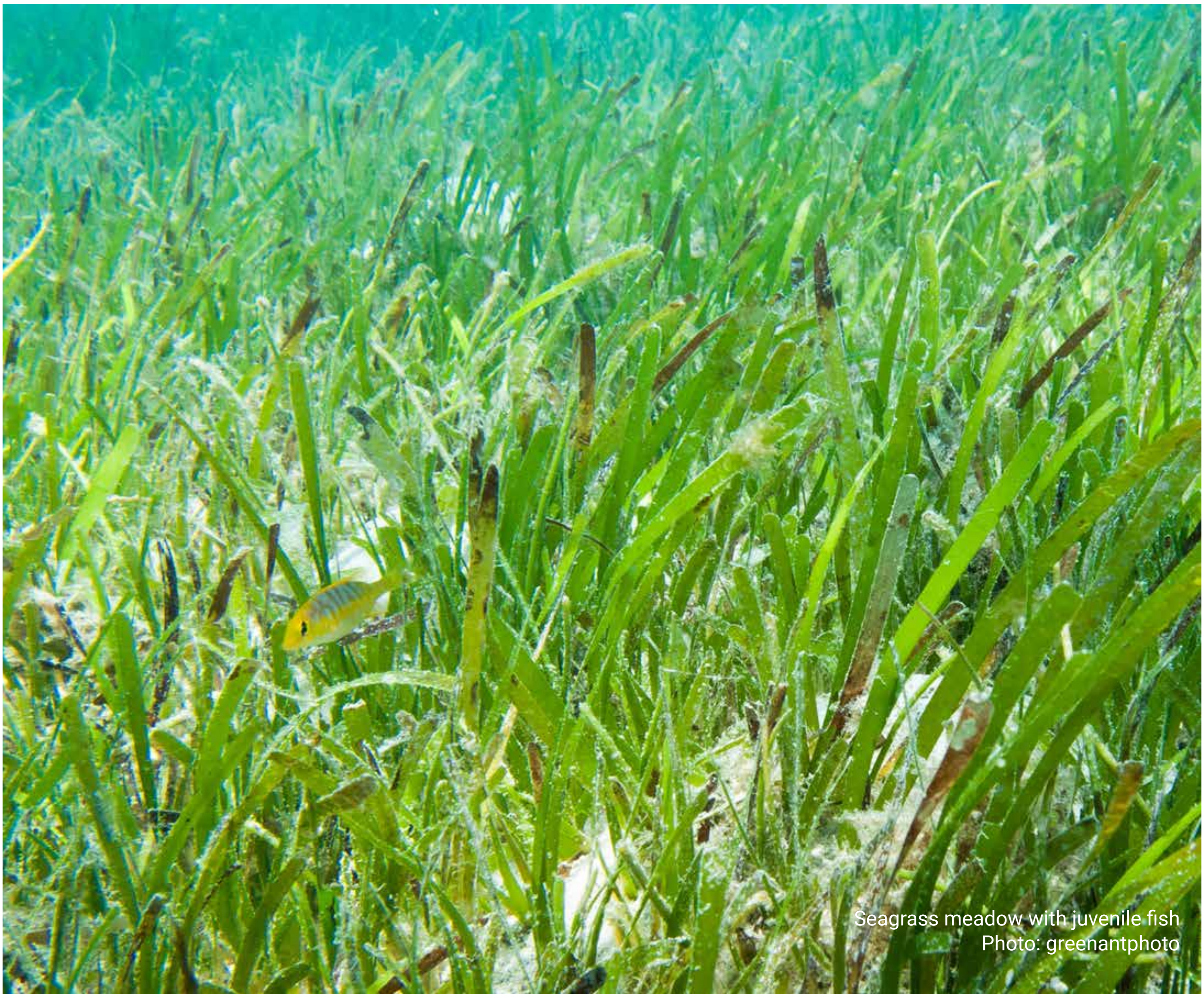
- The export of sediments and particulate nutrients to the Great Barrier Reef have increased for most river basins over the last 170 years since the arrival of Europeans. There are distinct patterns of sediment composition across the continental shelf of the Great Barrier Reef. The inner shelf (up to 20 metres water depth) is dominated by land-derived 'terrigenous' sediment shifting to predominantly marine sediment derived from corals, shells and other carbonates, in the outer shelf (>40 metres depth). *In situ* monitoring and remote sensing data show a clear spatial gradient of decreasing turbidity levels with increasing distance from river mouths, likely related to the depth of the water column (i.e., degree of wave resuspension) and the availability of sediment on the seafloor to be readily resuspended. [Q3.1]
- While most sediment-laden flood plumes are confined to the inner shelf of the Great Barrier Reef, at times during periods of large riverine discharge and low wind speeds, fine (<20 μm) terrigenous sediment and associated particulates can be carried to the middle shelf and even the outer shelf (particularly for the areas northwards of Bowen where the middle and outer shelf is closer to the coast). Reduced water quality can persist for up to six months due to frequent resuspension of this newly delivered sediment following large discharge events. Increases in sediment loads since the arrival of Europeans greatly influences the area of the inner and middle shelf affected by diminished light. Studies on particulate nutrients in flood plumes and river estuaries highlight the potential for rapid transformation of particulate nutrients to bioavailable forms (dissolved nutrient forms that are readily consumed by algae) within coastal areas. [Q3.1]
- Increases in the loads of fine sediments and particulate nutrients affect the quantity and quality of light (i.e., modified light spectrum towards 'less usable' light) reaching coral reefs, seagrass and other benthic organisms and can influence the behaviour and condition of animals including fish, particularly in inshore areas. This has resulted in persistent impacts on reef composition (including changes in the abundance and diversity of species at different depths, and increases in macroalgal growth), and variability in the distribution, abundance and composition of seagrass meadows. These direct effects can result in indirect effects on other taxa including seagrass-dependent dugong which can extend across the whole Great Barrier Reef. The greatest impacts of fine sediments and particulate nutrients occur in the inshore central and southern Great Barrier Reef (Wet Tropics to Burnett Mary Natural Resource Management regions). [Q3.2]
- Sedimentation, the settling of sediments and particulate nutrients onto surfaces, can also have negative direct effects on a variety of taxa including corals, causing tissue damage, reducing growth rates and altering microbial communities. Importantly, settled and suspended particulate matter can suppress recovery from other disturbance events (e.g., heatwaves, cyclones) and affect recruitment and early life stages of corals and fishes. [Q3.2]
- Overall, exports of anthropogenic fine sediment to the Great Barrier Reef are estimated to be 1.4 to 5 times higher than pre-development loads (depending on the basin). These estimates are supported by a range of evidence including modelling, geochemical and isotope tracing of the sources of exported material, and proxy records of exports over time in sediments and

coral cores. The Burdekin and Fitzroy basins are the largest exporters of total fine sediment and particulate nutrients to the Great Barrier Reef (including anthropogenic exports), each exporting an annual average load of over 3,000 kilotonnes and 1,300 kilotonnes of fine sediment per year, respectively, and more than 3,000 tonnes of particulate nitrogen per year. [Q3.3]

- Grazing land use is the largest contributor of fine sediment export to the Great Barrier Reef (especially in the Burdekin and Fitzroy regions), estimated to generate 60% of the total export and a larger proportion of the anthropogenic export, with all other land uses each contributing much smaller amounts. Intense land uses such as mining and developing urban areas can generate large sources of fine sediment locally but cover a relatively small area and overall exports are relatively small. It is estimated that gully erosion contributes around 50% of the total fine sediment load exported from the Great Barrier Reef catchment area, with the remainder comprised of almost equal contributions from streambank erosion and hillslope erosion. Each process can dominate in particular basins. [Q3.3]
- The most important primary biophysical drivers of anthropogenic sediment and particulate nutrient exports to the Great Barrier Reef include vegetation degradation (e.g., land/tree clearing, low ground cover, and changes in structure and function of grass species including a shift to non-native pastures, typically in response to long-term grazing pressure), surface disturbance from cattle trampling, feral animals, tillage in cropping areas, historical surface mining, unsealed roads and construction earthworks. While these drivers vary between erosion types, in different locations and at different times, gully erosion is strongly driven by surface disturbance and vegetation degradation / low ground cover, and streambank erosion is accelerated by removal or degradation of riparian vegetation and grazing pressure. Soil degradation, spatial concentration of runoff by roads, tracks and fence lines are also important drivers in some locations. Runoff detention by large dams has reduced exports significantly but has been outweighed severalfold by the other drivers, and dams are less effective at trapping fine-grained sediments of most ecological risk to downstream Great Barrier Reef ecosystems. [Q3.4]
- The Reef Water Quality Report Card 2020 estimated that 'Moderate' overall progress has been made towards meeting the Reef 2050 Water Quality Improvement Plan fine sediment load reduction target and 'Very Good' progress for the particulate nutrient load reduction targets. In some basins, targets are assumed to have been met (including several basins in the Cape York region) while in others, especially those that were not given management priority, there has been little progress. For some management actions it may take many years until the benefits of management are fully realised, and it may take decades to detect reduced exports in monitoring programs due to the high annual variability of exports controlled by river discharge. [Q3.3]
- The most effective management practices for reducing fine sediment and particulate nutrient export from the Great Barrier Reef catchment area vary between land uses and erosion types. Common practices for hillslope erosion include the use of moderate and adaptive grazing stocking rates, maintenance of at least 40% ground cover (but preferably >70%), regular periods of strategic rest from grazing (especially in the early wet season), cattle exclusion from fragile land-types, maintaining or reintroducing vegetation into landscapes (including pasture management and vegetation buffers), management of sediment delivery pathways within catchments (e.g., via management of roads, drains and gullies), and other practices that minimise soil runoff (such as green cane trash blanketing, zero/minimum tillage and controlled traffic farming). There is high variability in the cost-effectiveness of practices at the farm/project scale which is driven by several factors including a wide range of different practices and economic returns, location within the landscape and factors relating to sediment mobilisation and delivery. The way that cost-effectiveness is assessed between projects and programs is also inconsistent (i.e., different metrics and considerations). The adoption of management practices can be driven by a range of factors including costs and is discussed in detail in Theme 7. [Q3.5]
- While a range of gully and streambank projects have been undertaken in the Great Barrier Reef catchment area, the vast majority of works have not been quantitatively monitored for sediment and particulate nutrient reductions, with the exception of studies published within the National Environmental Science Program Tropical Water Quality Hub (2014 to 2021). Remediation of large alluvial gullies has been demonstrated to be a highly effective strategy to significantly reduce fine sediment loads delivered to the Great Barrier Reef, achieving over 90% fine sediment reductions within one to two years when a combination of treatments

is applied. Ongoing maintenance (including livestock exclusion) of the remediation sites is required to retain these benefits. Few studies focus on measuring the water quality benefits of streambank restoration, however, it is evident that bank erosion generally occurs at lower rates on vegetated streambanks than non-vegetated streambanks. [Q3.6]

- Large-scale remediation of high sediment yielding gullies is 26–60 times more cost-effective in achieving the same cumulative fine sediment reduction than lower-cost options for lower-yielding gullies. The limited available peer reviewed evidence shows that hillslope gully remediation, that is based on the use of low-cost check dams in gully floors and fencing, is less cost-effective compared to large high-yielding gullies. Alluvial gully treatments typically have shorter response times in terms of fine sediment reductions and can be treated at larger scales and in fewer locations, resulting in additional logistical efficiencies. Of relevance to management prioritisation, the available studies also indicate that a small number of gullies (~ 2% of the total number) contribute a substantial proportion of the sediment yield (30%), highlighting the need for targeting the high yielding gullies as a means of efficiently reducing fine sediment exports to the Great Barrier Reef. [Q3.6]
- Areas downstream of dams and closer to the coast lead to higher rates of sediment and particulate nutrient delivery to the coast, therefore the location of sites for targeting management is important when estimating management practice effectiveness and translating load reductions between the site, and what is delivered to ecosystems downstream. [Q3.4, Q3.5]



Seagrass meadow with juvenile fish
Photo: greenantphoto

The **confidence** rating of the questions within **Theme 3** was High (2 questions; in relation to spatial and temporal distributions and sources of sediments) and Moderate (4 questions; around the ecological impacts, biophysical drivers, and management practices), mostly due to Moderate relevance or Moderate consistency of the evidence in some instances, such as for certain ecosystems or certain land uses where less evidence was available.

The findings in this Theme are underpinned by a large body of evidence including multiple lines of evidence (i.e., monitoring, modelling, remote sensing, observations, radioisotope tracing studies). The **strength of evidence** across this Theme, considering the confidence, quantity and diversity of study types, is considered to be Moderate-High, with some exceptions related to certain ecosystems (such as wetlands), certain land uses (such as bananas/horticulture, urban and roads), and some management practices (such as streambank restoration), where there is less available evidence in the Great Barrier Reef.

The **key uncertainties** of the evidence identified for **Theme 3** relevant to policy and management include distinction of the impacts of anthropogenic versus 'natural' loads of fine sediment and particulate nutrients on Great Barrier Reef ecosystems, and the effects of sediment and particulate nutrients on freshwater wetlands and estuarine wetlands such as mangroves, marshes, and supratidal forests in the Great Barrier Reef. Monitoring of exports needs to continue to cover the full range of flood magnitudes and for long enough to detect trends in exports as short-term monitoring leaves much uncertainty about patterns of exports. This is particularly important in the context of climate variability and climate change-related influences such as increases in flood and drought severity, and the occurrence of fire followed immediately by high rainfall events.

Recent findings reinforce the lines of evidence that current fine sediment exports are above pre-development rates and have advanced understanding of the contribution of grazing pressures and vegetation degradation on hillslope and gully erosion. Studies on bioavailable nutrients (dissolved nutrient forms that are readily consumed by algae) within flood plumes and river estuaries also continue to highlight the potential for rapid desorption and mineralisation of particulate nutrients in the Great Barrier Reef. There is mounting evidence that reductions in end-of-catchment loads of fine sediments and particulate nutrients could improve the extent, abundance, diversity and health of Great Barrier Reef ecosystems, and their speed to recover from climate-related disturbances. In terms of management options, there is now clearly documented evidence of the effectiveness of the remediation of large-scale alluvial gullies in the Great Barrier Reef catchment area, supported by multiple lines of evidence. While there is recent qualitative evidence that rehabilitation of streambank erosion can be effective at site-scale, this has not been quantified at reach or subcatchment scale. For gully and streambank remediation, implementation of sustainable land management practices in the adjacent catchment area is important for long-term prevention of additional erosion and to maintain the water quality outcomes of the remediation actions.

Within **Theme 3**, the areas where further **knowledge is needed** that are most relevant to policy and management include: i) additional turbidity and light logger data from the middle shelf of the Great Barrier Reef (currently mostly informed by remote sensing and modelling outputs) to enhance the understanding of the influence of riverine discharge and associated loads beyond the inner shelf; ii) further development of new coral proxies to help reconstruct changes in sediment exposure in the Great Barrier Reef; iii) additional knowledge on the impacts of sediment and particulate nutrients on freshwater and estuarine wetlands; iv) greater understanding of the factors that affect the bioavailability of particulate nitrogen in a range of basins (i.e., soil types, carbon) and within the Great Barrier Reef; v) continuous and longer term monitoring of fine sediment and particulate nutrient exports at a range of locations to reduce uncertainties in end-of-catchment load estimates; vi) refinement of fine sediment export ratios through river basins, especially in those that include dams, and further delineation of channel and gully features in the catchment models; vii) identification of the primary biophysical drivers of export at smaller scales, on specific erosion processes, and on sediment connectivity, as reflected by sediment delivery ratios at multiple scales, through river basins, to refine the targeting and cost-effectiveness of water quality improvement programs; viii) establishment or, where applicable, continuation of, long-term monitoring to quantify the efficacy of management actions to reduce sediment export including grazing land management, riparian rehabilitation and gully remediation at a range of scales (site, subcatchment and catchment) and in the context of climate variability and climate change-related influences such as increases in flood and drought severity; ix) information on the longer-term effectiveness, costs and production outcomes of management actions for all land uses and rehabilitation activities, including maintenance requirements for gully and streambank treatments; and x) adoption of a consistent, peer-reviewed approach for assessing the cost-effectiveness of fine sediment and particulate nutrient management actions.

Summary information for Questions in Theme 3

The Table below summarises the evidence appraisal indicators and confidence ratings in the evidence base for each of the Questions within this Theme. The Confidence rating was determined by the overall relevance of studies to the question and the consistency of the body of evidence (refer also to Appendix 3: Glossary for explanation of indicators). *Note: In Diversity of items: Experimental (E), Meta-analysis (M-A), Modelling (M), Observational (O), Reviews (R), Theoretical or Conceptual (T).*

Question	Quantity of items	Diversity of items	Overall relevance	Consistency	Confidence
What are the spatial and temporal distributions of terrigenous sediments and associated indicators within the Great Barrier Reef? [3.1]	High (150)	High *(72% O, 11% O-M, 7% M, 7% T, 3% E)*	High	High	High
What are the measured impacts of increased sediment and particulate nutrient loads on Great Barrier Reef ecosystems, what are the mechanism(s) for those impacts and where is there evidence of this occurring in the Great Barrier Reef? [3.2]	Low-Moderate (196)	High *(40% O, 39% E, 13% R, 7% M, 1% M-A)*	Moderate	Moderate - High	Moderate
How much anthropogenic sediment and particulate nutrients are exported from Great Barrier Reef catchments (including the spatial and temporal variation in export), what are the most important characteristics of anthropogenic sediments and particulate nutrients, and what are the primary sources? [3.3]	High (119)	High *(64% O, 22% M, 9% O-M, 5% R)*	High	High	High
What are the primary biophysical drivers of anthropogenic sediment and particulate nutrient export to the Great Barrier Reef and how have these drivers changed over time? [3.4]	Moderate (135)	High *(36% O, 28% E, 22% R, 14% M)*	Moderate	High	Moderate
What are the most effective management practices for reducing sediment and particulate nutrient loss from the Great Barrier Reef catchments? What are the costs and cost-effectiveness of these practices, and does this vary spatially or in different climatic conditions? What are the production outcomes of these practices? [3.5]	Moderate (162) (32 grazing; 24 sugar; 40 cropping; 16 B&H; 36 urban; 14 roads)	Moderate *(29% O-GBR, 27% O- non-GBR, 25% R, 19% M)*	Moderate	Moderate	Moderate
What is the effectiveness of restoration works (e.g., gully and streambank) in reducing sediment and particulate nutrient loss from the Great Barrier Reef catchments, does this vary spatially or in different climatic conditions? [3.6]	Low-Moderate (88) (33 Gully, 55 Stream)	Moderate *(58% O, 16% E, 19% R, 7% M)*	Moderate	Moderate - High	Moderate

Evidence Statements for Questions in Theme 3

What are the spatial and temporal distributions of terrigenous sediments and associated indicators within the Great Barrier Reef? What is the variability of turbidity and photic depth in coastal and marine areas of the Great Barrier Reef? [3.1, 3.1.1]

Stephen Lewis, Zoe Bainbridge, Scott Smithers

The synthesis of the evidence for **Question 3.1** was based on 150 studies undertaken in the Great Barrier Reef and published between 1968 and 2022. The synthesis includes a *High* diversity of study types (72% observational i.e., monitoring, sediment grabs/cores, 11% combined observational/modelling i.e., remote sensing, turbidity measurements combined with numerical modelling, 7% computational modelling, 7% conceptual understanding and 3% modelling/experimental studies), and has a *High* confidence rating (based on *High* consistency and *High* overall relevance of studies).

Summary of findings relevant to policy or management action

There are distinct patterns of sediment composition across the continental shelf of the Great Barrier Reef. The inner shelf (up to 20 metres water depth) is dominated by land-derived 'terrigenous' sediment shifting to predominantly marine sediment derived from corals and shells in the outer shelf (>40 metres depth). These cross-shelf patterns are driven by a combination of the dominant south-east trade winds which typically 'hold' the sediment inshore and drive flood plumes along the coast, the depth limit of wave resuspension which is up to 22 metres, and cyclones that promote strong longshore shelf-parallel currents. While most sediment-laden flood plumes are also constrained within the inner shelf of the Great Barrier Reef, appreciable fine-grained (<20 µm) terrigenous sediment loads can be carried to the middle[14] shelf and even the outer shelf (particularly for the areas northwards of Bowen where the middle and outer shelf zones are closer to the coast) during periods of large riverine discharge that coincide with low wind speeds, although these events occur less frequently. *In situ* monitoring and remote sensing data show a clear spatial gradient of decreasing turbidity levels with increasing distance from river mouths. This spatial gradient is likely related to the depth of the water column (i.e., ability for wave resuspension) and the availability of sediment on the seafloor to be readily resuspended. Multiple lines of evidence from turbidity loggers, remote sensing and modelling show that elevated and prolonged turbidity levels and corresponding longer periods of diminished useable light in the water column in certain areas of the inner and middle shelfs of the Great Barrier Reef coincide with years of increased river discharge and associated sediment loads. The change in river discharge and increase in sediment loads since the arrival of Europeans greatly influences the area of the inner and middle shelfs affected by the diminished light.

Supporting points

- Several studies show that most river-exported terrigenous sediment is deposited and retained within river floodplains, river estuaries, close to river mouths and within the eastern sections of north-facing embayments. Nearshore and inshore fringing coral reefs also host considerable proportions of terrigenous sediments within their internal structures. Sediment modelling exercises indicate that most of the terrigenous sediment (including both coarse and fine particles) is deposited and retained in close vicinity to river mouths. However, a proportion of the fine terrigenous sediment (<20 µm) load can be carried within flood plumes to the inner and middle shelfs.
- There is abundant literature that show terrigenous sediment concentrations in flood plumes are highest at the river mouths with a rapid decline in concentrations within the 0 to 10 practical salinity units (PSU; i.e., a unitless scale that measures salinity of the water where 0 PSU = freshwater and ~35 PSU = seawater) salinity zone due to flocculation processes which occur when sediment particles stick together as a result of salinity changes or biological production. This 0 to 10 PSU zone typically occurs within 20 km of the river mouth and is dependent on the volume of discharge.
- Studies on particulate nutrients in flood plumes and river estuaries highlight the potential for rapid transformation of particulate nutrients to bioavailable forms (dissolved nutrient forms that are readily consumed by algae) within coastal areas. Frequent resuspension of sediments within estuaries and the

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[14] In terms of bathymetry, which is linked to sediment characteristics, the Great Barrier Reef is defined as inner shelf (up to 20 metres depth), middle shelf (20 to 40 metres depth) and outer shelf (more than 40 metres depth).

coastal zone helps promote rapid cycling of particulate nutrients which are largely mineralised through microbial communities.

- The quality of light for photosynthesis is predominantly influenced by the amount of suspended particulate matter in the water column. Turbidity as low as <5 nephelometric turbidity units (a measure for how cloudy the water is) can greatly attenuate light reaching the seafloor. The quality of light reaching the seafloor is critical to many communities including seagrass meadows and coral reefs.
- The dominant influences on turbidity (i.e., water clarity) and photic depth (i.e., the depth in the water column that photosynthetically usable light can reach) in the inner shelf of the Great Barrier Reef is primarily from wave-driven resuspension with tidal resuspension as a secondary influence. Resuspension of sediments on the inner shelf in conjunction with tidal and wave currents can transport sediments to other sediment repositories such as mangroves, beaches and sheltered embayments.
- Independent remote sensing analysis and modelling outputs support the findings that river discharge and associated loads significantly influence turbidity and photic depth regimes along sections of the inner and middle shelfs of the Great Barrier Reef.
- A proportion of the fine-grained (<20 μm) riverine sediment travels furthest in the Great Barrier Reef, settles as an uncompacted ‘fluffy layer’ on the seafloor and is hence more easily resuspended under less-energetic wave events relative to the existing compacted sediment on the seafloor. This process results in longer periods of diminished light in sections of the inner and middle shelfs in the years of above average discharge and sediment loads.
- Sediment cores taken offshore from the continental shelf (i.e., Queensland Trough) reveal that there is modern (i.e., over the past 8,000 years) terrigenous sediment flux to the continental shelf, accounting for up to 13% of the riverine inputs depending on the location, but the mechanism for such transport is unclear.
- While the recent research outputs (2016-2022 period) have made little change to the key conclusions for this question, the new research has strengthened the existing findings, and in some cases, contributed to form multiple lines of evidence. This includes consistent findings from additional remote sensing and modelling analysis as well as from new monitoring data.

What are the measured impacts of increased sediment and particulate nutrient loads on Great Barrier Reef ecosystems, what are the mechanism(s) for those impacts and where is there evidence of this occurring in the Great Barrier Reef? [3.2]

Catherine Collier, Aimee Brown, Katharina Fabricius, Stephen Lewis, Guillermo Diaz-Pulido, Fernanda Adame

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

Summary of findings relevant to policy or management action

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

Supporting points

- For **coral communities**, increased exposure to sediments and particulate nutrients on inshore habitats has persistent impacts on reef composition. For example, sediments can reduce the abundance of sensitive species and the availability of suitable settlement surfaces, while nutrients can increase the amount of macroalgae on reefs.
- Lower light levels caused by increased suspended particulate matter can impact the spatial extent of coral reefs by limiting where corals can grow. Some turbid inshore locations can support high coral abundances, but these coral communities are typically restricted to depths of 1-3 m and high currents. They are low in species diversity and composed of species that have the ability to cope with turbid conditions (e.g., can switch food sources and self-clean).
- For sponges, short-term exposure to high levels of suspended sediment affects growth, while long-term exposure reduces sponge abundance possibly by limiting recruitment.
- Settled and suspended particulates may negatively affect crustose coralline algae which are important coral settlement substrata, but the number of studies is limited. They may also affect the abundance of large benthic photosynthetic foraminifera. Settled sediment is energetically costly for corals to remove and impedes their recruitment.
- For **seagrass communities**, the distribution, abundance and composition of seagrass species are impacted by particulate loads and changes in light, which drive declines in abundance and extent, and cause shifts in species composition.
- Seagrass meadows are dynamic and will often recover with the rate depending on the extent of decline and the local and regional conditions that follow. Protracted recovery has been observed in several locations.
- Research on the mechanisms driving seagrass loss have focused on reductions in light caused by suspended particulate matter, and much less is known about the processes influencing recovery.
- For **fish communities**, elevated suspended and settled sediments can have physiological and behavioural effects. Sediments can negatively affect growth and time to metamorphosis of fish, alter juvenile gill morphology, reduce body condition and increase mortality. Suspended sediments can also interfere with visual cues that juvenile fish use to settle into habitats, impairing their ability to distinguish between live and dead coral, extend settlement time, and alter feeding patterns such as predation, foraging time and herbivory. Effects have only been investigated for a small number of fish families and thresholds for adverse impacts require refinement.
- This review highlights a critical knowledge gap on the effects of sediment and particulate nutrients on Great Barrier Reef **freshwater wetlands and estuarine wetlands** such as mangroves, saltmarshes and supratidal forests (above the intertidal zone).
- The composition of particulates, including particle size, sedimentology and particulate nutrient content, has a large influence on most of the impacts that have been documented.
- There are multiple lines of evidence supporting cause-effect relationships for increased suspended sediments and biota. This includes a wide range of study types, strong spatial associations between water quality conditions and biotic conditions demonstrated in dose-response relationships, logical time sequences (i.e., ecological changes following increased loads), several cases of high specificity (i.e., impact-specific sensitive indicators), and consistency of responses across populations, across regions and with studies from outside of the Great Barrier Reef. However, several contextual factors affect these relationships such as disturbance history, cumulative impacts from multiple disturbances and other local

environmental conditions (e.g., local hydrodynamics).

How much anthropogenic sediment and particulate nutrients are exported from Great Barrier Reef catchments (including the spatial and temporal variation in export), what are the most important characteristics of anthropogenic sediments and particulate nutrients, and what are the primary sources? [3.3]

Ian Prosser, Scott Wilkinson

The synthesis of the evidence for **Question 3.3** was based on 119 studies undertaken mostly in the Great Barrier Reef and published between 1990 and 2022. The synthesis includes a *High* diversity of study types (64% observational, 22% modelling, 9% combined and 5% reviews), and has 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 that current exports of fine sediments from the Great Barrier Reef catchment to the Great Barrier Reef are well above pre-development rates. Overall, exports of anthropogenic[15] fine sediment are 1.4 to 3 times higher than pre-development estimates, and in the largest basins 2 to 5 times above pre-development rates. Monitoring and modelling confirm that the Burdekin and Fitzroy basins are by far the largest exporters of total fine sediment and particulate nutrients to the Great Barrier Reef, each exporting an annual average load of over 1,300 kilotonnes of fine sediment per year and more than 3,000 tonnes of particulate nitrogen per year. These basins also have the highest anthropogenic exports. Grazing land use is the largest contributor of fine sediment export to the Great Barrier Reef, estimated to be 60% of the total load, with all other land uses each contributing much smaller amounts (linked to total land area). Hillslope, gully and streambank erosion are each important sources of fine sediment in particular regions. These findings are supported by multiple lines of evidence including monitoring, modelling and radioisotope tracing studies.

Supporting points

- Rates of increase[16] of fine sediment exports over pre-development rates are lower in the Cape York and Wet Tropics Natural Resource Management regions than in other regions.
- Following the Burdekin and Fitzroy basins, the Mary, Herbert and Burnett River basins are the next largest exporters of fine sediment to the Great Barrier Reef (up to 600 kilotonnes per year). Other basins in the Great Barrier Reef catchment that export notable fine sediment loads (over 150 kilotonnes per year) include the Don, O'Connell, Johnstone and Normanby basins. All of these basins have a high proportion of anthropogenic exports.
- It is estimated that 54% of the total export of fine sediment to the Great Barrier Reef comes from gully erosion, with almost equal contributions from streambank erosion (24%) and hillslope erosion (22%). Each process can dominate in particular basins. In the wet tropical climatic areas, hillslope erosion tends to be the dominant source. In the dry tropical areas, gully erosion is by far the biggest source. Intensity of erosion is influenced by soil properties, rainfall and other attributes.
- The estimated proportion of total fine sediment loads exported to the Great Barrier Reef from each land use is well established through modelling, supported by monitoring data. It is estimated that grazing lands contribute 60% of the total fine sediment load from 73% of the Great Barrier Reef catchment area, sugarcane contributes 10% from 1.2% of the area, irrigated and dryland cropping contribute 4% from 2.8% of the area, urban contributes 2% from 0.7% of the area, and bananas and horticulture contribute 1% from 0.2% of the area. Other land uses such as nature conservation and forestry collectively contribute 23% of the total fine sediment load from approximately 22.1% of the Great Barrier Reef catchment area, but this is natural, not anthropogenic export. Anthropogenic load contributions of agricultural and urban land uses are much higher than those of conservation areas.

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[15] The end-of-catchment anthropogenic load of fine sediment or particulate nutrients is calculated as the current end-of-catchment load minus the predicted end-of-catchment pre-development load.

[16] The rate of increase between the current and pre-development loads is formally referred to as the 'rate of acceleration' and is calculated by the division of the current load by the pre-development load.

- The land use contributing the largest export of fine sediment varies between regions. For example, grazing contributes significantly to exports in the Burdekin and Fitzroy regions, sugarcane contributes significantly to exports in the Wet Tropics and Mackay Whitsunday regions, and dryland cropping in the Fitzroy region. Urban land use contributes <5% of fine sediment export in all regions.
- Observational studies show that intense land uses such as mining and urban areas can generate large sources of fine sediment locally but cover a relatively small proportion of the Great Barrier Reef catchment area and overall exports are relatively low.
- The Burdekin, Fitzroy, Mary and Herbert River basins are also the largest exporters of particulate nutrients (nitrogen and phosphorus) to the Great Barrier Reef. There are no independent measures of pre-development particulate nutrient exports.
- Particulate nutrient export from the Great Barrier Reef catchment generally follows similar patterns to fine sediment due to the strong correlation between particulate nutrient and fine sediment. For both particulate nitrogen and phosphorus however, there is a more even distribution across the basins in terms of relative contributions than there is for fine sediment; this is partly linked to soil types.
- In most basins, hillslope erosion is estimated to be the most important source of particulate nutrients due to higher nutrient content in surface soils.
- Fine sediment and particulate nutrient export occurs mainly during floods and the larger the flood event in a particular basin, the greater the export. However, the intermittent frequency of large floods means that annual exports can vary by up to three orders of magnitude in the large dry basins such as the Burdekin and Fitzroy.
- The Reef Water Quality Report Card 2020 estimates that ’Moderate’ overall progress has been made towards meeting the fine sediment load reduction target and ‘Very Good’ progress for the particulate nutrient load reduction targets. In some basins, targets have been exceeded while in others which were not given management priority, there has been little progress. For some management actions it may be several years until the benefits of management are fully realised, and it will take decades to detect reduced exports in the monitoring program because of the high annual variability of exports controlled by river discharge.
- Significant improvements have been made to the Paddock to Reef Program SedNet model (referred to as Source Catchments) in the last few years and it now better matches observed patterns of fine sediment and particulate nutrients. It provides the best available estimates of fine sediment and particulate nutrient exports as a result of the consistency in approach across all 35 basins and the wealth of information that can be extracted from the results.

What are the primary biophysical drivers of anthropogenic sediment and particulate nutrient loss to the Great Barrier Reef and how have these drivers changed over time? What evidence is there to link low ground cover, vegetation and tree clearing with poor water quality and runoff? What is the relationship between land condition and sediment and particulate nutrient runoff for management of Great Barrier Reef catchments? [3.4, 3.4.1, 3.4.2]

Scott Wilkinson, Bruce Murray, Ian Prosser

The synthesis of the evidence for **Question 3.4** was based on 135 studies undertaken in the Great Barrier Reef and published between 1990 and 2022. The synthesis includes a *High* diversity of study types (36% observational, 28% experimental, 22% review studies, and 14% modelling studies), and has a *Moderate* confidence rating (based on *High* consistency and *Moderate* overall relevance of studies).

Summary of findings relevant to policy or management action

The most important biophysical drivers of anthropogenic sediment and particulate nutrient export to the Great Barrier Reef are vegetation degradation and soil surface disturbance. Rainfall is a natural driver which determines the timing of exports. Vegetation degradation is caused by tree clearing (or more generally, land clearing) associated mainly with grazing and cropping land uses, low ground cover primarily from overgrazing and drought, and changes in the structure and function of vegetation including a shift to non-native grass species. Streambank erosion rates are several times higher where riparian tree cover has been removed. Gully and streambank erosion have been greatly accelerated by vegetation degradation and collectively deliver 77% of the sediment and 40–50% of the particulate nutrient export, from a very small proportion of the catchment area. Hillslope erosion rates increase sharply as cover declines below 30–50% because low ground cover exposes soil to erosion by rain splash and scour and increases the efficiency of sediment transport from hillslopes to streams. Vegetation degradation within stream channels, floodplains and wetlands also reduces sediment deposition in those areas. Surface disturbance, including trampling by cattle, tillage in cropping areas, unsealed roads and construction earthworks, is an important biophysical driver especially where it occurs around gullies and streambanks and in areas of erodible soils. Actions that reverse vegetation degradation and prevent surface disturbance can reduce export through reducing erosive forces and increasing erosion resistance, especially when actions are targeted within gully networks and riparian zones. Soil degradation, increases in runoff volumes, runoff concentration by roads, tracks, fence lines and drainage systems are less significant at the Great Barrier Reef scale, but are important drivers in some areas. The construction of large dams that detain some runoff has reduced anthropogenic exports of sediments and particulate nutrients to the Great Barrier Reef in some river basins. Climate change is projected to increase the magnitude of large floods and the severity of droughts, both of which are likely to exacerbate vegetation degradation, surface disturbance and soil degradation.

Supporting points

- The erosion rate of gully walls is inversely related to vegetation cover so it can be expected that gully wall revegetation will reduce sediment export. Revegetation of rapidly eroding gullies, or those in erodible soil, requires physical treatments to support establishment of vegetation.
- Surface disturbance such as tillage, trampling by cattle or feral pigs is a contributor to anthropogenic export of sediment and particulate nutrients especially around gullies and streambanks.
- Reversing vegetation degradation without active intervention is a challenging prospect, so targeting efforts to the most actively eroding features within catchments is likely to be important to efficiently reduce exports, however, assessment of cost-effectiveness of different options is also required.
- Overgrazing during droughts is a primary cause of vegetation degradation and can be avoided by maintaining forage consumption within limits of biomass availability during droughts, including by destocking.
- Soil degradation can include soil compaction, decline in soil fauna and carbon rundown, particularly in more erodible soil types including soils that have depth profiles with texture contrasts. It can increase exports by reducing the capacity for water to infiltrate the surface and be available to support plant survival, and by increasing the rates of surface runoff.
- An increase in runoff detention in large reservoirs is the only driver studied which has substantially decreased anthropogenic sediment and particulate nutrient exports to the Great Barrier Reef. For example, construction of the Burdekin Falls Dam in 1987 decreased sediment export from the Burdekin River basin by 35%. This driver is less effective at capturing the fine particulates that have most impact in the marine environment, has negative impacts on freshwater ecology, and is much more costly than interventions that stabilise erosion directly.
- Land condition is a measure of forage productivity based on forage composition, ground cover, and soil surface characteristics. While land condition can indicate differences in erosional status between the extremes of very low and very high ground cover, it has not been consistently related to hillslope soil loss and it is difficult to measure.
- Changes in the biophysical drivers over time are best documented in the Burdekin and Fitzroy River basins. Significant events have included: surface disturbance associated initially with the introduction of livestock and subsequently with alluvial mining in the Upper Burdekin catchment, vegetation degradation associated with expansion and intensification of grazing which increased Burdekin basin sediment export to record levels by the 1950s, historical and ongoing land/tree clearing including but not limited to the Brigalow bioregion which resulted in Fitzroy River basin sediment export increasing around the 1950s, expansion of cropping, dam construction and road and urban earthworks. More recent construction of large dams has had a smaller effect on exports than the cumulative effect of the other drivers. Ongoing vegetation degradation including land/tree clearing, and surface disturbance, appear to be contributing to expansion in coastal water quality impacts in recent decades, especially where they occur in areas prone

to or experiencing gully and streambank erosion.

- Climate change is projected to increase the magnitude of large floods, the severity of droughts and alter fire regimes, all of which may exacerbate vegetation degradation and gully and streambank erosion processes to increase future export volumes and concentrations. Therefore, the need for vegetation protection in areas of sediment supply will become increasingly important. The overall effect of climate change on sediment and particulate nutrient yields has received limited attention to date and remains poorly understood due to complex interactions with vegetation and land use.

What are the most effective management practices (all land uses) for reducing sediment and particulate nutrient loss from the Great Barrier Reef catchments, do these vary spatially or in different climatic conditions? What are the costs and cost-effectiveness of these practices, and does this vary spatially or in different climatic conditions? What are the production outcomes of these practices? [3.5]

Rebecca Bartley, Bruce Murray

The synthesis of the evidence for **Question 3.5** was based on 162 studies undertaken mostly in the Great Barrier Reef catchments (with Australian literature also included if relevant), published between 1990 and 2022. The synthesis includes a *Moderate* diversity of study types (29% observational from Great Barrier Reef, 27% observational from broader Australia, 25% reviews and 19% modelling), and has a *Moderate* confidence rating for all land uses (based on *Moderate* consistency and *Moderate* overall relevance of studies across land uses).

Summary of findings relevant to policy or management action

The most effective management practices for reducing sediment and particulate nutrient loss from the Great Barrier Reef catchment area vary between land uses, but common practices across land uses include maintaining or reintroducing vegetation into landscapes (including pasture management and vegetation buffers), reducing the hydrological connectivity of flow pathways (via management of roads, drains, gullies etc.), and other practices that minimise soil runoff (such as green cane trash blanketing, zero/minimum tillage and controlled traffic farming). Agricultural areas downstream of dams and closer to the coast lead to higher rates of sediment and particulate nutrient delivery to the coast, therefore the spatial location of sites needs to be considered when estimating management practice effectiveness and translating between the farm site, and ecosystems downstream. There is a lack of data on the cost and production implications of those interventions, and there is not always a “win-win” scenario between improving water quality and increasing profit. For most land uses very few studies have evaluated changes at the whole-of-business level including productivity. The quantity, diversity, and spatial relevance of studies was considerably lower in the evidence for bananas/horticulture, urban and roads compared to grazing, sugarcane and cropping.

Supporting points

- The greatest proportion of total fine sediment loads exported to the Great Barrier Reef are from grazing areas, followed by ‘other’ land uses (nature conservation, forestry, roads, dairy), sugarcane, cropping, urban and bananas/horticulture. Cropping, urban and bananas/horticulture can generate high loads per unit area, but the overall areas are relatively small.
- In **grazing** lands (32 studies), effective practices include moderate and adaptive stocking rates, minimum ground cover levels maintained above 40%, but are most effective when ≥70%, regular periods of strategic rest from grazing (especially in the early wet season), cattle exclusion from fragile land-types, soil amelioration and pasture establishment to assist recovery of large areas of low cover or bare ground, and consideration of vegetation buffers (especially near drainage areas and when using fire as a management tool). The effectiveness of these management practices varies spatially and under different climatic conditions.
- In **sugarcane** lands (24 studies), effective practices include the gradual elimination of water furrows following laser-levelling and repairing eroding drain banks (more effective for coarse sediment), green cane trash blanketing, zero tillage and controlled traffic farming. Other practices associated with higher overall costs include sediment traps, precision farming, and river and stream bank stabilisation. There is significant heterogeneity in cost estimates and farm gross margins between regions and (to a lesser

extent) across farm sizes.

- In **cropping** lands (40 studies), effective practices include the use of contour banks and soil conservation structures on cropping lands >1% slope, retention of crop residues (stubble), reduced tillage, crop rotation and retaining ground cover to reduce erosion and improve yield. The additional benefits of cropping best practice have been demonstrated repeatedly, including improved economic viability and productivity, across different soils and mechanisation systems.
- **Banana and horticulture** (16 studies) practices generally align with cropping and sugarcane. Grass buffer strips can provide between 30 and 50% trapping efficiency for fine sediment in bananas. There is limited information on the economic outcomes of practices and production outcomes.
- In **urban areas** (36 studies, all external to the Great Barrier Reef), effective practices aim to reduce runoff and are linked to improving filtration, hydrological connectivity of impervious surfaces, and greater runoff retention times. Combining treatments into treatment trains (which are a set of hydrologically linked treatments) is more effective than single treatments. For most technologies, there is a relative paucity of reliable field data and few studies that provided any cost or cost-effectiveness data.
- For **roads** (14 studies, all external to the Great Barrier Reef), effective practices include revegetation on roadsides, engineering drainage design, and specific erosion control measures such as the use of erosion control blankets, geotextiles, silt fences and compost/mulch. For unsealed roads, road surface gravelling can also be effective, however, this varies with gravel type. While there are guidelines for road management relevant to construction and maintenance, there are limited studies of the water quality and cost outcomes of treatments. The distribution, density and water quality impacts of roads is not documented.
- Overall, the evidence for all land uses was limited by a lack of measured (as opposed to modelled) runoff and water quality field data combined with land management practice and cost information to demonstrate improvements for many practices.
- There is high variability in the cost-effectiveness of practices at the farm/project scale which is driven by several factors including a wide range of different practices and economic returns, location within the landscape and factors relating to sediment mobilisation and delivery. The way that cost-effectiveness is assessed between projects and programs is also inconsistent. Therefore, there are substantial benefits in prioritising projects for investment at the regional scale based on the key metrics of interest (e.g., sediment reductions) before applying cost-effective metrics at smaller scales.
- Information on the best management practices for reducing sediment export and their impacts on agricultural production and profitability (all land uses), roads and urban systems is a significant knowledge gap and is considered important for increasing uptake of practices to improve water quality outcomes across all land uses in the Great Barrier Reef catchment area.

What is the effectiveness of restoration works (e.g., gully and streambank) in reducing sediment and particulate nutrient loss from the Great Barrier Reef catchments, does this vary spatially or in different climatic conditions? What are the costs and cost-effectiveness of these works, and does this vary spatially or in different climatic conditions? What are the production outcomes of these practices? [3.6]

Andrew Brooks, James Daley, Tim Pietsch

The synthesis of the evidence for **Question 3.6** was based on 88 studies (33 gully remediation and 55 streambank remediation), undertaken in the Great Barrier Reef catchment area and other national and international locations, published between 1990 and 2022 with some earlier streambank studies. The synthesis includes a *Moderate* diversity of study types (58% observational, 19% reviews, 16% experimental and 7% modelling), and has a *Moderate* confidence rating (based on *Moderate* consistency for gullies and *Moderate to High* consistency for streambank studies and *Moderate* overall relevance of gully and streambank studies).

Summary of findings relevant to policy or management action

There are a small number of published studies undertaken in the Great Barrier Reef catchment area that assess the effectiveness and costs of gully remediation for reducing fine sediment export, and none that demonstrate a relationship between site-scale streambank stabilisation and downstream water quality. The large-scale remediation of alluvial[17] gullies has been demonstrated to be an effective strategy to significantly reduce fine sediment load delivered to the Great Barrier Reef. Gully remediation treatments can include major earth works and reshaping, soil treatment, installation of rock chute structures, earth bunds and water points, fencing and revegetation. A combination of these treatments can achieve over 90% fine sediment reduction within one to two years. In contrast, direct hillslope gully treatments appear less effective in reducing fine sediment exports (7 to 17% effectiveness). Destocking catchments may also reduce hillslope gully sediment yields by up to 60%, after ~25 years, however there is limited information on the practicality and costs of this approach. Streambank rehabilitation treatments include interventions to increase riparian vegetation, either directly through planting, or indirectly through the removal of disturbance pressures such as grazing to encourage natural colonisation, and in some cases bank reprofiling and stabilisation, which enables subsequent revegetation via planting and/or natural colonisation. Rehabilitation works cannot currently be evaluated due to limited measurement of treatment effectiveness, but studies have shown that bank erosion generally occurs at lower rates on vegetated streambanks than non-vegetated streambanks. There is a need to refocus efforts from site-scale management to whole-of-system approaches that seek to maximise recovery of riparian vegetation at the river reach to network scale, rather than focus on individual erosion sites. While streambank rehabilitation will assist in reducing sediment export in the Great Barrier Reef catchment area, estimates of return on investment are poorly understood.

Supporting points

- Apart from the studies published in the National Environmental Science Program Tropical Water Quality Hub (2014 to 2021), none of the gully and streambank projects undertaken in the Great Barrier Reef catchment area have quantitatively monitored sediment and particulate nutrient reductions as part of the evaluation of treatment options.
- Studies of gully remediation treatments undertaken in other parts of the world are of limited value for comparison to the Great Barrier Reef context due to the significant geographic and climatic differences, limited measurement of water quality and failure to differentiate between the fine and coarse sediment fractions.
- In the locations studied, a small number of high-yielding gullies (~2% of the total number) account for a substantial proportion of the sediment yield (30%). Alluvial gullies contribute a large proportion of the sediment yield from this top 2% of gullies and typically have high sediment delivery ratios. This highlights the need to prioritise and target gully remediation efforts to efficiently and cost-effectively reduce fine sediment exports to the Great Barrier Reef. While there are also large, high-yielding hillslope gullies in the Great Barrier Reef catchment area, there are no documented examples of these being remediated.
- While large, high-yielding gullies can be expensive to remediate (e.g., more than $500,000), they are a significant and spatially concentrated source of sediment, have shorter response times for fine sediment reductions, and can be treated at larger scales and in fewer locations. Evidence from alluvial gully remediation examples indicates that these treatments can be 26 - 60 times more cost-effective in achieving the same cumulative fine sediment reductions than lower-cost options for lower-yielding gullies, e.g., <$600 per tonne of sediment abated compared to >$13,000 per tonne of sediment abated.
- Although robust methods exist to calculate the cost-effectiveness of gully remediation projects, there is no consistency between projects and investment programs, and agreement on a standardised peer-reviewed method should be a priority. This is critical to assess and compare project viability, capture baseline data and monitor the effectiveness of gully remediation treatments ultimately leading to improved assessments of the cost-effectiveness of remediation design and implementation life.
- In most situations, particulate nutrient reductions from alluvial gully remediation typically track the reductions in fine sediment, however dissolved nutrients can increase where organic matter is added to improve soil condition. The use of organic products such as mulch or hay with a high carbon:nitrogen ratio is more likely to ensure a reduction in dissolved inorganic nitrogen runoff.

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[17] There are two major gully types; alluvial (or river associated) and colluvial (or hillslope gullies). This distinction is based on the material the gullies are eroding into: alluvium - sediments deposited overbank from rivers and streams; and colluvium -sediments derived from *in situ* weathering on slopes and/or downslope processes on hillslopes.

- The evidence of the water quality benefits of streambank rehabilitation from Australian and international literature is limited and focused on small scale (<150 ha) catchments. This evidence has limited applicability to the scale of the Great Barrier Reef River channel network. There are also a wide range of factors that influence river dynamics, posing additional challenges for evaluation.
- Maintenance of gully and streambank projects is critical to prevent further degradation and ensure treatments continue to be effective for many decades. The costs of ongoing maintenance are largely unknown but are required to quantify whole of life costs to inform future policy and management decisions.
- Undercapitalised treatment options are less effective and carry greater risk of future failure. At present it is not known whether the trade-off between initial capitalisation and ongoing maintenance costs will be more or less expensive across the life of the treatment.
- Obtaining quantitative monitoring data at a range of scales (site, subcatchment and catchment) is essential to evaluate the effectiveness, costs and production outcomes of gully and streambank projects and to maximise the benefits of remediation projects.

Livestock by stream
Photo: Scott Wilkinson

Satellite image central Great Barrier Reef
Photo: TropWATER

Theme 4: Dissolved nutrients – Catchment to Reef

Theme 4: Dissolved nutrients – Catchment to Reef

Context

Nutrients occur naturally in ecosystems, however anthropogenic activities have increased the amount of nutrients reaching Great Barrier Reef ecosystems mostly through land-based runoff, with impacts that vary in extent and severity depending on the ecosystem and distance from the coast. Across the Great Barrier Reef, a 60% reduction in the 2009 anthropogenic end-of-catchment dissolved inorganic nitrogen loads is required to meet the 2025 targets defined in the Reef 2050 Water Quality Improvement Plan. Substantial effort is required to meet these targets, especially in the basins delivering the largest dissolved inorganic nitrogen loads to the Great Barrier Reef, particularly in the context of other increasing stressors including climate change.

The synthesis of the evidence for **Theme 4** included a total of **1,272** studies extracted and synthesised for **9** questions (with some overlap in the evidence between questions) (Figure 8). This Theme reviews the evidence of the causal relationships between impacts, sources and management of nutrients (with a focus on dissolved forms of nitrogen and phosphorus) influencing the Great Barrier Reef. Similar to Theme 3 (sediments and particulate nutrients), it starts with the evidence of the ecological processes within the Great

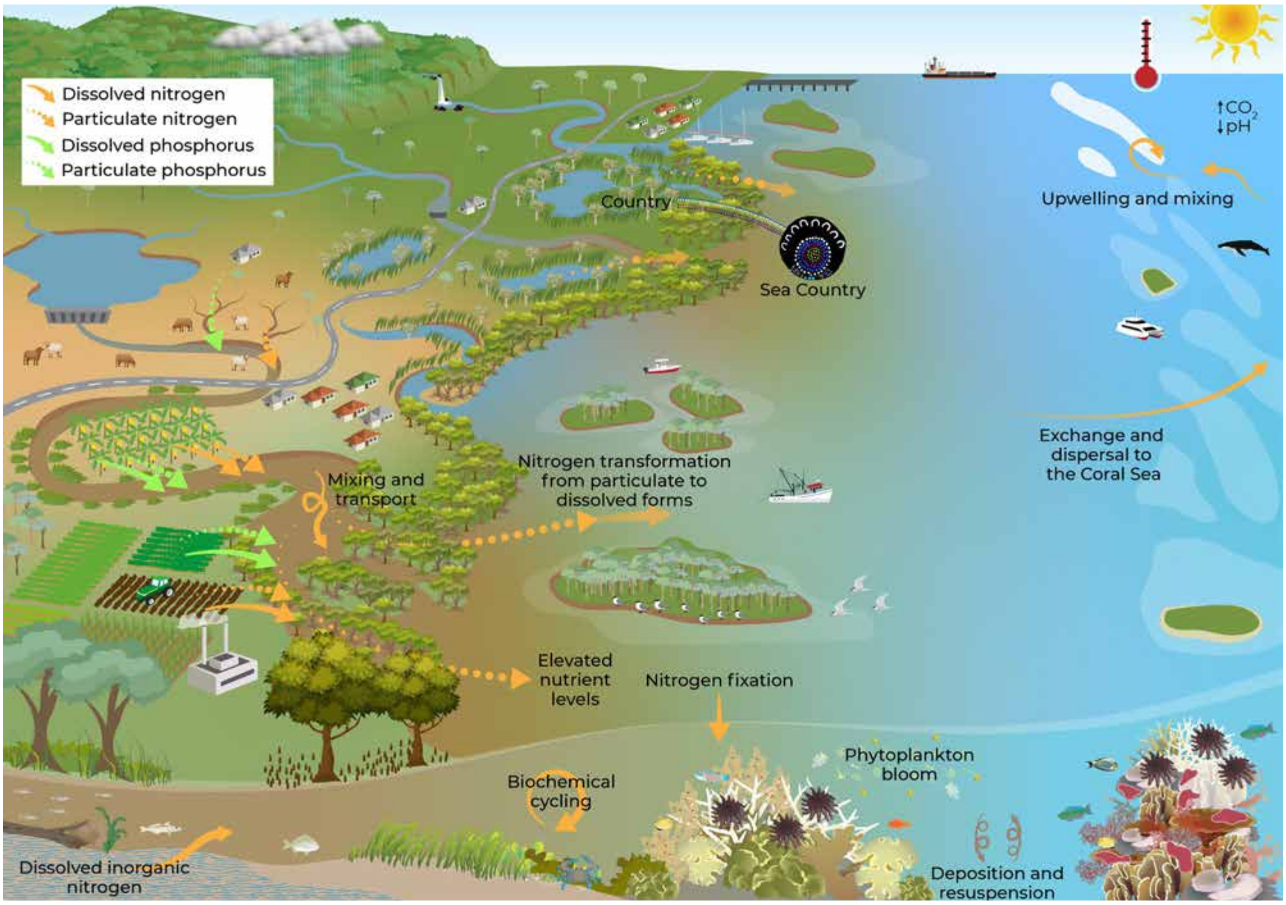

Figure 8. This diagram is a pictorial representation of the scope of Theme 4. It represents the Great Barrier Reef catchment and marine environment and shows the ecological impacts of nutrients on aquatic ecosystems and biota including the influence of flood plumes which mostly affect inshore and midshelf areas. The primary source of dissolved nutrients is sugarcane, with much smaller contributions from urban land uses, bananas and other horticulture, but these can be locally important. Transport pathways are also shown for nitrogen and phosphorus. Nutrients are transported from the catchment to the Great Barrier Reef mostly through surface runoff, subsurface drainage and groundwater movements, with volumes and frequency influenced by rainfall, fertiliser application, erosion and river transport times. Examples of potential management practices to minimise dissolved nutrient export are synthesised and include reducing fertiliser application rates and review of the role of wetlands and other vegetation as measures for reducing nutrient export to the Great Barrier Reef.

Barrier Reef including the spatial and temporal distributions of dissolved nutrients and associated indicators (Q4.1), and the measured impacts of those nutrient loads on Great Barrier Reef ecosystems (Q4.2), with a specific question on the key drivers of the population outbreaks of crown-of-thorns starfish, including the contribution of nutrients from land-based runoff and alternative hypotheses (Q4.3). The primary sources of anthropogenic dissolved nutrients are presented (Q4.4), with expansion of the evidence of the biophysical drivers, transport and delivery processes from the catchment area to the Great Barrier Reef (Q4.5). Synthesis of the most effective management practices for reducing dissolved nutrient export from the Great Barrier Reef catchment area provides insights for policy and management (Q4.6). Finally, three questions focus on different aspects of wetlands and their potential role in improving water quality, including their efficacy (Q4.7), costs and cost drivers (Q4.8) and potential ecosystem services (Q4.9). The question addressing crown-of-thorns starfish outbreaks (Q4.3) and the wetland questions (Q4.7, 4.8 and 4.9) were identified by policy representatives as very high priority for clarifying the weight of evidence in a consistent and non-biased way due to increasing stakeholder interest in future investment programs.

Summary Statement for Theme 4

Convergence was reached for this Summary Statement among all authors within the Expert Group for Theme 4 (listed in **Appendix 1**).

The synthesis of the evidence for **Theme 4** included a total of **1,272** studies extracted and synthesised for **9** questions (with some overlap in evidence between questions).

The **summary of findings** relevant to policy or management action for **Theme 4** are:

- Nutrients, especially nitrogen and phosphorus, play a crucial role in the water quality and overall health of Great Barrier Reef ecosystems, supporting coral reefs, seagrass meadows and fisheries. Nitrogen is generally considered the major limiting nutrient in marine waters, both globally and in the Great Barrier Reef, however, phosphorus can limit primary productivity at certain times and locations. Multiple lines of evidence demonstrate that nutrient concentrations originating from land-based activities follow a cross-shelf gradient with the highest concentrations found in estuaries and inshore waters, and lower values in midshelf and offshore waters. Peak concentrations are usually found during the wet season (December to May), between Cooktown and Gladstone, adjacent to areas of more intensive catchment development and in waters influenced by river discharge. Weather patterns, river discharge and associated land-based inputs, as well as marine processes such as upwelling and nitrogen fixation are among the key drivers of nutrient variability, with oscillations over time. [Q4.1]
- Excessive amounts of dissolved inorganic nutrients can have detrimental effects on Great Barrier Reef ecosystems. In coral reefs, the most severe impacts may be indirect, for instance, excess nutrient availability on inshore reefs is generally (but not always) positively correlated with increased fleshy macroalgal abundance which can reduce coral settlement and recruitment, outcompete corals, reduce coral cover and negatively affect coral calcification. Excess nutrients might also contribute to coral-eating crown-of-thorns starfish outbreaks (see below). Direct effects of elevated nutrients include reduced coral calcification, negative impacts on coral reproduction, and potentially reducing thermal tolerance to bleaching. [Q4.2]
- There is no clear evidence of direct negative impacts of increased dissolved inorganic nutrients on seagrass ecosystems, and although elevated nutrients may be beneficial for mangrove growth, they can interact with climate stressors such as drought (low rainfall and low humidity) causing mangrove decline. There is limited evidence of the impact of dissolved inorganic nutrients on Great Barrier Reef wetland ecosystems. [Q4.2]
- During high river discharge events, elevated nutrient levels cause phytoplankton blooms that sometimes coincide with developing crown-of-thorns starfish larvae. These blooms increase the amount of food available for larvae which can increase survival, growth, and development rates, though it has not yet been shown that crown-of-thorns starfish outbreaks are limited by larval supply. Crown-of-thorns starfish outbreaks in the Great Barrier Reef start on midshelf reefs between Cairns and Lizard Island – the crown-of-thorns starfish ‘initiation area’, which occasionally receives nutrient-enriched flood plumes from rivers. Although land-based nutrient runoff may contribute to outbreaks, other factors such as marine upwelling, life history traits including high fecundity, and the

effect of predator removal (e.g., fishing) may also be important. Combining evidence from these different factors will contribute to a more complete understanding about when, where and how population outbreaks will occur. [Q4.3]

- Overall, exports of anthropogenic dissolved inorganic nitrogen are twice as high as pre-development rates, mainly as a result of fertiliser-adding land uses. 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 (exporting over 500 tonnes per year, each). [Q4.4]
- Anthropogenic exports of dissolved inorganic nitrogen are greatest in basins dominated by sugarcane including those in the Wet Tropics, Burdekin and Mackay Whitsunday Natural Resource Management regions. Increased erosion from grazing and other land uses can also contribute to nutrient export, with transformation of particulate nutrients to dissolved forms (termed bioavailable nutrients) during transport. Other land uses including urban, bananas and other horticulture contribute smaller amounts but can be locally important. Surface runoff, subsurface movement and groundwater are all significant transport pathways of dissolved nutrients to the Great Barrier Reef. Most export occurs in the wet season, with chronic and continuously high exports in wet tropical catchments. [Q4.4, Q4.5]
- Primary biophysical drivers of anthropogenic dissolved nutrient exports to the Great Barrier Reef are fertiliser application, altered catchment hydrology leading to changed (typically shorter) water residence time in rivers and reduced interaction of surface and subsurface runoff with floodplains, and erosion. Increased rates of fertiliser application and low nutrient use efficiency, increased cultivation area, low efficiency irrigation systems and heavy rainfall can lead to increased nutrient export, especially nitrogen, in surface and subsurface runoff and groundwater. [Q4.5]
- During river transport, nutrients can be transformed by a range of processes such as denitrification, desorption of nutrients from soil particles, plant uptake and burial, remineralisation, and deposition to sediment. However, the majority of nutrient loads are delivered from the source to the Great Barrier Reef World Heritage Area. 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 these improvements to export loads; however, for some management actions it may be several years until the benefits of management are fully realised. [Q4.4, Q4.5]
- The most effective and profitable management practice for reducing dissolved nitrogen exports from the Great Barrier Reef catchment area is reducing nitrogen fertiliser applications to industry recommended rates, with consistent results across different land uses, climates, and management contexts. Further rate reductions give consistent water quality benefits, but productivity and profitability varies. In sugarcane, other management practices include the use of Enhanced Efficiency Fertiliser, mill mud application, improved irrigation, crop residue management, improved farming systems (such as growing legumes in between sugarcane crops) and burying fertiliser. For many of these management practices, the effectiveness and profitability is not clearly demonstrated and, for some, varies depending on climate, soil and seasonal characteristics. The effectiveness and profitability of practices for reducing dissolved phosphorus exports are less clear, as is the situation for crops other than sugarcane. The adoption of management practices can be enhanced by a range of factors as discussed in detail in Theme 7. [Q4.6]
- For urban and non-agricultural land uses, structural measures that include vegetation or biological components such as constructed wetlands, biofilters, algal ponds and existing riparian zones have considerable potential for removal of diffuse runoff nutrients and may also be important for management of wastewaters. Improvements in technologies for wastewater management also show that systems such as membrane filtration and chemical addition are likely to perform well. Non-structural controls such as policy, planning, regulation and compliance appear to work best when applied as part of an integrated approach, and recycling and reuse show considerable potential. [Q4.6]
- The global evidence indicates that tropical wetland systems can retain, process and in some cases, export nutrients, sediments and pesticides with a wide-ranging capacity for pollutant retention. The evidence also shows that natural and near-natural wetlands are typically more effective at nutrient removal (certain forms) and pesticide removal than constructed or restored wetlands, and sediment is often retained in wetlands but can be remobilised in large flow events. There are few peer reviewed

studies that comprehensively measure or model wetlands' efficacy or costs of water quality improvement in the Great Barrier Reef catchment area. Critical factors for optimising the efficacy of water quality improvement include: the presence and maintenance of vegetation communities; hydrological characteristics including the wetland size relative to the contributing catchment area, flow rate, loss pathways and water residence time; and the type, form and input concentration of the targeted pollutant. Available evidence indicates that the costs of treatment wetlands are highly variable. These factors, and the need for ongoing maintenance, need to be carefully considered when planning for the use of wetland systems as a water quality improvement tool in the landscape. [Q4.7, Q4.8]

- Natural and near natural wetlands provide many benefits to society and the environment including regulating ecosystem services such as improved water quality and carbon sequestration, supporting services such as nutrient cycling and provision of habitat, cultural services such as aesthetics and recreation and provisioning services including food, water and other resources. In the Great Barrier Reef catchment area, these wetlands and services are under pressure due to expansion of coastal agriculture, urban and industrial development. Wetlands can be restored to enhance water quality benefits but without a long-term plan of maintenance, and clear definition of restoration goals, restoration project sites have a high risk of returning to a degraded state, reducing the services they provide. The historical loss of natural wetlands across floodplains and the degradation of those ecosystems remaining are important considerations for determining future protection and management opportunities for wetlands in the Great Barrier Reef catchment area. [Q4.7, Q4.9]

Sargassum growing on a reef

Photo: Canva

The **confidence** rating of the questions was High for one question (addressing the sources of dissolved nutrients), and Moderate for the remaining eight questions, mostly explained by Moderate relevance of the evidence to the question for studies that were not originally designed to address some of the questions, and Moderate consistency as a result of alternate hypotheses or where less evidence was available. The Moderate ratings for relevance and consistency also reflect the considerable natural variability in sources of nutrients, in the very diverse organisms that constitute the various Great Barrier Reef ecosystems and their variable responses.

The findings in this Theme are underpinned by a large body of evidence including multiple lines of evidence (including monitoring, modelling, remote sensing, meta-analysis, experimental research and observations). The **strength of evidence** across this Theme, considering the confidence, quantity and diversity of study types, is considered to be Moderate, with limited evidence around wetland systems, and on nutrient management options beyond those related to sugarcane.

The **key uncertainties** of the evidence identified for **Theme 4** relevant to policy and management include the following: effects of increased dissolved inorganic nutrients on freshwater streams and wetlands in the Great Barrier Reef catchment area; the magnitude and distribution of nitrogen fixation in wetlands, coastal and marine waters; the relative importance of the hypotheses explaining the occurrence of crown-of-thorns starfish outbreaks; the interactions between elevated nutrients and other stressors on the ecosystems including climate change factors such as warming and ocean acidification; understanding of nutrient transformations to better assess the effectiveness of management actions; accounting for variability and unpredictability in the effectiveness of management practices for reducing dissolved inorganic nitrogen in sugarcane and other crops; the management of dissolved phosphorus discharges from all agricultural land uses; the heterogeneity in cost data depending on agro-ecological, social and economic factors; and the contribution of groundwater to nutrients entering and being processed in wetlands which is likely to be an important consideration when evaluating their performance in pollutant removal.

Recent findings continue to identify fertiliser inputs, erosion, surface runoff and rainfall as key factors influencing nutrient concentrations in freshwater, and there has been an increased understanding of the transformation from particulate to dissolved forms (termed bioavailable nutrients). In terms of dissolved nutrient impacts on ecosystems, while there has been limited new research since 2016, investigations have focused on the combined effects of nutrients with other climate change-related pressures including warming, and ocean acidification, and the relationship between elevated nutrients and macroalgae. The combined impacts of multiple factors that contribute to crown-of-thorns starfish outbreaks, and the role of anthropogenic nutrient inputs in this context, is now better understood, however new research has also highlighted the complexity and variability of these interactions. In the catchment, the potential benefits of Enhanced Efficiency Fertiliser application in sugarcane have been clarified, and knowledge of the interactions between climate and fertiliser dynamics is improving. New research has begun to assess the effectiveness of wetland and treatment systems for water quality improvement in agricultural areas.

Within **Theme 4**, the areas where further **knowledge is needed** that are most relevant to policy and management include: i) a more complete picture of nutrient sources and distributions in the Great Barrier Reef (e.g., dissolved inorganic nitrogen from the Fitzroy region, and potential links to soil erosion) including temporal and spatial variability, nutrient budgets, links to land-based inputs, outcomes from management changes, and timescales for change; ii) the role of oceanographic processes in driving variability in marine nutrient concentrations; iii) links between elevated nutrients and other ecosystem impacts such as bleaching, coral disease, microbioerosion and microbial communities; iv) the effects of increased dissolved inorganic nutrients on freshwater streams and wetlands; v) factors contributing to crown-of-thorns starfish outbreaks including demography, ecology, reproductive potential and recruitment limitations, feeding rates and predation rates; vi) transformation processes, export and impacts of phosphorus in all ecosystems, vii) quantification of the generation of bioavailable nutrients from soil erosion and the timeframes of nutrient transformation; viii) the effects of climate, soil and seasonal conditions on nitrogen demand and crop growth to better assess the production and economic impacts of different nitrogen fertiliser rates and forms; ix) quantification of groundwater contributions of nutrients to wetlands; and x) standardised approaches to monitor and evaluate the efficacy of wetlands for the purpose of water quality improvement, with additional information on the cost-effectiveness of these systems and potential impact on the multitude of ecosystem services they provide to humans and the environment.

Summary information for Questions in Theme 4

The Table below summarises the evidence appraisal indicators and confidence ratings in the evidence base for each of the Questions within this Theme. The Confidence rating was determined by the overall relevance of studies to the question and the consistency of the body of evidence (refer also to Appendix 3: Glossary for explanation of indicators). *Note: In Diversity of items: Experimental (E), Meta-analysis (MA), Mixed (X), Modelling or Remote sensing (M), Observational (O), Reviews (R), Theoretical or Conceptual (T).*

Question	**Quantity of items**	**Diversity of items**	**Overall relevance**	**Consistency**	**Confidence**
What is the spatial and temporal distribution of nutrients and associated indicators within the Great Barrier Reef? [4.1]	High (106)	*High (55% O, 8% R, 37% M)*	Moderate	High	Moderate
What are the measured impacts of nutrients on Great Barrier Reef ecosystems, what are the mechanisms for those impacts and where is there evidence of this occurring in the Great Barrier Reef? [4.2]	High (157)	*High (43% O, 29% E, 15% R, 12% M, 1% T)*	Moderate	Low - Moderate	Moderate
What are the key drivers of the population outbreaks of crown-of-thorns starfish (COTS) in the Great Barrier Reef, and what is the evidence for the contribution of nutrients from land-runoff to these outbreaks? [4.3]	High (183)	*High (38% O, 30% E, 29% T-R-M, 3% X)*	Moderate	Moderate	Moderate
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? [4.4]	High (61)	*High (54% O, 23% M, 11.5% R, 11.5% X)*	High	High	High
What are the primary biophysical drivers of anthropogenic dissolved nutrient export to the Great Barrier Reef and how have these drivers changed over time? [4.5]	Moderate (52)	*High (58% O, 25% R, 12% M, 5% X)*	Moderate	Moderate	Moderate
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 and cost-effectiveness of these practices, and does this vary spatially or in different climatic conditions? What are the production outcomes of these practices? [4.6]	Moderate (294)	*High (46% E, 21% M-T, 15% R, 13% O, 5% X)*	Moderate - High	Moderate - High	Moderate
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)? [4.7]	High (238)	*High (45% E, 28% O, 14% M, 7% T, 3% X, 3% R)*	Moderate	Moderate	Moderate

Question	**Quantity of items**	**Diversity of items**	**Overall relevance**	**Consistency**	**Confidence**
What are the measured costs, and cost drivers associated with the use of natural/near natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in Great Barrier Reef catchments in improving water quality? [4.8]	Low-Moderate (56)	*High (41% M, 39% R, 20% O)*	Moderate	High	Moderate
What role do natural/ near natural wetlands play in the provision of ecosystem services and how is the service of water quality treatment compatible or at odds with other services (e.g., habitat, carbon sequestration)? [4.9]	High (125)	*High (31% O, 18% R, 18% M, 16% T, 12% E, 5% X)*	Moderate	High	Moderate

Cane landscape
Photo: Rick Abom

Evidence Statements for Questions in Theme 4

What is the spatial and temporal distribution of nutrients and associated indicators within the Great Barrier Reef? What is the variability of nutrients in coastal and marine areas of the Great Barrier Reef? [4.1, 4.1.1]

Barbara Robson, Aimee Brown, Sven Uthicke

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

Summary of findings relevant to policy or management action

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

Supporting points

- Multiple lines of evidence provide a temporal record of nutrient distribution across the whole Great Barrier Reef. This includes coral core data that provides insight into pre-development conditions, ocean colour data extending back to 1969, data from ad hoc *in situ* studies from the 1990s, and routine monitoring from 1989 at some locations (e.g., the 'Cairns transect' from the Barron River mouth to midshelf areas) to present. The majority of studies focus on inshore and/or midshelf waters, with relatively few studies including estuary or offshore nutrient concentrations. The largest source of inshore nutrient data is the Great Barrier Reef Marine Monitoring Program which started in 2005.
- Multiple datasets show that total phosphorus, total nitrogen, dissolved inorganic nitrogen, phosphate and silica concentrations follow a cross-shelf gradient from higher values in estuaries, mangrove creeks and inshore waters to lower values in midshelf waters. In offshore waters, relatively high concentrations of dissolved inorganic nitrogen and chlorophyll *a* can sometimes occur in areas of oceanic upwelling.
- Concentrations of total phosphorus, total nitrogen, dissolved inorganic nitrogen and phosphate are elevated in flood plumes (relative to ambient concentrations) and in areas of sediment resuspension. Chlorophyll *a* concentrations are also elevated in flood plumes where light is sufficient. Silicate concentrations follow similar spatial patterns but have not been as well studied. Little observational data is available for micronutrients, including iron.
- Flood plumes in the Great Barrier Reef, carrying land-based nutrients and other pollutants, are usually constrained to distances within 25 kilometres of the coast, but can extend up to 50 kilometres from the coast after major flood events; into midshelf waters. In general, the spatial extent of flood plumes is greater in the central and southern Great Barrier Reef than in the Cape York region. Most flood plumes travel northwards up the coast from their source rivers, though this can vary with the wind direction and rate of river discharge.
- Most terrestrial particulate nutrients are deposited within 10 kilometres of river mouths, but dissolved

nutrients are carried further and are taken up by biota and transformed into phytoplankton biomass (measured as chlorophyll *a*). Higher chlorophyll *a* concentrations are often observed in the mixing zones at the edge of flood plumes.

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

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

Guillermo Diaz-Pulido, Catalina Reyes-Nivia, Maria Fernanda Adame, Angela Arthington, Catherine Collier, Catherine Lovelock

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

Summary of findings relevant to policy or management action

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

Supporting points

- Macroalgal abundance follows a clear gradient across the Great Barrier Reef shelf, with fleshy macroalgal abundance highest in inshore areas and lowest in offshore areas. Nutrient addition does not always enhance macroalgal growth rates or lead to enhanced biomass, therefore it is simplistic to assume that the macroalgal gradient can only be attributed to land-based inputs of nutrients in inshore reefs. The effects of nutrient enrichment need to be considered in combination with other factors, particularly grazing by fish, sedimentation, ocean acidification and warming.
- Evidence is limited for the effects of dissolved inorganic nitrogen and dissolved inorganic phosphorus on crustose coralline algae (important for reef building), but available studies show enhanced growth under elevated conditions. The lower abundance of crustose coralline algae on inshore reefs compared to offshore reefs may be related to increased sediment loads and a reduced seawater calcium carbonate saturation state in inshore reefs.
- Comparing the effects of dissolved inorganic nutrients between and among regions is challenging due to limited spatial data. Reef communities from the Mackay Whitsunday Natural Resource Management region, and to some extent the Burdekin region have been relatively well studied, but there is a significant lack of information from other areas of the Great Barrier Reef.
- There is still debate about whether elevated dissolved inorganic nitrogen raises the susceptibility of corals to thermal stress and contributes to coral bleaching. Computer simulations both support and reject this hypothesis, and severe mass bleaching of corals in 2016 did not show a water quality effect. However, there is mounting evidence from international research groups that supports the hypothesis that nutrient enhancement can reduce thermal bleaching thresholds in corals.
- Crown-of-thorns starfish larval development can benefit from elevated nutrients which can enhance phytoplankton biomass (measured by chlorophyll *a* concentration), but up to a limit as excessive phytoplankton concentrations may reduce larval performance. However, there is evidence that crown-of-thorns starfish larvae can also survive in low nutrient water. Elevated nutrients may exacerbate the incidence or severity of outbreaks, but are likely to be one of several contributing factors along with predator removal and inherent life history traits.
- Evidence suggests that declining water quality (increased nutrients and sediment loads combined) contributes to seasonal outbreaks in coral disease in the Great Barrier Reef. However, a direct link between coral disease and dissolved inorganic nutrients has not been demonstrated yet and future studies should specifically address this gap.
- Bioerosion patterns show variable responses in coral reefs across the natural water quality gradient, however there is limited evidence examining the causes. Inshore reefs have lower rates of total bioerosion relative to midshelf and offshore reefs which typically exhibit high bioerosion rates due to the presence of microborers and increased grazing activity by parrotfish. Higher levels of nutrients and organic matter in inshore and midshelf reefs may explain increased abundance of macroborers leading to increased bioerosion rates. These relationships require further investigation.
- Microbial communities are very responsive to elevated nutrients and thus to gradients of water quality across the Great Barrier Reef. The effects cannot be generalised as benthic and planktonic bacterial communities, and microphytobenthos, are highly variable in species composition but this is a rich target for research to find indicators of water quality.
- Phytoplankton biomass (measured as chlorophyll *a* concentrations) responds positively to nutrient availability. The impact of elevated phytoplankton biomass on coral reefs and seagrass meadows is mostly via reduction of water clarity and consequently reduced light availability for symbiotic corals and seagrasses.
- While elevated nutrients can increase seagrass growth rates and distribution, elevated epiphytic growth has been documented on estuarine seagrasses (possibly from increased nutrients) which can lead to reduction of plant photosynthesis. It is unclear if this condition is contributing to seagrass decline.
- The direct and indirect effects of increased dissolved inorganic nutrients on freshwater streams and

wetlands in the Great Barrier Reef is poorly understood and may vary with differences in landscape characteristics, rainfall, flow regimes, and among ecosystems and organisms.

What are the key drivers of the population outbreaks of crown-of-thorns starfish (COTS) in the Great Barrier Reef, and what is the evidence for the contribution of nutrients from land-runoff to these outbreaks? [4.3]

Ciemon F. Caballes, Katie Sambrook, Morgan S. Pratchett

The synthesis of the evidence for **Question 4.3** was based on 183 studies, primarily undertaken within the Great Barrier Reef (but including others for comparison) and published between 1990 and 2023. The synthesis includes a *High* diversity of study types (38% observational/analytical, 30% experimental, 29% conceptual/review/modelling approaches and 3% mixed) and has a *Moderate* confidence rating (based on *Moderate* consistency and *Moderate* overall relevance of studies).

Summary of findings relevant to policy or management action

Population outbreaks of the coral-eating crown-of-thorns starfish represent one of the most significant biological disturbances on coral reefs and remain one of the principal causes of widespread declines in live coral cover on the Great Barrier Reef. Understanding the key drivers of outbreaks on the Great Barrier Reef is fundamental for establishing relevant management responses. There are several hypotheses to explain why outbreaks occur, but they have been typically considered as discrete entities. The most prominent hypotheses include natural causes due to inherent life history characteristics, and others that take into account anthropogenic influences such as the effects of predator removal on different life stages, and water quality changes causing enhanced larval success. This synthesis finds supporting evidence for each of these hypotheses and proposes that the hypotheses are more likely to be complementary rather than mutually exclusive, with a combination of elements resulting in a ‘perfect storm’ that can trigger an outbreak. Combining evidence from the different hypotheses will contribute to a more complete understanding about when, where and how population outbreaks will occur.

Supporting points

- Crown-of-thorns starfish outbreaks mostly occur on midshelf reefs in the Great Barrier Reef.
- The body of evidence suggests that primary outbreaks of crown-of-thorns starfish on the Great Barrier Reef are most likely driven by a combination of the most prominent hypotheses: natural causes, predator removal, and enhanced nutrients.
- *Natural causes hypothesis:* This hypothesis argues that crown-of-thorns starfish naturally possess inherent life history traits that predispose populations to significant spatial and temporal fluctuations. This hypothesis is supported by evidence of high fecundity, high fertilisation rates, and fast growth that predisposes them to naturally occurring extreme fluctuations in reproductive success and population size. These traits, coupled with the time required for recovery and regrowth of their coral prey, may explain the periodicity (~14 to 17 years) of recurrent outbreaks events on the Great Barrier Reef.
- *Predator removal hypothesis:* This hypothesis argues that crown-of-thorns starfish populations are normally regulated by high rates of predation on post-settlement life stages and that outbreaks arise when predator populations are reduced (e.g., through fishing). The evidence shows that in areas where fishing is prohibited, the incidence of crown-of-thorns starfish outbreaks is generally lower, while the prevalence of sublethal injuries on crown-of-thorns starfish is higher, compared to areas open to fishing. In addition, laboratory, field experiments and modelling studies also indicate that predation rates on post-settlement juveniles can be significant and may regulate crown-of-thorns starfish populations.
- *Nutrient hypothesis:* This hypothesis argues that enhanced nutrient supply from river runoff (especially after extreme rainfall events) increases primary production, particularly in coastal and inshore marine waters, resulting in a phytoplankton bloom. Phytoplankton blooms could be beneficial for crown-of-thorns starfish larvae by increasing food supply, thereby promoting faster growth and lower mortality. The following evidential chain was established for this review:
    1. Nutrient loads delivered to inshore waters and some midshelf sections of the Great Barrier Reef (particularly between Cooktown and Cairns where midshelf reefs are closer to the coast) have increased as a result of historical agricultural development in the Great Barrier Reef catchment

area;

2. The concentration and availability of nutrients increases following large river discharges, although crown-of-thorns starfish outbreaks do not consistently occur in the aftermath of large river discharge events;
3. Phytoplankton blooms and shifts in phytoplankton community structure resulting from nutrient enrichment during flood events have been documented, although there is some uncertainty whether phytoplankton concentration (chlorophyll *a* levels) or specific phytoplankton species that become dominant during blooms, or a combination of both, is necessary to drive enhanced survivorship and development rates in crown-of-thorns starfish larvae;
4. Survival, growth, and development rates are generally higher for well-fed larvae, but there is a lower and upper threshold for optimal food levels;
5. The fundamental assumption that larval supply is generally limiting, such that outbreaks arise due to pronounced and temporary increases in larval survivorship due to enhanced food supply, has yet to be explicitly tested; and
6. Outbreaks of crown-of-thorns starfish on the Great Barrier Reef start on midshelf reefs in the Northern sector of the Great Barrier Reef (between Cairns and Lizard Island, and possibly further north), an area commonly referred to as the crown-of-thorns starfish ‘initiation area’. The ‘initiation area’ overlaps with the area where nutrient-enriched river discharge enters the midshelf waters of the Great Barrier Reef on a regular basis. Larvae produced by primary outbreak populations are subsequently retained on source reefs or dispersed to reefs south of the ‘initiation area’ according to prevailing hydrodynamic regimes, thereby resulting in secondary outbreaks.
7. The evidence to date suggests that water quality management programs in isolation will have a limited effect on controlling crown-of-thorns starfish outbreaks on the Great Barrier Reef. However, improving water quality through minimising sediment, nutrient, and pollutant runoff, and implementing stricter regulations on fishing, particularly through no-take marine protected areas, offers the best resistance to a natural pest while simultaneously enhancing the resilience of reef ecosystems to withstand or recover from outbreaks.

- In summary, while crown-of-thorns starfish may be naturally predisposed to outbreaks because of key life history traits, it is likely that anthropogenic impacts on water quality and predator fish stocks have exacerbated the incidence or severity of outbreaks, and/or undermined the capacity of reef ecosystems to withstand these cyclic pest irruptions.

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? [4.4]

Ian Prosser, Scott Wilkinson

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[18] 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,

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[18] 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.

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 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.

What are the primary biophysical drivers of anthropogenic dissolved nutrient loss to the Great Barrier Reef and how have these drivers changed over time? What proportion of nutrient is lost by surface and subsurface pathways? How do nutrients transform during the transport and delivery to the Great Barrier Reef lagoon (e.g., bioavailability of particulate nutrients)? [4.5, 4.5.1, 4.5.2]

Michele Burford, Jianyin (Leslie) Huang, Zoe Bainbridge, Joanne Burton, Mohammad Bahadori, Gillian McCloskey, Michael Newham

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

Summary of findings relevant to policy or management action

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

Supporting points

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

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

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? What is the potential of Enhanced-Efficiency-Fertilisers (EEFs) in reducing nitrogen runoff and what are the primary challenges in implementation? What are the implications of mill mud application in influencing nitrogen losses and what are the primary challenges for implementation? What are the primary factors that influence nutrient losses from irrigated areas and how can these be managed? [4.6, 4.6.1, 4.6.2, 4.6.3]

Peter Thorburn, Kirsten Verburg, Marina Farr, Tony Weber, Maria Vilas, Caleb Connolly, Rohan Eccles

The synthesis of the evidence for **Question 4.6** was based on 294 studies, undertaken across the Great Barrier Reef catchment area and wider Australia for non-agricultural/urban-related evidence and published between 1990 and 2022 (plus a few older references dating back to 1976 for non-agricultural/urban evidence). The synthesis includes a *High* diversity of study types (46% experimental, 21% modelling or conceptual, 15% reviews and secondary analysis, 13% observational and 5% other including mixed studies, social and behavioural), and has a *Moderate* confidence rating (based on *Moderate* consistency and *Moderate* overall relevance of studies).

Summary findings relevant to policy or management action

Reduced application of nitrogen fertiliser is a consistent means of reducing dissolved inorganic nitrogen exported from fields via all pathways (runoff, leaching and gaseous losses) in different agricultural land uses, climates and management contexts in the Great Barrier Reef catchment area. In sugarcane, nitrogen application rates above industry best practice can result in avoidable nitrogen loss, increase the cost of production and reduce economic returns. However, reducing fertiliser nitrogen rates "too much" can impact on productivity and hence on profitability at the farm and sugarcane mill, although the definition of "too much" is variable. Enhanced-efficiency fertilisers may reduce both dissolved inorganic nitrogen export via leaching and mitigate risks of productivity losses when nitrogen fertiliser applications are reduced. However, the results are highly variable across sites and years and consistent benefits are often only seen when averaged across sites and seasons. There are limited studies that assess the effectiveness, productivity or cost-effectiveness of other sugarcane management practices including mill mud application, subsurface application of fertiliser, improved irrigation, crop residue management and various attributes of improved farming systems (e.g., tillage, fallow legumes) in reducing dissolved inorganic nitrogen export. There is little peer reviewed evidence on the effectiveness of management practices for reducing dissolved inorganic nitrogen export in crops other than sugarcane, or on the management of dissolved phosphorus exports. For urban/non-agricultural land uses, structural measures that include vegetation or biological components, such as wetlands, biofilters, algal ponds and existing riparian zones have considerable potential for removal of diffuse runoff nutrients and may also be important for management of wastewater. Non-structural controls for nutrient management in non-agricultural land uses including policy, planning, regulation, compliance and education, appear to work best when completed as part of an integrated approach. Recycling and reuse of wastewater shows considerable potential, provided that there is careful consideration of the location of water reuse.

Supporting points

- The possible impacts of reducing nitrogen fertiliser rates on productivity and profitability in sugarcane are variable and can be affected by climate, soil and seasonal conditions. As a result, the optimum nitrogen fertiliser rate (i.e., the rate giving near maximum profitability) is both unknown and unpredictable for a specific sugarcane crop. Reducing fertiliser rates reduces the cost of production for crops; however, there may be additional costs such as expenditure on capital or an increase in other business expenses in doing that and there is a risk that productivity will be reduced.
- Reducing nitrogen rate (or applying enhanced-efficiency fertilisers) is likely to provide greater water quality benefits for crops starting later in the year, as the magnitude of dissolved inorganic nitrogen losses will generally be greater closer to the start of the wet season and first rainfall events. This timing may also affect the productivity impact of reduced nitrogen applications.
- Enhanced-efficiency fertilisers act by reducing the concentration of the mobile form of inorganic nitrogen (nitrate) in soils which helps to reduce leaching. Benefits of using enhanced-efficiency fertilisers are likely to be greatest for crops starting in mid- to late-season, in wetter regions and wetter growing seasons. Increased productivity will only occur if dissolved nitrogen leaching is reduced and crop growth at that time is responsive to the additional nitrogen available in the soil. These conditions are more likely on permeable soils. There is limited evidence quantifying the benefits of enhanced-efficiency fertilisers in reducing dissolved inorganic nitrogen losses.
- There is some evidence that applying mill mud to sugarcane can increase losses of dissolved phosphorus, but not nitrogen. Reducing fertiliser application rates in crops following mill mud application seems prudent to reduce risk of additional dissolved phosphorus and nitrogen losses; however, the benefits of these interactions have not been quantified. In addition, the extent to which fertiliser applications can be reduced following mill mud application without impacting on crop productivity is unclear.
- The effect of improved irrigation practices on dissolved nutrient losses or on farm productivity in the Great Barrier Reef catchment area is uncertain, with most information derived from mechanistic modelling studies in sugarcane. The available results indicate that high irrigation efficiency resulting from lower irrigation application rates is predicted to reduce dissolved inorganic nitrogen losses from sugarcane crops, but there is a risk that productivity is also reduced. While there is evidence that well-designed and managed automated furrow irrigation systems on sugarcane farms can be profitable, the water quality outcomes of these systems are not clear. Limited evidence suggests that converting to a fully automated irrigation system on banana farms may potentially provide economic benefits.
- There is limited evidence on the effectiveness of management practices for reducing dissolved inorganic

nitrogen export in bananas, horticulture and grains. Mechanistic cropping systems models, that have been useful in providing insights in sugarcane production, are not well developed or tested for these crops.

- Factors that influence the cost-effectiveness and productivity of nutrient management practices in cropping include farm size and layout, rainfall patterns, soil type, landholder experience and distance to a processing plant or market. Program and administration costs, transaction costs and the time taken to adopt practices and for benefits to accrue are also important. Better recognition of these factors and more consistent monitoring and reporting will improve understanding of the cost-effectiveness of achieving improved water quality.
- In non-agricultural areas, planning and regulatory requirements are driving innovation in nutrient treatment. The use of planning and regulatory approaches continues to support the application of suitable nutrient management actions (both structural and non-structural) and are most effective when considered in conjunction with specific treatment controls. Biofilters appear to be the most cost-effective treatment systems in this case, but this is based on limited data and modelling studies. Improvements in technologies for wastewater management also show that systems such as membrane filtration and chemical addition are likely to perform well.

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)? What are the key factors that affect the efficacy of natural/near natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in Great Barrier Reef catchments in improving water quality and how can these be addressed at scale to maximise water quality improvement?) [4.7, 4.7.1]

Nathan Waltham, Katie Motson, Bianca Molinari

The review of the evidence for **Question 4.7** was based on 238 studies, undertaken in tropical and subtropical locations and published between 1990 and 2022. The synthesis includes a *High* diversity of study types (45% experimental, 28% observational, 14% modelling, 7% theory-based, 3% mixed and 3% reviews), and has a *Moderate* confidence rating (based on *Moderate* consistency and *Moderate* overall relevance of studies).

Summary findings relevant to policy or management action

The focus of this review was the efficacy of natural and near-natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in water quality improvement (nutrients, sediments and pesticides) in agricultural landscapes. Global evidence has revealed that wetlands can process, retain and in some cases export nutrients (dissolved and particulate) and sediments from multiple land uses, with a wide-ranging capacity for pollutant retention. However, there are few peer reviewed studies that comprehensively measure or model their efficacy for water quality improvement in the Great Barrier Reef catchment area. Wetlands are highly dynamic ecosystems, and efficacy can be variable, affected by local conditions such as soils, topography, hydrology, climate, land use and vegetation communities. Critical factors for optimising the efficacy of water quality improvement include: the presence and maintenance of vegetation communities; hydrological characteristics including the wetland size relative to the contributing catchment area, flow rate, loss pathways and water residence time; and the type and input concentration of the targeted pollutant. The establishment of long-term and values-based whole-of-system management plans are also essential and must include adequately resourced and regular monitoring on the performance, health and function of the wetlands and associated flora and fauna, and long-term maintenance plans. Global evidence shows that natural and near-natural wetlands are typically more effective at nutrient and pesticide removal than constructed or restored wetlands, and that sediment is often retained in wetlands but can be remobilised in large flow events. Therefore, ensuring the long-term protection and health of existing natural and near-natural wetlands is critical. Further evidence of the efficacy of wetlands for pollutant management in agricultural landscapes is needed to increase confidence that wetlands could be used as a water quality improvement tool for managers and landholders in the Great Barrier Reef catchment area.

Supporting points

- Research on the efficacy of wetlands in terms of water quality improvements has largely occurred in the United States (49% of total studies examined) and China (18%), with very few studies in Australia (6%, n = 15), of which 13 were from the Great Barrier Reef catchment area. The parameters assessed also vary: 72% of studies measured nutrient concentrations, 8% pesticide concentrations and 2.5% sediments; the remainder examined various combinations of these pollutants.
- While local studies have measured denitrification rates in wetland soils and plant nutrient processing rates, it is not possible to derive long-term nitrogen removal from these data or assess wetland performance without knowledge of the wetland hydrology (mainly residence time). There are no studies that measure the pesticide/herbicide removal efficacy of wetlands in the Great Barrier Reef catchment area, only studies that measure *in situ* concentrations.
- The evidence demonstrates high variability in nutrient, sediment and pesticide removal efficiency between wetland types and locations within agricultural landscapes. This is illustrated by the range of efficiencies for parameters including total suspended sediments: -4–94%; total nitrogen: -4–97%; total phosphorus: 1.8–97.6% and pesticides: 14.3–100%. These differences are strongly driven by the vegetation community (extent and maintenance; reported in 36% of studies) and hydrology (control and residence time; reported in 20% of studies). The mean efficacy and variability between wetland types is also highlighted (note that those with less than five studies have low confidence):
    - For natural wetlands: total nitrogen reduced by 63.5% (5 studies, range 27–96.4%), total phosphorus reduced by 74.5% (3 studies, range 59–97.6%), total suspended sediment reduced by -45% (2 studies, range -1–91%) and pesticide reduced by 98.5% (2 studies, range 97–100%).
    - For near natural wetlands: total nitrogen reduced by 33.5% (6 studies, range 11.6–83%), total phosphorus reduced by 54.6% (6 studies, range 6–93%) and there were no results for total suspended sediments or pesticides.
    - For restored wetlands: total nitrogen reduced by 38% (1 study), total phosphorus reduced by 52.4% (2 studies, range 25.7–59%), total suspended sediments reduced by 34.9% (2 studies, range -4–73.8%) and there were no results for pesticides.
    - For treatment wetlands: total nitrogen reduced by 46.4% (40 studies, range -4–97%), total phosphorus reduced by 49.3% (38 studies, range 1.8–96.5%), total suspended sediments reduced by 57.1% (10 studies, range 1.1–94%) and pesticide reduced by 69.2% (16 studies, range 3.6–100%).
    - For bioreactor systems: total nitrogen reduced by 80% (1 study), there were no results for total phosphorus or total suspended sediments, and pesticide removal was 47% (2 studies, range 14.3–100%).
- There is no standard approach for monitoring and evaluating the efficacy of wetlands for water quality improvement in the Great Barrier Reef catchment area. Studies have had different research questions, experimental approaches, equipment use, water quality variables of interest, and the frequency and duration of monitoring. Site-based performance reporting should be presented relative to the catchment load, providing greater context when considering whole-of-catchment water quality improvement.
- Since the 2017 Scientific Consensus Statement there has been increased research effort to quantify the efficacy of wetlands as a tool for water quality improvement. This research, in conjunction with the development of the Queensland Government's values-based framework, provides a positive foundation for understanding the values and ecological function of wetlands, and increasing confidence in pollutant removal efficiencies.
- More research is needed to decipher which wetland types are likely to be most beneficial for water quality improvement in different settings (i.e., land uses, groundwater contribution, climates, and soils), configuration of multiple systems in the landscape, the spatial and temporal drivers of variability, quantification of delivery pathways (surface and groundwater), pesticide removal efficiencies (particularly those found to impact Great Barrier Reef ecosystems), improved characterisation of nutrient processing, long-term changes in wetland nutrient and sediment stores, and evidence of the timescales over which management interventions are likely to be effective.

What are the measured costs, and cost drivers associated with the use of natural/ near natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in Great Barrier Reef catchments in improving water quality? [4.8]

Megan Star, Syezlin Hasan, James C. R. Smart, Carla Wegscheidl

The synthesis of the evidence for **Question 4.8** was based on 56 studies undertaken mostly internationally (only 9 were from Australia) and published between 1990 and 2022. The synthesis includes a *High* diversity of study types (41% modelling, 39% reviews and 20% observational), and has a *Moderate* confidence rating (based on *High* consistency and *Moderate* overall relevance of studies).

Summary of findings relevant to policy or management action

A limited number of studies have fully assessed the cost-effectiveness of wetland systems (including natural/near natural wetlands, restored, treatment/constructed wetlands and other treatment systems) in the removal of pollutants in the Great Barrier Reef catchment area. Within the available studies, measured costs have been reported for treatment systems using best practice approaches. These measured costs include upfront costs, ongoing costs and in some instances the opportunity costs, reported over a specified time using standard discount rates[19]. There is limited understanding of the variation of costs across different types of wetland treatment systems in the Great Barrier Reef. International studies contained relevant information, but transfer of the findings to the Great Barrier Reef can be challenging because of differing climatic and policy contexts. Overall, it was identified that cost-effective nitrogen reductions can occur when a wetland treatment system is designed at a landscape scale (i.e., subcatchment or catchment) taking into account broader landscape processes including hydrology and topography and the links between them. Many studies showed that the strongest driver of cost-effectiveness for wetland projects was the effectiveness of nitrogen removal based on initial placement in the landscape, landscape characteristics such as nutrient inputs, vegetation, rainfall, hydrology and topography, comprehensive planning and design, and ongoing maintenance of the project. International studies highlighted that long term investments were most successful when there was a clear definition of investor's objectives and outcomes, which were reflected in policy and program design, and subsequent projects.

Supporting points

- Currently, there are no long-term monitored assessments of the cost-effectiveness of nutrient removal from wetlands in the Great Barrier Reef region that are based on complete sets of measurements of both costs and nutrient removals, hindering comparison to other management actions. Measured costs for eight constructed wetlands completed in Great Barrier Reef catchments varied considerably ranging from an annualised present value cost of $3,075 to $31,588 per hectare per year (in FY 2020/21 AUD) over a 25-year period.
- Measured costs and cost drivers for wetland projects designed for pollutant removal can be categorised into studies that assess costs, focus on optimisation and prioritisation or discuss implications for policy and program design.
- The actual costs of projects for different wetland types are driven by several factors including size, construction, opportunity costs, monitoring requirements and maintenance.
- Public and private investors have different objectives and expectations for investment outcomes. This will influence the minimum level of return on investment required for a wetland project designed for pollutant removal to be viable. Furthermore, different investors may seek different outcomes from wetland design and project implementation (e.g., different suites of co-benefits) which could influence the wetland attributes to be incorporated, impacting on project cost.
- Cost drivers of the cost-effectiveness of projects are typically biophysical or associated with policy setting and adoption:
    - Biophysical cost drivers include consideration of whole-of-system landscape processes (such

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[19] Discounting brings costs in future years back into current dollar terms. Discount rate is the rate at which this occurs and is typically 5-7%.

  as hydrology, receiving water quality, and topography of the landscape at a paddock and overall catchment scale), the current land use, the quantity of nutrient inputs in relation to wetland size, residence time, pollutant type and whether or not there are opportunities for co-benefits.
  - Policy setting and adoption cost drivers include specific requirements under incentive programs such as inclusion of certain locations, period of management, maintenance and/or monitoring requirements, complexity of application processes, and opportunities for secondary benefits.
- Measured costs of wetland projects need to be captured over a consistent timeframe and discount rate to evaluate the effectiveness of programs. This includes costs during the pre-construction phase (e.g., conceptualisation, design, planning, landholder engagements, approvals), construction phase (e.g., earthworks, planting), and post-construction phase (e.g., monitoring, maintenance, repair).
- Long-term opportunity costs and ongoing maintenance costs must be considered in assessing the cost effectiveness of wetland projects. These are also important considerations in defining the length of funding programs and monitoring requirements, potentially (and most likely) extending beyond the life of the initial funding program.
- Opportunities to deliver co-benefits such as biodiversity outcomes from wetland restoration projects are well documented, particularly in large landscape-scale wetlands. The details of the co-benefits being sought must be included from the initial project design as well as the policy and program design. These may also require different monitoring and reporting, and potentially be influenced by different cost drivers that must be considered.
- Long-term international projects (in Denmark and Sweden) have demonstrated that average costs of nitrogen abatement for individual wetland projects typically increase (after correcting for inflation) as the number of willing landholders declines, and the locations where wetland treatment is likely to be most effective are already utilised. Furthermore, if implementation is undertaken at landscape scale (i.e., where a number of landholders are required to be involved to achieve the best outcomes), the transaction costs incurred in obtaining landholder participation will increase further.
- Internationally, management approaches undertaken in the edge of headlands or vegetated drains and buffer strips have been implemented as best management practices. However, such practices can also generate unintended negative impacts for landholders such as introduction of invasive species (e.g., pigs) or difficulty in headland management (e.g., less available space and increased water retention on headlands leading to getting bogged). Studies from Canada, the United States, Denmark and Sweden also indicate that burdensome management requirements (e.g., monitoring and reporting, labour intensive tasks such as hand pulling weeds) can deter farmers from signing up to wetland incentive programs.

What role do natural/ near natural wetlands play in the provision of ecosystem services and how is the service of water quality treatment compatible or at odds with other services (e.g., habitat, carbon sequestration)? [4.9]

Nathan Waltham, Catherine Lovelock, Maria Fernanda Adame, Katie Motson

The synthesis of the evidence for **Question 4.9** was based on 125 studies, primarily undertaken outside of the Great Barrier Reef, and published between 1990 and 2022. The synthesis includes a *High* diversity of study types (31% observational, 18% modelled, 18% reviews, 16% theoretical, 12% experimental and 5% mixed), and has a *Moderate* confidence rating (based on *High* consistency and *Moderate* overall relevance of studies).

Summary of findings relevant to policy or management action

Natural and near-natural wetlands in the Great Barrier Reef catchment area include lacustrine (e.g., lakes), palustrine (e.g., vegetated swamps, billabongs), estuarine, and riverine wetlands. These wetlands support many ecosystem services including regulating services such as improved water quality and carbon sequestration, supporting services such as nutrient cycling and habitat provision, cultural services such as aesthetics and recreation, and provisioning services including food, water and other resources. However, these services are under threat in response to expansion of coastal agriculture development, as well as urban and industrial expansion. In tropical/subtropical wetlands, stressors that compromise wetland water quality can impact the ecosystem services wetlands provide. For instance, connectivity and hydrology have an important role in protecting water quality and other wetland ecosystem services; disruption to connectivity or hydrology can change water chemistry with flow on effects to aquatic organisms (e.g., fish kills). In Great Barrier Reef coastal and floodplain areas where historical wetland losses are high, the capacity of the remaining wetlands to process the volume of pollutants they receive is likely to be reduced. Therefore, restoration efforts and engineering interventions may be required to increase the water quality improvement efficiency, and the associated delivery of associated ecosystem services, for the wetlands remaining within the Great Barrier Reef catchment area. While wetlands can be restored to enhance water quality conditions, the maintenance following restoration works or intervention activities is critical. Without a long-term maintenance plan and a mechanism to fund these works, restoration sites have a high chance of returning to a degraded state. Wetland risk mitigation presents the greatest opportunity to enhance and protect the range of wetland ecosystem services provided within the Great Barrier Reef catchment. Although there is considerable research and management interest, greater commitment is needed to fund monitoring and evaluation of restoration works, as well as for maintenance. There is also a need for policies and planning to achieve long-term protection and conservation of the remaining natural and near-natural wetlands in the Great Barrier Reef catchment area.

Supporting points

- This synthesis identified a small number of research studies in the Great Barrier Reef catchment area compared to studies on natural and near-natural wetlands from overseas, with most studies from the United States (35%), China (11%), South America (11%), and Australia (10%). Most studies have focused on estuarine settings (32%), 22% on riverine systems, 12% on palustrine/lacustrine, 17% investigated a combination of habitats, whilst 17% were from unidentified settings.
- Since 2016, studies investigating the ecosystem services provided by natural, near-natural, and restored wetlands in the Great Barrier Reef catchment area have included assessment of water treatment efficacy and nutrient processing, fish biodiversity and water quality in restored wetlands, in addition to carbon storage potential and avoided greenhouse emissions. Water quality in wetlands underpins many co-benefits, such as biodiversity and the ecosystem services that result from diverse populations of flora and fauna (e.g., fish, plankton, and macroinvertebrates), including increased food and habitat for birds, and greater potential for recreation such as bird watching, wetland aesthetics and fishing.
- Mangroves, saltmarshes, and other floodplain native vegetation communities provide coastal protection, sequester carbon, and process nutrients that help to improve water quality. However, a limited number of studies have indicated that natural and near-natural wetlands have a wide-ranging capacity for both pollutant export and retention. While the international literature shows that the ecosystem services provided by wetlands are considerable, more research is needed to quantify these ecosystem services (e.g., environmental, economic, and social value) within the Great Barrier Reef catchment area.
- Trade-offs between water quality improvement and other services in natural and near-natural wetlands can include instances where hydrology or connectivity are affected. For example, seasonal wetland flooding has been found to result in greater connectivity among wetlands, micro-habitat creation, enhanced nutrient dynamics and carbon storage, flood protection, freshwater provision, and improved local water quality, but may lead to less favourable conditions for agricultural production.
- The Queensland Government has developed a values-based framework for the restoration, rehabilitation, and protection of coastal wetlands. This framework focuses on the components and processes in wetlands that maximise restoration success and ecosystem services for beneficiaries (user groups such as tourism, fishing, recreational and cultural). A whole-of-system approach is required so that the interconnected components and processes of the wetland systems, and landscape more broadly, are examined and understood, and management approaches are aligned with restoration goals.
- Ongoing monitoring and evaluation of restored, natural, and near-natural wetlands in the Great Barrier Reef catchment area is required to better understand the potential impacts of restoration actions on wetland values, water quality, and other ecosystem services. The Queensland Government is currently developing frameworks designed to provide managers with a tool to consistently examine and evaluate restoration projects in Queensland.
- Inclusion of all beneficiaries in a co-design process early in the project cycle (design, implementation, and maintenance) is important for defining and achieving ecosystem service goals. The potential implications of future climate change projections, such as sea level rise and more severe weather events (e.g., cyclones), for wetland treatment and restoration projects must also be considered.

Tractor spraying pesticides
Photo: Rob Milla

Themes 5 and 6: Pesticides and Other Pollutants - Catchment to Reef

Themes 5 and 6: Pesticides and Other Pollutants - Catchment to Reef

Context

Pesticides are used to protect crops and vegetated areas from pest organisms (e.g., weeds, insects and fungal disease). Pesticides have been detected in sediments and waters of rivers, creeks, wetlands, estuaries, and the inshore parts of the Great Barrier Reef. The types and concentrations of pesticides in fresh, estuarine and marine ecosystems vary between catchments and regions, reflecting the main land uses in each area. Pesticides have been reported to affect a range of marine organisms including corals, microalgae, crustose coralline algae and seagrass, with increasing evidence of their impacts on freshwater, wetland and estuarine ecosystems. The Reef 2050 Water Quality Improvement Plan pesticide target is to protect at least 99% of aquatic species at end-of-catchments by 2025. Other pollutants that may affect the Great Barrier Reef and are covered in the 2022 Scientific Consensus Statement include metals, plastics, persistent organic pollutants, per- and poly-fluoroalkyl substances, personal health care products, coal, and sunscreens.

The synthesis of the evidence for **Theme 5** included a total of **591** studies extracted and synthesised for **3** questions (Figure 9). This Theme reviews the evidence of the causal relationships between the risk, impacts and management of pesticides influencing the Great Barrier Reef. It starts by assessing the spatial and temporal distributions of pesticides within the Great Barrier Reef, their potential effects on local species and ecological risks to the freshwater and marine ecosystems (Q5.1), followed by the delivery processes and sources of pesticides found in Great Barrier Reef ecosystems (Q5.2). Synthesis of the most effective management practices for reducing pesticide risk in Great Barrier Reef ecosystems provides insights for

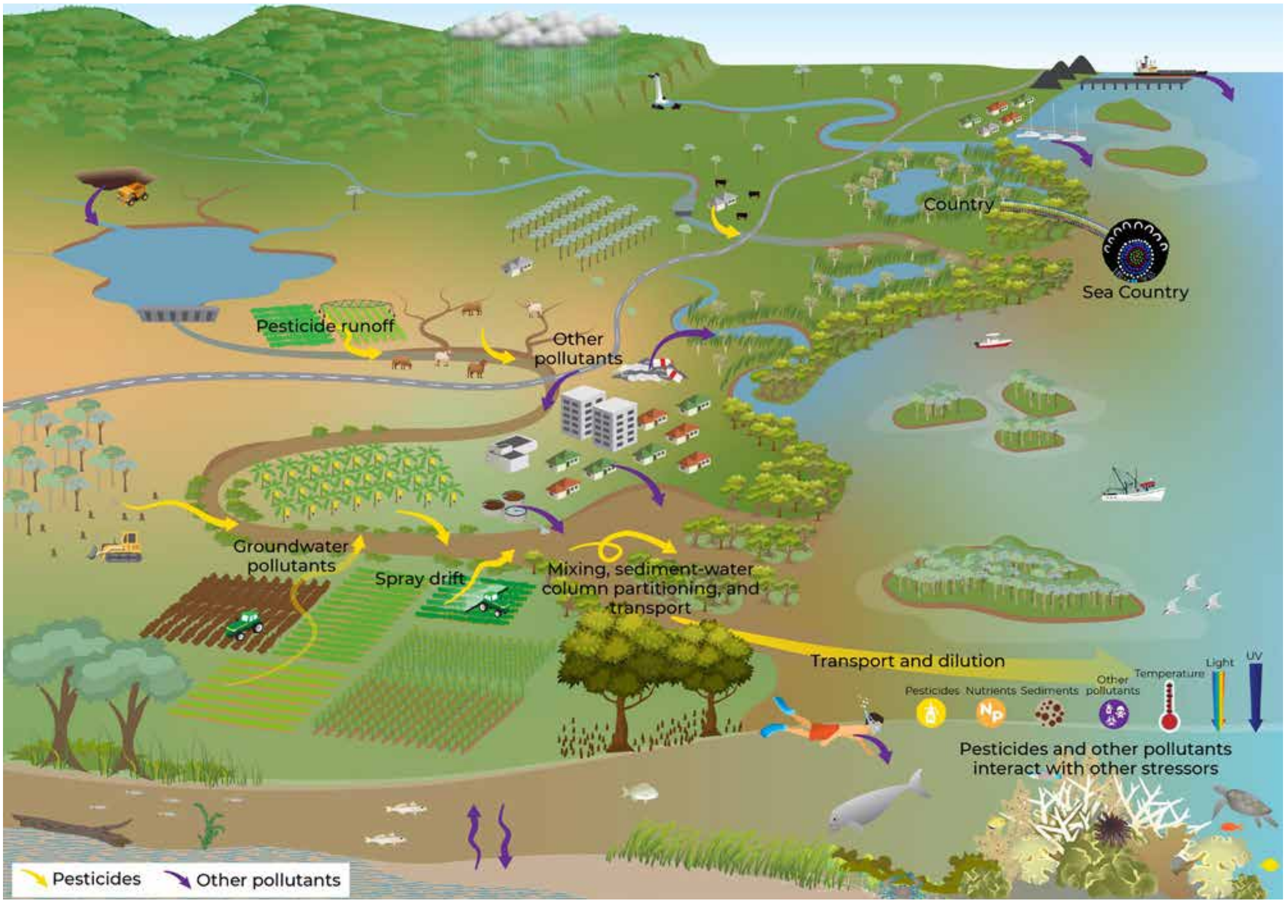

Figure 9. This diagram is a pictorial representation of the scope of Themes 5 & 6. It represents the Great Barrier Reef catchment and marine environment and shows the ecological impacts of pesticides and other pollutants on aquatic ecosystems and biota including the influence of flood plumes which mostly affect inshore and midshelf areas. The primary sources are shown, of which agriculture is the main contributor for pesticides, with industry, urban and other uses among the key sources for other pollutants. Transport pathways are also shown, including surface and subsurface runoff and groundwater movement. Examples of potential management practices to minimise pesticide risk are also synthesised.

policy and management (Q5.3). **Theme 6** included **92** studies extracted and synthesised for **1** question that covers the spatial and temporal distribution, risk, and primary sources of other pollutants in Great Barrier Reef ecosystems (Q6.1).

Summary Statement for Themes 5 and 6

Convergence was reached for this Summary Statement among all authors within the Expert Group for Themes 5 and 6 (listed in **Appendix 1**).

The synthesis of the evidence for **Theme 5** included a total of **591** studies extracted and synthesised for **3** questions (with some overlap in evidence between questions). For **Theme 6**, it included **92** studies extracted and synthesised for **1** question.

The **summary of findings** relevant to policy or management action for **Themes 5 and 6** are:

- **Pesticides** are ubiquitous across monitored Great Barrier Reef ecosystems including end-of-catchment waterways, palustrine wetlands (e.g., vegetated swamps) and in estuarine and nearshore marine habitats. Their presence in the offshore marine environment is largely unknown. Concentrations of pesticides (invariably as mixtures) are greatest in wetlands, followed by end-of-catchment then marine locations, with concentrations decreasing with greater distance from the site of application. Exposure of marine ecosystems to pesticides is closely linked to flood plume dispersal. Modelling suggests that pesticide exposure is highly dynamic, changing by orders of magnitude within hours. [Q5.1]
- Sites in the Mackay Whitsunday region, along with Barratta Creek in the Burdekin region, that feature intense cropping and lower discharge (related to rainfall), consistently record higher concentrations of pesticides and higher risk than other locations. [Q5.1]
- Annual trends in pesticide concentrations are difficult to identify over the short term; however, a long-term analysis indicated that photosystem II herbicide concentrations increased in some inshore sites of the Great Barrier Reef. [Q5.1]
- Pesticides are designed to control agricultural pest species and virtually all tested pesticides are potentially harmful to non-target aquatic species of the Great Barrier Reef region. For example, photosystem II herbicides consistently impact all photosynthetic marine organisms of the Great Barrier Reef that have been tested, including corals and seagrasses. Other simultaneous pressures, including heatwave conditions and variation in light were shown to increase the sensitivity of Great Barrier Reef species to pesticides, indicating that guideline values applied under some conditions in the field are likely to underestimate the risk to aquatic ecosystems. [Q5.1]
- Monitored pesticides that contribute most to risk in all Great Barrier Reef ecosystems examined include atrazine, diuron, imidacloprid and metolachlor. Photosystem II herbicides dominate the contribution to risk in many waterways; however, non-photosystem II pesticides make substantial contributions to risk at specific locations, and their influence appears to be increasing since 2016. [Q5.1, Q5.2]
- Sugarcane areas are the largest contributor to end-of-catchment pesticide concentrations, and are dominated by photosystem II herbicides. While pesticides are used over large areas of grazing lands, the relative ecological toxicity to aquatic organisms of the dominant pesticide, tebuthiuron, is low compared to other photosystem II herbicides. Other land uses including forestry, horticulture, banana growing, and urban areas can be large users of some pesticides, but their total area within the Great Barrier Reef catchment area is relatively low. Nonetheless, they can contribute to pesticide concentrations. Catchments with minimal agricultural activity, such as the Ross and Kolan basins, have the lowest photosystem II herbicide contributions. Imidacloprid is the most commonly detected insecticide in the Great Barrier Reef catchment area and is associated with banana, sugarcane and urban activities. [Q5.2]
- The key factors that influence export of pesticides to the Great Barrier Reef are pesticide application rates, the timing between pesticide application and rainfall (longer timeframes between application and significant rainfall/irrigation are associated with lower pesticide exports), irrigation regimes, and pesticide properties such as persistence. Other factors that can influence delivery of pesticides to the Great Barrier Reef include soil characteristics, pesticide formulations (more soluble pesticides are more vulnerable to dispersal), climatic conditions and particularly extreme weather events, and catchment characteristics. [Q5.2]
- Most pesticide exported to the Great Barrier Reef is via surface runoff. Pesticide export via groundwater may be a contributor in some

basins, although this has only been measured in the Wet Tropics region and Lower Burdekin floodplain. [Q5.2]

- The most effective management practices for reducing pesticide risk from the Great Barrier Reef catchment area vary between land uses. Practices that demonstrably reduce pesticide risk from agricultural land uses include reducing the total amount of pesticide applied through lower application rates (within label recommendations), improving application methods, timing of application in relation to weather risk periods, switching to pesticide products with lower environmental risk and reducing soil erosion through retaining cover, controlled traffic, and improved irrigation management for pesticides with greater soil sorption. These findings have remained relatively consistent through time, and across climatic regimes and farming systems of the Great Barrier Reef catchments. A range of non-chemical pesticide control measures (integrated pest management, cultural controls that modify the pest's growing environment) hold considerable potential for reducing reliance on chemical control measures, but most are yet to be trialled in the Great Barrier Reef catchment area with respect to long-term pesticide use reductions, efficacy and economic outcomes. [Q5.3]
- In the assessment of cost-effectiveness of pesticide management in agricultural industries, economic returns remain variable. However, for sugarcane, progressing from traditional to industry standard herbicide management is generally profitable across sugarcane districts. The adoption of management practices can be driven by a range of factors including costs and is discussed in detail in Theme 7. [Q5.3]
- For non-agricultural lands, pesticide management options largely rely on non-structural controls such as regulations, and improved wastewater treatment processes (e.g., membrane bioreactors, reverse osmosis). The emergence of significant pesticide resistance across multiple industries has started to cause considerable changes in pesticide use and other alternative pest control measures. [Q5.3]
- **Other pollutants** detected in the waters, sediments and biota of the Great Barrier Reef include metals, persistent organic pollutants, per- and poly-fluoroalkyl substances, plastics, pharmaceutical, veterinary, and personal health care products, coal and fly ash and sunscreens. Assessment of spatial patterns, temporal trends and ecological risks for ecosystems and individual biota is severely limited by data availability. There are very few routine monitoring programs for these pollutant groups, with the exception of some monitoring within the Regional Report Cards (e.g., Gladstone, Dry Tropics and Mackay Whitsunday) for which the raw data are not publicly available. [Q6.1]
- Metal concentrations in water and sediments are higher in more industrial and developed coastal environments compared to less developed catchments and offshore areas. Concentrations of metals in water above national water quality guideline values are rarely documented, but have been recorded in some studies including copper (associated with legacy mining in the Fitzroy basin), mercury (associated with sugarcane in the Tully catchment) and aluminium (from acid sulfate soils in Trinity Bay, Cairns). Biota found inshore (e.g., seagrass, algae, turtles, corals) have higher concentrations of metals in their tissues than those found offshore. Although ecotoxicological studies indicate that the ecological risks from metals in the Great Barrier Reef are relatively low and constrained to a few small locations, the combined risks from mixtures have not been assessed. [Q6.1]
- Persistent organic pollutants are associated with industry, oil spills, coal, and urbanisation. They are detectable in Great Barrier Reef sediments (generally below guideline values, with exceptions such as following oil spills) and biota, and from the limited data available, decrease across an inshore to offshore gradient. Persistent organic pollutants can affect fish physiology and behaviour, coral reproduction and trophic food webs. [Q6.1]
- Plastics, including microplastics and fibres, are extensively distributed in coastal and marine environments. Coastal sites are influenced by surrounding land use, river and stormwater inputs, while offshore sites are mostly influenced by recreational activities, tourism, commercial shipping and fishing. Plastics have been recorded in zooplankton, crustaceans, fishes, birds and turtles from the Great Barrier Reef, with ecological risks varying across species, feeding behaviour and life stages. [Q6.1]
- A more cohesive and coordinated approach to examine the interaction of multiple pollutants and stressors, including climate change, is required. Ecotoxicological studies that employ multiple lines of evidence are urgently required for all pollutant groups identified in the Great Barrier Reef to understand the risks that these pollutants pose to Great Barrier Reef biota and ecosystems. [Q6.1]

The **confidence** rating of the questions within **Themes 5 and 6** was Moderate to High for the pesticide questions, and Limited to Moderate for the 'Other pollutants' question, due to the limited evidence available for most of the other pollutant groups.

The findings in these Themes are underpinned by a growing body of evidence (although larger for pesticides than for other pollutants), including multiple lines of evidence (i.e., monitoring, modelling, observations, remote sensing, experimental, and secondary studies). The **strength of evidence** across these Themes considering the confidence, quantity and diversity of study types, is High for pesticides, and Low for other pollutants, with limited evidence for per- and poly-fluoroalkyl substances, pharmaceutical, veterinary, and personal health care products, coal and fly ash, and sunscreens.

The **key uncertainties** of the evidence identified for Themes 5 and 6 relevant to policy and management included the spatial distribution of pesticides in some ecosystems of the Great Barrier Reef, such as some freshwater and inshore marine ecosystems and most wetland, estuarine and offshore ecosystems; limited temporal pesticide data overall, which restricts the capacity to determine if changes to pesticide management are improving water quality outcomes; limited understanding of the toxicity of many alternative pesticides detected in Great Barrier Reef waterways; the proportion of pesticides contributed by groundwater in different catchments of the Great Barrier Reef; standardised assessment methods for cost-effectiveness of improved pesticide management across different agricultural land uses; the effectiveness of stormwater treatment measures such as wetlands; and distribution, sources and ecological risks of some of the 'other pollutant' groups including many metals, persistent organic pollutants, per- and poly-fluoroalkyl substances, pharmaceutical, veterinary, and personal health care products, coal and fly ash, and sunscreens.

Recent findings continue to identify the spatial and temporal distribution of pesticides on Great Barrier Reef ecosystems, including a prominent modelling exercise that simulated the distribution of the photosystem II herbicide diuron in the Great Barrier Reef. In terms of impacts, additional field and laboratory research has focused on the toxicity of pesticides to Great Barrier Reef species, including the combined effects of pesticide mixtures, as well as other simultaneous pressures such as heatwave conditions. Recent studies have strengthened previous evidence of the link between photosystem II herbicides and agricultural activities, particularly sugarcane, and highlighted the relationship between timing of pesticide application and timing of localised rainfall (first flush) with runoff risk. Emerging findings also include greater recognition of pesticide risk in management frameworks, allowing management practices to be better targeted to manage specific risks, renewed focus on Integrated Pest Management concepts and increasing acknowledgement of variable water quality benefits from tillage-crop residue retention practices. Several 'alternative' pre-emergent herbicides (metribuzin, metolachlor, etc.) have been recently identified that present similar ecosystem risk profiles to at least some of the priority photosystem II herbicides such as atrazine. In relation to 'other pollutants', recent research included an extensive per- and poly-fluoroalkyl substances sampling program, studies on the distribution of plastics and their effects on selected biota, experimental research on the effects of coal on corals, and some advances in ecotoxicological tools for assessing the effects of pollutants on turtles.

Within **Themes 5 and 6**, the areas where further **knowledge is needed** that are most relevant to policy and management include: i) experimental studies on the effects of pesticides mixtures and in combination with other co-stressors on Great Barrier Reef species and the implications for water quality guidelines; ii) further model developments to improve the ability to estimate pesticide risk, such as expanding the model to include all pesticides identified in the Great Barrier Reef, and additional *in situ* field validation using observations of pesticide concentrations from the Great Barrier Reef Catchment Loads Monitoring Program and the Marine Monitoring Program; iii) time lags and pesticide migration in groundwater; iv) the contribution of particle bound pesticides to off-site migration, and the drivers of transport to better characterise ecological risk to receiving ecosystems; v) the properties, persistence, delivery pathways and ecological toxicity of the newer emerging alternative pesticides such as imazapic and fluroxypyr; vi) the efficacy and economic outcomes of non-chemical pesticide control measures; vii) additional data to assess the management effectiveness of many insecticides and fungicides in farming systems, including usage patterns, current presence in the environment, half-lives, sorption, runoff potential and ecotoxicology; viii) assessment of the chemical risk of wastewater re-use where tertiary treatment is not occurring; ix) fundamental exposure data and establishment of water and sediment guideline values for pesticides and their degradation products and for most of the 'other pollutant' groups including coal, per- and poly-fluoroalkyl substances, pharmaceutical, veterinary, and personal health care products and sunscreens; x) establishment of sediment guideline values for some metals (e.g., manganese, aluminium, arsenic), and refinement of water quality guideline values to include tropical species; and xi) the interactions of multiple pollutants and stressors, including climate change.

Summary information for Questions in Themes 5 and 6

The Table below summarises the evidence appraisal indicators and confidence ratings in the evidence base for each of the Questions within these Themes. The Confidence rating was determined by the overall relevance of studies to the question and the consistency of the body of evidence (refer also to Appendix 3: Glossary for explanation of indicators). *Note: In Diversity of items: Experimental (E), Mixed (X), Modelling or Remote sensing (M), Observational (O), Reviews (R), Theoretical or Conceptual (T).*

Question	**Quantity of items**	**Diversity of items**	**Overall relevance**	**Consistency**	**Confidence**
What is the spatial and temporal distribution of pesticides across Great Barrier Reef ecosystems, what are the (potential or observed) ecological impacts in these ecosystems and what evidence is there for pesticide risk? [5.1]	High (231)	High *(45% E, 29% O, 18% X, 8% R)*	High	High	High
What are the primary sources of the pesticides that have been found in Great Barrier Reef ecosystems and what are the key factors that influence pesticide delivery from source to ecosystems? [5.2]	High (109)	High *(31% O, 29% E, 23% R, 17% M-X)*	High	Moderate – High	Moderate - High
What are the most effective management practices for reducing pesticide risk (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? [5.3]	High (251)	High *(36% E, 32% O-R, 32% X)*	Moderate	Moderate	Moderate
What is the spatial and temporal distribution and risk of other pollutants in Great Barrier Reef ecosystems, and what are the primary sources? [6.1]	Low – Moderate (92) (44 metals; 19 POPs; 1 PFAS; 19 plastics; 4 PVPs; 5 Coal)	Low – High *(depending on pollutant)* *(77% O, 23% E)*	Low – High (depending on pollutant)	Low – High (depending on pollutant)	Limited - Moderate (Moderate for Metals, POPs and Plastics; Limited for PFAS, PVPs, Coal and Sunscreen)

Evidence Statements for Questions in Themes 5 and 6

What is the spatial and temporal distribution of pesticides across Great Barrier Reef ecosystems, what are the (potential or observed) ecological impacts in these ecosystems and what evidence is there for pesticide risk? [5.1]

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The synthesis of the evidence for **Question 5.1** was based on 231 studies, undertaken primarily in the Great Barrier Reef and published between 1990 and 2022. The synthesis includes a *High* diversity of study types (45% experimental, 29% observational, 18% mixed studies, and 8% secondary) and has a *High* confidence rating (based on *High* consistency and *High* overall relevance of studies).

Summary of findings relevant to policy or management action

Pesticides are ubiquitous across monitored Great Barrier Reef ecosystems including end-of-catchment waterways, palustrine wetlands (e.g., vegetated swamps) and in estuarine and nearshore marine habitats. Concentrations of pesticides are greatest in wetlands, followed by end-of-catchment then marine locations, with concentrations decreasing with greater distance from river mouths. The majority of pesticides in all Great Barrier Reef habitats occur as mixtures. Exposure of marine ecosystems to pesticides is closely linked to flood plume dispersal and is highly dynamic, changing by orders of magnitude within hours. Based on the available, but limited, published data, there is more evidence that pesticide concentrations are increasing rather than decreasing in Great Barrier Reef marine ecosystems. Pesticides are designed to control agricultural pest species and virtually all tested pesticides are reported as harmful to non-target aquatic species of the Great Barrier Reef. For example, photosystem II (PSII) herbicides consistently impact all photosynthetic marine organisms of the Great Barrier Reef that have been tested, including corals and seagrass. Other simultaneous pressures, including heatwave conditions and variation in light were shown to increase the sensitivity of Great Barrier Reef species to pesticides, indicating that guideline values applied under some conditions in the field are likely to underestimate the risk to aquatic ecosystems. The guideline values in the Pesticide Risk Metric were used to assess the simultaneous exposure risks of 22 pesticides on aquatic species in the Great Barrier Reef. Sites in the Mackay Whitsunday region, along with Barratta Creek in the Burdekin region which featured intense cropping and lower discharge (related to rainfall), recorded consistently higher concentrations of pesticides and higher risk than other locations. Pesticides that contribute most to risk in all Great Barrier Reef ecosystems monitored include atrazine, diuron, imidacloprid and metolachlor, but their contribution varies with site. Risk to aquatic ecosystems reduces with distance from the source of pesticides.

Supporting points

- Extensive monitoring programs in the Paddock to Reef program (primarily the Great Barrier Reef Catchment Loads Monitoring Program and the Marine Monitoring Program) have consistently identified pesticides in >99% of water samples. Since 2016/17: 1) over 70 pesticides and their transformation products have been identified in Great Barrier Reef waters; 2) most pesticides were detected as mixtures (>70% of samples); 3) the most frequently quantified pesticides across all Great Barrier Reef habitats were atrazine, diuron, hexazinone, imazapic, imidacloprid and metolachlor.
- Pesticide concentrations were typically higher in fresh and marine waters during wet seasons compared to dry seasons, with rapid increases at the start of the wet season followed by a gradual decrease.
- The concentration of imidacloprid at some freshwater sites and PSII herbicides at some marine sites has increased.
- The effects of PSII herbicides on photosynthetic efficiency have been measured in Great Barrier Reef species including seagrass, coral, coral symbionts, algae and jellyfish and include reduced growth and mortality (if assessed). Laboratory tests indicate that contemporary insecticides negatively affect fish and marine invertebrates including corals, barnacles, crabs, shrimp and prawns. Non-PSII herbicides and fungicides have also been shown to negatively affect Great Barrier Reef species, but more research is needed to improve water quality guideline values for these pesticides.
- An extensive review of toxicity studies with species relevant to the Great Barrier Reef found that the Pesticide Risk Metric Guideline Values are suitable to assess the risk of pesticides and pesticide

mixtures.

- In line with international evidence, several experimental studies on species found in the Great Barrier Reef have shown that mixtures of herbicides generally conform with the concentration addition model of joint action. Additional studies focused on Great Barrier Reef species would strengthen current evidence that low concentrations of individual pesticides with different modes of action contribute to the overall effect of the mixture.
- All *in situ* biological studies to date have found strong correlations between adverse biological effects and concentrations of individual pesticides, sometimes with pesticide mixtures. However, the adverse effects might also be correlated with other co-stressors in the field, so it has not yet been possible to determine causation.
- A simulation exercise using the eReefs marine model indicated that diuron is typically transported by coastal plumes in a northward direction from river mouths. Rapid changes in diuron concentrations (within hours) highlighted the dynamic exposure of marine waters and that the Pesticide Risk Metric PC99 Guideline Value for this herbicide was often exceeded across 1,000 km^2 (peaking at 1,400 km^2) of inshore areas in simulations from 2016 to 2018 (including 175 km^2 of seagrass and 20 km^2 of coral habitat). Further model developments are required to improve the ability to estimate patterns of pesticide risk, such as expanding the model to include all pesticides identified in the Great Barrier Reef, and additional *in situ* field validation using observations of pesticide concentrations from the Marine Monitoring Program.

What are the primary sources of the pesticides that have been found in Great Barrier Reef ecosystems and what are the key factors that influence pesticide delivery from source to ecosystems? [5.2]

Michelle Templeman, Sarah McDonald

The synthesis of the evidence for **Question 5.2** was based on 109 studies undertaken mostly in the Great Barrier Reef catchment area and published between 1990 and 2023. The synthesis includes a *High* diversity of study types (31% observational, 29% experimental, 23% reviews and 17% other including modelling), and has a *Moderate to High* confidence rating (based on *Moderate to High* consistency and *High* overall relevance of studies).

Summary of findings relevant to policy or management

Pesticides, including herbicides, insecticides and fungicides, continue to be detected in most basins in the Great Barrier Reef catchment area. Sugarcane areas are the largest contributor to end-of-catchment pesticide concentrations, dominated by photosystem II inhibiting herbicides (PSII herbicides). While pesticides are used over large areas of grazing lands, the relative ecological toxicity of the dominant pesticide, tebuthiuron, is low compared to other PSII herbicides. Other land uses including, horticulture, banana growing and urban areas can be large users of some pesticides, but their total area within the Great Barrier Reef catchment area is relatively small. Herbicides, specifically PSII herbicides, are the most common and abundant pesticide type measured in end-of-catchment monitoring followed by other herbicide types and insecticides. Catchments with minimal agricultural activity, such as the Ross and Kolan basins, have the lowest PSII herbicide contributions. Imidacloprid is the most commonly detected insecticide in the Great Barrier Reef catchment area and is associated with banana, sugarcane and urban activities. The key factors that influence export of pesticides to the Great Barrier Reef are pesticide application rates, the timing between pesticide application and rainfall, irrigation regimes, and pesticide properties such as persistence. Other factors that can influence delivery of pesticides to the Great Barrier Reef include soil characteristics, pesticide formulations, climatic conditions and particularly extreme weather events, and catchment characteristics.

Supporting points

- Overall, there is no substantive evidence to indicate that the main land use contributions to pesticide concentrations in the Great Barrier Reef catchment area have significantly changed since the 2017 Scientific Consensus Statement.
- The 2009 to 2016 Great Barrier Reef Catchment Loads Monitoring Program focused on end-of-catchment loads with a target of 50% reduction in five key PSII herbicides (ametryn, atrazine, diuron, hexazinone and

tebuthiuron) by 2025. In 2017, the assessment methodology shifted to a risk-based profile, assessing concentrations of 22 pesticides (including non-PSII and PSII herbicides and three insecticides) at end-of-catchment locations to estimate ecological risk in a Pesticide Risk Metric.

- Across all monitored basins between 2016 and 2020, the relative contribution of PSII herbicides to the overall pesticide risk increased from 47% to 57%, other herbicides increased from 32% to 35%, while insecticides decreased from 17% to 7%. These findings do not necessarily indicate a reduction in the use of insecticides, but their relative contribution to the overall pesticide risk is lower.
- Application rate and time between application and rainfall continue to be the biggest drivers of pesticide export from sugarcane. A range of studies have identified that the critical time period for pesticide runoff is 1-25 days after application. The longer the timeframe from application to runoff rainfall, the lower the relative amount of pesticide exported.
- The first rainfall event of the wet season (typically described as the 'first flush' event) often delivers the greatest proportion of pesticides to the Great Barrier Reef. The proportion delivered is enhanced where short timeframes between application and rainfall occur. Pesticide contributions typically reduce with subsequent rainfall events. Similarly for irrigated areas, the greatest losses tend to be associated with the first irrigation event.
- Pesticide export profiles from irrigated sugarcane are similar to rainfall events, but irrigation can lead to higher ecological risk in receiving systems due to extended periods of exposure and limited flushing or dilution.
- The addition of adjuvants (substances or compounds added to pesticide formulations to improve their activity) is designed to reduce pesticide mobility offsite. However, some studies have shown these responses can be variable across soil types and climatic zones, leading to inconsistent effects on mobility.
- Variations in pesticide chemistry, use of alternative pesticides and associated adjuvants can influence export of pesticides off-site. Typically, pesticides with more polar chemistries (water-soluble) such as hexazinone and 2,4-D have lower sorption rates and are more vulnerable to dispersal, particularly under rainfall or irrigation events.
- Although most pesticide export to the Great Barrier Reef is via surface runoff, pesticide export via groundwater may be a contributor in some basins. While export via groundwater has been measured in a few studies in the Wet Tropics region and Lower Burdekin floodplain, the overall proportion of groundwater pesticide contributions is unknown. Groundwater contributions can also have significant lag effects from the timing of application, with pesticide export potentially continuing for years after application, leading to uncertainties in the understanding of pesticide migration.
- Pesticide concentrations in the Great Barrier Reef catchment area are typically reported as a dissolved concentration incorporating both the dissolved and particulate phases. Better understanding of the contribution of particle bound pesticides to off-site migration, and the drivers of transport, is important for characterising ecological risk to receiving ecosystems.
- There are fewer studies assessing the properties, persistence, delivery pathways and ecological toxicity of the newer emerging alternative pesticides such as imazapic and fluroxypyr.

What are the most effective management practices for reducing pesticide risk (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? [5.3]

Aaron Davis, Mark Silburn, Tony Weber, Megan Star

The synthesis of the evidence for **Question 5.3** was based on 251 studies, undertaken primarily in Great Barrier Reef catchments with a small number of studies from elsewhere in Australia and some international evidence for non-agricultural land uses. Studies were published between 1990 and 2022. The synthesis includes a *High* diversity of study types (36% experimental, 32% secondary-observational and 32% mixed studies), and has a *Moderate* confidence rating (based on *Moderate* consistency and *Moderate* overall relevance of studies).

Summary of findings relevant to policy or management action

The most effective management practices for reducing pesticide risk from the Great Barrier Reef catchment area vary between land uses. Practices that demonstrably reduce pesticide risk from agricultural land uses include reductions in the total amount of pesticide applied through lower application rates (within label recommendations), improved application methods, timing of application in relation to weather risk periods, use of pesticide products with lower environmental risk, reducing soil erosion through retaining cover, controlled traffic and improved irrigation management for pesticides with greater soil sorption. These findings have remained relatively consistent through time. The effectiveness of these practices also remains relatively consistent across climatic regimes and farming systems of the Great Barrier Reef catchments. Assessment methods for cost-effectiveness of improved pesticide management across different agricultural land uses in the Great Barrier Reef catchment area has been inconsistent and requires an agreed approach to support future assessments. For non-agricultural lands, pesticide management options largely rely on non-structural controls such as regulation and improved wastewater treatment processes. The emergence of significant pesticide resistance across multiple industries is likely to impose (and in some cases has already resulted in) considerable changes in pesticide use and other alternative pest control measures.

Supporting points

- A range of non-chemical pesticide control measures (integrated pest management, cultural controls that modify the pest's growing environment) hold considerable potential for reducing reliance on chemical control measures, but most are yet to be trialled with respect to long-term pesticide use reductions, efficacy and economic outcomes. Much of the new research (since 2016) has essentially reinforced previous conclusions about the efficacy of many established practices for managing pesticide risks from agricultural lands. Key issues and emerging findings since 2016 include greater recognition of pesticide risk in management frameworks, allowing management practices to be better targeted to manage specific risks, renewed focus on Integrated Pest Management concepts and increasing acknowledgement of variable water quality benefits from tillage-crop residue retention practices.
- The more recent research emphasis on comparative ecosystem risk profiles of a broader range of pesticides has identified that several 'alternative' pre-emergent herbicides (metribuzin, metolachlor etc.) present similar ecosystem risk profiles to at least some of the priority PSII herbicides such as atrazine.
- Data required to assess the management effectiveness of many insecticides and fungicides used in Great Barrier Reef farming systems is particularly lacking, including usage patterns, current presence in the environment, half-lives, sorption, runoff potential and ecotoxicology under conditions relevant to the Great Barrier Reef catchment and its aquatic ecosystems.
- Recent results from paddock studies suggest that water quality improvements associated with management practice change can be affected significantly by the contribution of particular 'knockdown' herbicides included in mixtures, an outcome not captured in previous research. Better understanding of the comparative environmental risks posed by herbicide mixtures from different management practices, for multiple land uses, is important for future policy directives.
- Most studies that assessed the effectiveness of management practices focused exclusively on the assessment of the losses of pesticides from surface water pathways, with limited measurement of losses to groundwater.
- In the assessment of cost-effectiveness of pesticide management in agricultural industries, economic returns remain critically dependent on region-specific variables including biophysical characteristics and enterprise structure, especially in relation to farm size and location. However, for sugarcane, progressing from traditional to industry standard herbicide management was reported to be generally profitable and provide return on investment across all farm sizes and sugarcane districts.
- A limited number of studies have compared specific water quality risks among practices across broad climatic zones or farming systems. Broad findings were generally consistent across both. Factors relating to variability in soil properties such as soil pesticide half-lives, rather than climate, appear to play significant roles in the spatiotemporal behaviour of pesticides.

- Few studies have examined how pesticide practice change can influence crop production (crop yield), and available results tended to focus on broader implications of pesticide impacts. Assessment of pest management in conjunction with nutrient management would also provide further insights for changes in yields and productivity outcomes.
- The recent move to incorporate and benchmark the relative ecosystem risks of different paddock scale herbicide practices is an improvement from simple load-based comparisons, but these are still largely based on comparisons between individual pesticides. The lack of frameworks and risk-based metrics that accommodate paddock scale data including pesticide mixtures, and subsequent downstream aquatic ecosystem risk, has posed challenges for the assessment of pesticide management practice change.
- In urban areas, there is limited evidence that stormwater treatment measures such as wetlands and infiltration basins are effective. In wastewater treatment, the existing tertiary treatment measures (e.g., membrane bioreactors, reverse osmosis) can be effective for pesticide removal in some cases.
- Accumulation of micropollutants such as pesticides is occurring in some diffuse runoff treatment systems (e.g., wetlands) but whether this accumulation indicates effective treatment or a potential fate pathway is unclear.
- Assessment of the chemical risk of wastewater re-use where tertiary treatment is not occurring is needed as there is a potential for pesticides to be transferred to the end use environments of the recycled water.

What is the spatial and temporal distribution and risk of other pollutants in Great Barrier Reef ecosystems, and what are the primary sources? [6.1]

Anthony Chariton, Natalie Hejl

The synthesis of the evidence for **Question 6.1** was based on 92 studies undertaken in the Great Barrier Reef and published between 1990 and 2023. The synthesis includes a *Low to High* diversity of study types (77% observational studies and 23% experimental studies) and has a *Limited to Moderate* confidence rating depending on the pollutant and is based on mixed but mostly *Low to Moderate* consistency and *Moderate* overall relevance of studies.

Summary of findings relevant to policy or management action

While nutrients, sediments and pesticides are well documented and routinely monitored in the Great Barrier Reef, there are many other pollutants that can enter the waters and sediments that could impact a range of ecosystems. In this synthesis, seven pollutant groups were examined (Great Barrier Reef studies in brackets): metals (44), Persistent Organic Pollutants (POPs; 19), Per- and poly-fluoroalkyl substances (PFAS; 1), plastics (19), pharmaceutical, veterinary, and personal health care products (PVPs; 4), coal and fly ash (5), and sunscreens (none). Fundamental data and establishment of water and sediment guideline values for most pollutant groups in the Great Barrier Reef are lacking, most notably for coal, per- and poly-fluoroalkyl substances, pharmaceutical, veterinary, and personal health care products and sunscreens. This prevents any reliable assessment of spatial patterns, temporal trends, or exposure risk for ecosystems and biota. Sediment guideline values still need to be established for some metals (e.g., manganese, aluminium). This limits the ability to assess ecological risks, particularly for tropical ecosystems, as guidelines are predominantly derived from temperate biota. Across pollutant groups, most datasets have a coastal focus and involve the same few locations, notably Port Curtis (Gladstone), Hay Point (Mackay), Townsville and Cairns. Few offshore environments have been sampled, with high variability in the types of pollutants assessed between the studies. In contrast to programs assessing nutrients, sediments and pesticides in the Great Barrier Reef, there are very few routine monitoring programs for these pollutant groups, with the exception of some monitoring within the Regional Report Cards (e.g., Gladstone, Dry Tropics and Mackay Whitsunday) for which the raw data are not publicly available. A more cohesive and co-ordinated approach to examine the interaction of multiple pollutants and stressors, including climate change, is required. Ecotoxicological studies that employ multiple lines of evidence are urgently required for all pollutant groups identified in the Great Barrier Reef to understand the risks they pose to Great Barrier Reef biota and ecosystems.

Supporting points

Metals

- Metal concentrations in water and sediments are higher in more industrial and developed coastal environments compared to less developed catchments and offshore areas. There is limited published temporal data for metal concentrations in water, sediments and biota in the Great Barrer Reef generally, and more particularly in less developed areas.
- Concentrations of metals in water above national water quality guideline values are rarely documented, but have been recorded in some studies including copper (associated with legacy mining in the Fitzroy basin), mercury (associated with sugarcane in the Tully catchment) and aluminium (from acid sulfate soils in Trinity Bay, Cairns). These metals may be more widespread than currently recognised due to the limited data collection.
- Elevated concentrations of metals in sediments have been recorded adjacent to heavily urbanised environments including: manganese and nickel in Port Curtis; copper, nickel and zinc in Townsville Harbour; and cadmium from acid sulfate soils in Trinity Bay.
- There is some evidence that biota found inshore (e.g., seagrass, algae, turtles, corals) have higher concentrations of metals in their tissues than those found offshore and that levels can increase following runoff events.
- From the available ecotoxicological studies, the ecological risk from metals in the Great Barrier Reef is relatively low and constrained to a few locations. However, there is a lack of recent data to complete this assessment and available studies rarely considered metal speciation which is an important factor for determining metal bioavailability and ecological risk.

Persistent Organic Pollutants (POPs)

- POPs are associated with industry, oil spills, coal, and urbanisation. Some sources remain uncertain as it is unknown whether some restricted products (e.g., PCBs which require importation approval from the Department of Home Affairs under Regulation 4AB) are still being used in the region or whether the sources are legacy.
- POPs are detectable in Great Barrier Reef sediments, and from the limited data available, decrease across an inshore to offshore gradient. POPs are generally below guideline values where they have been recorded but there are exceptions (e.g., following oil spills).
- Experimental studies have shown that POPs can affect fish physiology and behaviour, coral reproduction and trophic food webs at a range of concentrations.

Per- and poly-fluoroalkyl substances (PFAS)

- There are insufficient data to provide insights about spatial or temporal patterns of PFAS in the Great Barrier Reef.
- From the single study available, PFAS were not detected at most sites in the three Natural Resource Management regions that were sampled (Wet Tropics, Mackay Whitsunday, and Fitzroy); however highly industrialised areas were not sampled.

Plastics

- Plastics, including microplastics and fibres, are extensively distributed in coastal and marine environments.
- The sources and types of plastics vary with geographic location. Coastal sites are influenced by surrounding land use (e.g., urbanised area), river and stormwater inputs. Offshore sites are influenced by recreational activities, tourism, commercial shipping and fishing.
- Plastics have been recorded in zooplankton, crustaceans, fishes, birds and turtles from the Great Barrier Reef. The ecological risks may vary markedly depending on species, feeding behaviour and life stages.

Pharmaceutical, veterinary, and personal health care products (PVPs)

- There are insufficient data to provide insights about spatial or temporal patterns and/or the ecological consequences of PVPs in the Great Barrier Reef.

- The sources of PVPs remain unclear, however, the limited evidence suggests that PVPs are more dominant near wastewater overflows and stormwater discharges.

Coal and fly ash

- There are insufficient data to provide insights about spatial or temporal patterns of coal and fly ash in the Great Barrier Reef.
- Polycyclic aromatic hydrocarbons (PAHs), which are most likely derived from coal, were detected in coastal sites near Hay Point (Mackay) and up to 40 nautical miles from the coast.

Sunscreens

- There were no Great Barrier Reef studies on sunscreens and hence the spatial and temporal distribution, sources and ecological impacts of UV blockers within the Great Barrier Reef are unknown. Data from international studies suggest that recreational use and wastewater are the primary sources.

Coastal industrial site
Photo: J Jones.
© Commonwealth of Australia (Reef Authority)

Farming community
Photo: shotbydave

Themes 7 and 8: Human dimensions of water quality improvement and Emerging Science

Themes 7 and 8: Human dimensions of water quality improvement and Emerging Science

Context

Declining water quality in the Great Barrier Reef was formally recognised by the Australian and Queensland Governments in 2003 under the first Reef Water Quality Protection Plan. Since then, there has been considerable investment to develop programs and instruments that generate water quality benefits through the adoption of land management practices in agricultural and non-agricultural lands. Outcomes have been mixed and therefore it is important to consider the whole policy and innovation process that defines management practices and designs the instruments for delivery, identify the levers or mechanisms that can accelerate adoption, and to understand the behavioural, economic, social and cultural factors that hinder or enable the uptake of management practices for water quality improvement.

There is an increasing commitment by those working in Great Barrier Reef water quality policy and management to more effectively engage and involve Traditional Owners, and specifically, integrate Indigenous people and knowledge into decision-making frameworks for the Great Barrier Reef. Options identified to progress this objective include direct consultation and broader engagement via the update of the Reef 2050 Water Quality Improvement Plan, but drawing on published evidence could also provide useful insights from elsewhere in Australia and around the world in setting the direction for future work.

Management actions for water quality improvement can provide financial returns to agricultural sectors and other industries such as tourism and fishing in the Great Barrier Reef. Additional co-benefits of these actions can be direct, where the land management practice leads to improvements in agricultural production, or indirect through for example, changes in vegetation structure and composition leading to increased biodiversity or carbon sequestration in the soil. The co-benefits can be private such as productivity benefits, or public such as environmental or Indigenous outcomes. These opportunities are of significant and increasing interest to the wider community and require a holistic catchment to reef approach to management. Monitoring and evaluation of projects and programs designed to improve coastal and marine water quality also need to be holistic and are an essential part of collaborative planning and design, and for assessing environmental, social and management change, tracking progress towards program objectives and targets, and informing and improving decision making. Learnings from successful approaches to monitoring and evaluation in the Great Barrier Reef and around the world are highly relevant to the future management of the Great Barrier Reef.

The synthesis of the evidence for **Theme 7** included a total of **311** studies extracted and synthesised for **3** questions (Figure 10). **Theme 7** provides the evidence of the project and program design and human dimensions of water quality management in the Great Barrier Reef catchment area. This Theme reviews the evidence on the programs and instruments used to drive improved land management actions for water quality benefits in the Great Barrier Reef (Q7.1), identifies the behavioural, economic, social, and cultural factors that hinder or enable the uptake of management practices to improve water quality outcomes (Q7.2) and the critical success factors for greater Indigenous involvement in water quality decision making in the Great Barrier Reef (Q7.3) (Figure 11).

Theme 8 included a total of **341** studies, extracted and synthesised for **2** questions (Figure 12). The questions in this Theme identify future directions and emerging opportunities in Great Barrier Reef water quality management. This Theme reviews the evidence of the potential co-benefits (such as biodiversity, carbon and productivity) of land management to improve water quality outcomes for the Great Barrier Reef (Q8.1), and the key attributes of successful monitoring and evaluation programs to support coastal and marine water quality management (Q8.2). Both questions are highly relevant in the context of increasing pressures from climate change and the need to accelerate water quality improvements.

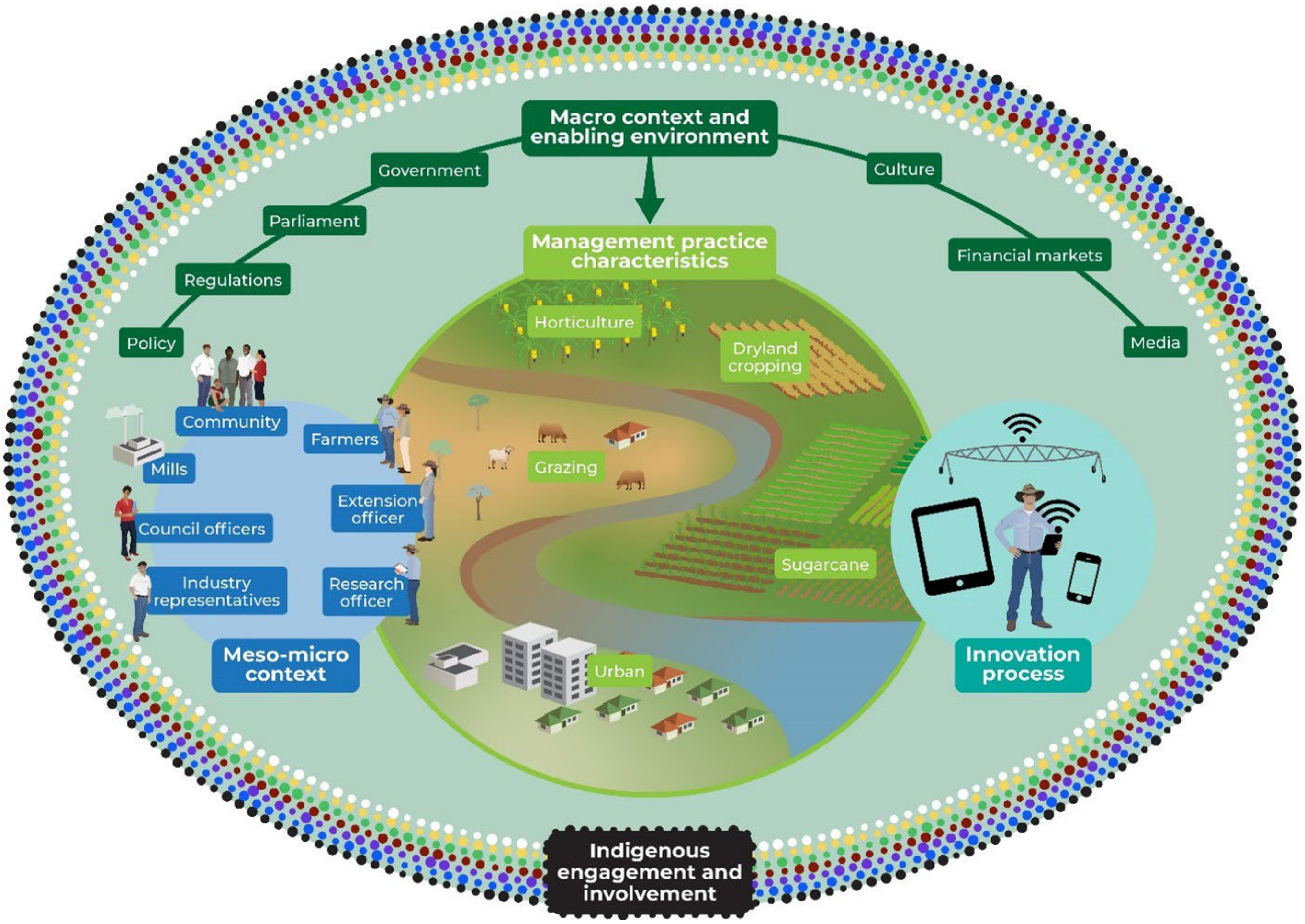

Figure 10. This diagram provides a pictorial representation of the scope of Theme 7. It represents the overall context for water quality improvement programs and instruments, the factors that influence the uptake of management practices to improve water quality at various levels (macro, meso and micro levels), and includes a review of the success factors for greater Indigenous involvement in water quality decision making.

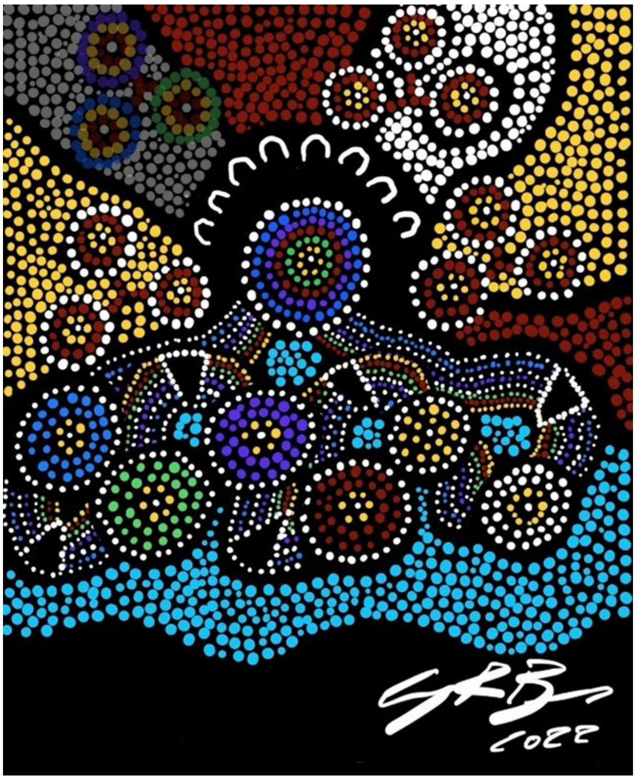

Figure 11. Aboriginal artwork prepared by Conway Burns, Dugoo Duwalami – Heart meeting place – representing a roundtable for the Great Barrier Reef, previous engagement and involvement pathways, Traditional Owner groups that have not been effectively involved to date, and future pathways involving two-way knowledge sharing, and ensuring improved holistic outcomes for the species, habitats and people connected to the Great Barrier Reef through truly collaborative management.

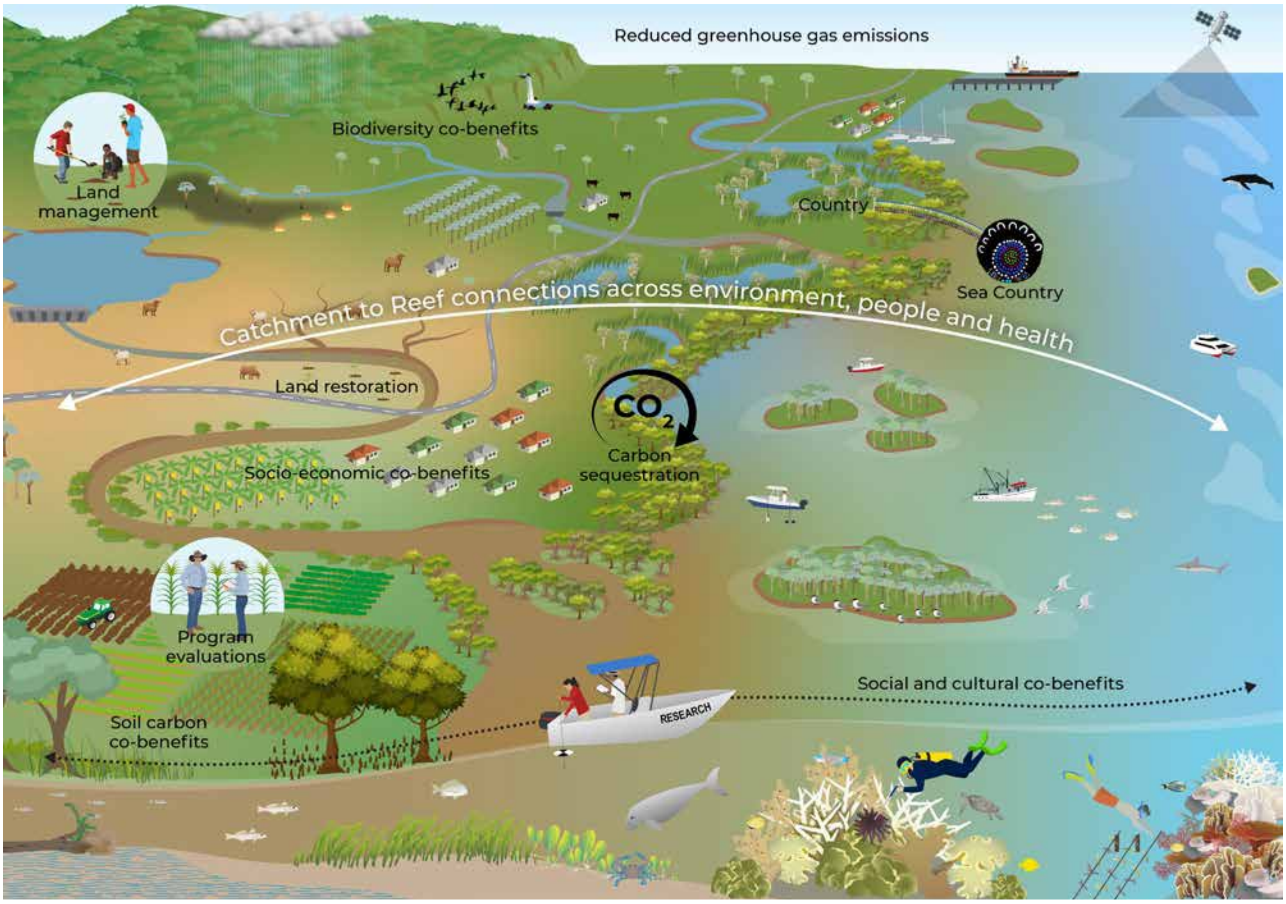

Figure 12. This diagram is a pictorial representation of the scope of Theme 8. It represents the Great Barrier Reef catchment and marine environment and shows elements of the questions within this Theme including potential co-benefits of land management to improve water quality outcomes (note that socio-economic benefits are covered in other Themes), and attributes of successful Monitoring & Evaluation programs to support coastal and marine water quality management in the Great Barrier Reef.

Summary Statement for Themes 7 and 8

Convergence was reached for this Summary Statement among all authors within the Expert Group for Themes 7 and 8 (listed in **Appendix 1**).

The synthesis of the evidence for **Theme 7** included a total of **311** studies extracted and synthesised for **3** questions. For **Theme 8**, it included **341** studies extracted and synthesised for **2** questions (with some overlap in evidence between questions).

The **summary of findings** relevant to policy or management action for **Themes 7 and 8** are:

- The Australian and Queensland governments have invested AUD$1.1 billion over the last 20 years to improve Great Barrier Reef water quality through a range of initiatives focused on the management of private land under the Reef Trust Program, Reef Trust Partnership (Australian Government) and the Reef Water Quality Program (Queensland Government). Investment has focused mostly on instruments of extension (51%) and financial instruments with extension (36%), followed by physical works such as on-ground gully remediation (5%), regulation and compliance (4%) and financial instruments in the absence of extension (3%). Investment has also been made into the innovation processes needed to develop the improved management practices but quantification of the level of investment is not available. Most of the investment has been in the sugarcane and grazing industries. Conclusions on which programs and instruments are most effective for driving changes to land management practices to improve water quality are limited by data and information that met the peer review standard required for inclusion in the Scientific Consensus Statement. [Q7.1]
- The most well-developed and consistently applied understanding of the cost-effectiveness

of water quality outcomes has been conducted for Reef Trust investments. For grazing, cost-effectiveness ranged from AUD$16 per tonne to AUD$17,000 per tonne of fine sediment removed. For sugarcane, cost-effectiveness ranged from AUD$49 to AUD$554 per kg of dissolved inorganic nitrogen removed. Effectiveness has only been assessed in terms of the estimated pollutant load reductions, and other benefits, such as broader social change or capacity building, have not yet been included in evaluations of effectiveness. [Q7.1]

- For urban land uses, Regional Partnerships and the associated Regional Report Card initiatives are creating a forum for benchmarking urban water management activities. The Urban Water Stewardship Framework can be used to rate relative risk to water quality from urban water management activities and identify what aspects need improvement. A “C” or Moderate ranking was achieved for overall urban water management in 2021, indicating that as a collective, councils were meeting current minimum industry standards, but were not yet at best practice management levels. [Q7.1]
- The factors that influence the uptake of management practices to improve water quality operate at various levels. These levels can be described as ‘macro’ (governance, culture, media, economics, policy and legislation), ‘meso’ (industry, research and development agencies and community), ‘micro’ (individuals and relationships to people) and practice or behaviour characteristics. The macro context, which includes the enabling environment and governance systems, directs and moulds what occurs at each level and hence influences efficiency and effectiveness. [Q7.2]
- Landholder distrust and suspicion of certain groups including government, scientists involved in Great Barrier Reef research, and program delivery organisations, is a key factor hindering uptake of management practices. To overcome this distrust, management practices for agricultural and urban land managers should be developed, tested and scaled using collaborative processes that actively involve key actors in the relevant communities, value chains and innovation systems, from planning through to evaluation. Context and the processes used to engage with the land managers are critical to the development and uptake of management practices. However, factors that may be associated with improved uptake include levels of human and social capital, economies of size, presence of trusted advisors and bottom-up development of practices. [Q7.2]
- While real and perceived economic factors are important to landholder decision making, even profitable practices can take time to be adopted because of the interactions within and between economic factors and landholders, research, extension, industry and community attitudes and systems. Less profitable practices are likely to take even longer and will require further development of approaches, supporting policies and instruments. [Q7.2]
- Additionally, for all land uses, demonstrating links between practice change and improved water quality outcomes was identified as an important factor that could enable practice adoption. Other factors for sugarcane include social norms, adoption costs, compatibility with farming systems, economies of size effects, and the interaction of technology characteristics and context. For grazing, factors include the interaction of weather and climate with property and decision-maker context, financial and other support over time, transaction costs and skills required. For urban, social resilience, and innovative and adaptive capacity may be important factors. [Q7.2]
- Determining the critical success factors for greater Indigenous involvement in water quality decision making and management for the Great Barrier Reef requires Indigenous knowledge and input. Currently, there is a lack of peer reviewed and published material related to Indigenous knowledge and water quality improvement in the Great Barrier Reef. However, several critical factors and key learnings were identified from national and international studies. These include increased understanding and knowledge of Indigenous culture and connection to Country, helping to establish trust and respect between all partners through relationship building, support for increased capacity to engage and become involved in programs, support for improved capability to collaborate and deliver across all aspects of planning and delivery, and adoption of an adaptive management approach to program delivery. [Q7.3]
- The co-benefits of land management practices for water quality improvement vary spatially with bioregions, land use and landscape connectivity and the specific co-benefit being sought such as biodiversity, soil carbon and productivity. Potential co-benefits of management practices within the Paddock to Reef Water Quality Risk Framework have been identified for the major land uses in the Great Barrier Reef catchment area. For example, reductions in grazing

pressure and changes in the timing of grazing lead to increased vegetation cover, particularly of perennial grasses, which improves water infiltration and reduces runoff, and can lead to improved soil carbon and biodiversity. In sugarcane and grain cropping systems, improved nitrogen management (type, timing, and quantity applied) can reduce nitrous oxide and greenhouse gas emissions. The use of break-crops, rotations, controlled traffic farming, and trash blanketing, has demonstrated benefits for soil health. For horticulture, maintaining ground cover, inter-row, and headland management, can also support biodiversity outcomes by providing habitat or, for example, reducing pollutant runoff into aquatic ecosystems. However, there are few studies that specifically evaluate these co-benefits. Furthermore, whole of life cycle analysis is required for optimising the outcomes of co-benefits, supported by alignment of on-ground and management investment frameworks. [Q8.1]

- Systematic and consistent monitoring and evaluation of projects and programs designed to improve water quality is essential to assess environmental, social and management change, track progress towards program objectives and targets, and inform and improve decision making. Attributes of coastal and marine water quality monitoring and evaluation programs that have successfully driven positive change for management include: those that adopt the system drivers, pressures, state, impact and responses (typically shortened to DPSIR) framework; recognise ecosystem services and marine natural capital; adopt multidisciplinary frameworks; report on the interactions between environmental and human health; and support connections between people and the Great Barrier Reef through the use of citizen science and greater involvement in decision making processes. [Q8.2]
- The Reef 2050 Integrated Monitoring and Reporting Program and the Paddock to Reef Integrated Monitoring Modelling and Reporting programs are among the most comprehensive and integrated catchment to reef monitoring programs in the world. These programs recognise links between drivers, pressures and state through the reporting of environmental, social and economic indicators. However, the connections between environment and people could be strengthened with greater recognition that human wellbeing is intrinsically linked to the health of Great Barrier Reef ecosystems. Potential improvements drawn from the global evidence base include greater recognition and quantification of complex social, cultural, economic and environmental values and their interconnections, extension of existing multidisciplinary frameworks to incorporate human health, and enhanced community engagement including direct participation in monitoring programs. [Q8.2]

The **confidence** rating of the questions within **Themes 7 and 8** was Limited for the Indigenous involvement question, and Moderate for the other questions, mostly due to the limited availability of Great Barrier Reef-specific peer reviewed literature on these topics, and Moderate consistency across study findings.

The findings in these Themes are underpinned by a growing body of evidence, including multiple lines of evidence (i.e., quantitative, qualitative and experimental research, observations, modelling and reviews or other secondary studies). However, there is a large body of evidence in unpublished literature for the questions within these Themes which potentially constrains the findings. The **strength of evidence** across these Themes, considering the confidence, quantity and diversity of study types, is Moderate, with limited peer reviewed evidence around the mix of programs to drive improved water quality benefits, and the question on the factors of success in Indigenous engagement in water quality management and decision making.

The **key uncertainties** of the evidence identified for **Themes 7 and 8** relevant to policy and management included the lack of standard collaborative approaches to plan, monitor, evaluate and report on effectiveness of programs; very limited evidence on factors influencing uptake in urban environments, particularly at the practice to meso-level; overall, limited Great Barrier Reef-specific peer reviewed literature on human dimensions of water quality management (e.g., effectiveness of regulations and extension, disadoption) and factors contributing to successful Indigenous involvement in water quality management; and limited evidence of the flow-on effects of biophysical co-benefits on social and economic outcomes. The body of evidence presented in the review of success factors for Indigenous involvement is inherently limited by the scope of the question posed, and the findings presented within peer reviewed publications, some of which may not be directly appropriate for Traditional Owners in Australia. Further engagement with local Traditional Owner groups to determine the successes and learnings from existing engagements within the Great Barrier Reef context is necessary to fully address the question.

Recent findings continue to reinforce that the ongoing protection and restoration of the Great Barrier Reef, including water quality management, is a ‘wicked’ problem, which requires adoption of transdisciplinary innovation processes. Evidence of mistrust between farmers, government and scientists has become more evident, with multiple studies identifying mistrust as a major factor hindering the uptake of management practices to improve water quality outcomes. The focus to date on individual factors influencing adoption, which are varied and context specific, downplays the higher level (e.g., governance and industry) policies and practices that can increase mistrust. Despite the complexity, time and cost involved, the solution requires high levels of engagement, partnering and collaboration, along with transdisciplinary and multidisciplinary planning, research and development processes, to deliver the best outcomes. Recent research has also focused on Indigenous participation in environmental management and decision-making, documenting key learnings from proposed and ongoing collaborative work from around the world. Collaborative decision-making is crucial for Great Barrier Reef management, but there have been both successes and failures in engaging stakeholders and improving water quality. Global experiences reinforce that integrated adaptive catchment management can be strengthened by greater understanding of the linkages between biophysical, social and economic systems, supported by robust monitoring and evaluation of these factors. This integrated approach will also support the identification, development and implementation of co-benefits. The role of the community and stakeholders in monitoring and evaluation programs for coastal and marine water quality programs is also receiving greater recognition globally and is highly relevant to the Great Barrier Reef.

Within **Themes 7 and 8**, the areas where further **knowledge is needed** that are most relevant to policy and management include: i) how collaborative and transdisciplinary innovation systems can be incorporated into the support of management practices that bring economic, environmental, cultural and social benefits; ii) the effectiveness of programs and instruments to drive improved land management action for Great Barrier Reef water quality benefits, in terms of type and extent of change, success metrics across different scales (among different audiences), as well as potential water quality impact (ideally beyond the life of programs or projects) using an agreed consistent approach; iii) ongoing review, development and evaluation of collaborative monitoring and evaluation processes (in different contexts) for the macro governance system, the innovation process system, industry, research development, extension and farming systems; iv) strategies for scientists, extension staff, policy and management professionals to communicate key messages about Great Barrier Reef water quality in the current media environment; v) how to link scaling processes to the innovation processes so that they lead to improved uptake of management practices; vi) approaches for integrating Traditional Ecological Knowledge and western science; vii) greater understanding of co-benefits generated from engagement in programs and instruments (human and social capital), and assessment of the opportunities to maximise co-benefits of water quality improvement practices from all land uses and under a range of future climate scenarios.

Summary information for Questions in Themes 7 and 8

The Table below summarises the evidence appraisal indicators and confidence ratings in the evidence base for each of the Questions within these Themes. The Confidence rating was determined by the overall relevance of studies to the question and the consistency of the body of evidence (refer also to Appendix 3: Glossary for explanation of indicators). *Note: In Diversity of items: Experimental (E), Mixed (X), Modelling or Remote sensing (M), Observational (O), Quantitative (Q), Qualitative (L), Reviews (R), Secondary data analysis (S-A), Theoretical or Conceptual (T).*

Question	Quantity of items	Diversity of items	Overall relevance	Consistency	Confidence
What is the mix of programs and instruments (collectively and individually) used in the Great Barrier Reef catchments to drive improved land management actions for Great Barrier Reef water quality benefits and how effective are they? [7.1]	Low (86)	Moderate - High *(80% O, 20% M)*	Moderate - High	Low - Moderate	Limited - Moderate
What are the behavioural (attitudinal), economic, social and cultural factors that hinder or enable the uptake of management practices that aim to improve water quality outcomes for the Great Barrier Reef? [7.2]	High (106)	High *(29% X, 17.5% Q, 17.5% T, 15% L, 12% S-A, 9% R)*	High	Moderate	Moderate
What are the critical success factors for greater Indigenous involvement in water quality decision making in the Great Barrier Reef region? [7.3]	Low (119)	Low *(70% R, 30% O)*	Low	Moderate	Limited
What are the co-benefits e.g., biodiversity, carbon, productivity, climate change, and drought resilience, of land management to improve water quality outcomes for the Great Barrier Reef? [8.1]	Moderate (97)	High *(46% E, 40% R, 9% O, 5% X)*	Moderate	Moderate	Moderate
What are the key attributes of successful monitoring and evaluation programs to support coastal and marine water quality management, and what examples are there of innovative monitoring and evaluation frameworks, methods and approaches that are applicable to the Great Barrier Reef? [8.2]	High (244)	High *(48% R, 32% O, 15% E, 5% M)*	High	Moderate	Moderate

Evidence Statements for Questions in Themes 7 and 8

What is the mix of programs and instruments (collectively and individually) used in the Great Barrier Reef catchments to drive improved land management actions for Great Barrier Reef water quality benefits and how effective are they? [7.1]

Anthea Coggan, Diane Jarvis, Mara Emmerling, Ella Schirru, Bianca Molinari

The synthesis of the evidence for **Question 7.1** was based on 86 studies conducted across the Great Barrier Reef catchment area and published between January 2015 and 31 March 2023. The synthesis includes a Moderate to *High* level of diversity of study types (for the 52 studies reporting on programs in the agricultural sector this included 80% observational from primary and secondary data and 20% modelled studies) and has a *Limited to Moderate* confidence rating (based on *Low to Moderate* consistency and *Moderate* (agriculture) and *High* (urban) overall relevance of studies).

Summary of findings relevant to policy or management action

The Australian and Queensland Governments have sought to improve Great Barrier Reef water quality through investment in a range of initiatives focused on the management of private land under the Reef Trust Program, Reef Trust Partnership (Australian Government) and the Reef Water Quality Program (Queensland Government, agricultural and urban land). This investment is estimated at AUD$1.1 billion over the last 20 years, with approximately AUD$390 million of this for on-ground projects from 2017-2022. Investment has focused specifically on the instruments of extension (51%), followed by financial instruments with extension (36%). Less investment has been allocated directly to physical works such as on-ground gully remediation (5%), regulation and compliance (4%) and financial instruments in the absence of extension (3%). Despite the magnitude of the investment, there is no standard way to understand and report on effectiveness of these programs in generating water quality benefits. It is therefore not possible to draw, from the available peer reviewed literature, defining conclusions about which instruments are consistently effective at driving changes to land management practices to improve water quality outcomes, including when and where they have been most effective. The quality of the limited peer reviewed evidence is also variable. Further, a significant proportion of available evidence examining the performance of Great Barrier Reef water quality improvement projects and programs exists in non-peer reviewed outputs. Ensuring that studies are formally peer reviewed and published will support more transparent and accessible program evaluations, and better consistency and comparability among assessment approaches all of which will contribute to informing future investments.

Supporting points

- Programs and instruments used in the Great Barrier Reef catchment area to drive improved land management actions for water quality benefits are largely funded by the Australian and Queensland Governments, and sometimes a combination of these. Most of the investment has been in the sugarcane and grazing industries.
- In the agricultural industries, land management actions for water quality benefits have primarily been generated through facilitative instruments (extension), incentive-based instruments (primarily financial incentives) and regulation/coercion. For urban land, actions have been motivated mostly through facilitative instruments and regulation.
- The synthesis assessed the effectiveness of programs and instruments using criteria for whether a program or instrument achieved its objectives and graded these based on indicators of effectiveness. The highest assessment level for effectiveness was when a water quality outcome was known or modelled. Additional information such as cost-effectiveness, insights from modelled studies and literature that critiqued the effectiveness of different methods was also included. Relevant observations include:
    - Most peer reviewed evidence focuses on the effectiveness of extension (primarily in grazing and sugarcane) and is based on assessment of landholder uptake of program objectives (which range from landholder interest in a program through to land management practice change) more so than a measured water quality outcome. For other agricultural industries (bananas for horticulture and cotton and grains for cropping), the effectiveness of the intervention was well understood for program objectives such as increased engagement and skills improvement, but it was less common for studies to report on water quality outcomes.

  - Studies that evaluated the effectiveness of financial instruments tended to include water quality outcomes in effectiveness measures more so than assessments of extension. For example, a recent study evaluated 23 projects funded by the Reef Trust and reported on pollutant reduction, cost-effectiveness and other measures of success.
  - The most well-developed and consistently applied understanding of the cost-effectiveness of water quality outcomes has been conducted for Reef Trust investments. The Reef Trust assessment reports that for grazing, cost-effectiveness ranged from AUD$16 to AUD$17,000 per tonne of fine sediment removed. For sugarcane, cost-effectiveness ranged from AUD$49 to AUD$554 per kg of dissolved inorganic nitrogen removed. Effectiveness was only assessed in terms of the estimated pollutant load reductions and did not include other benefits such as broader social change or capacity building.
- There is very little peer reviewed evidence on the effectiveness of regulation more broadly. There is no peer reviewed evidence on the effectiveness of regulations specifically aimed at improving the quality of water entering the Great Barrier Reef, including the (2019) Reef protection regulations established under the Environmental Protection (Great Barrier Reef Protection Measures) and Other Legislation Amendment Bill 2019.
- For urban land uses, Regional Partnerships and the associated Regional Report Card initiatives are creating a forum for benchmarking urban water management activities. The Urban Water Stewardship Framework can be used to rate relative risk to water quality from urban water management activities and identify what aspects need improvement. A “C” ranking was achieved for overall urban water management in 2021, indicating that as a collective, councils were meeting current minimum industry standards, but were not yet at best practice management levels.
- An evaluation of the effectiveness of broader procedural governance was not included.

What are the behavioural (attitudinal), economic, social and cultural factors that hinder or enable the uptake of management practices that aim to improve water quality outcomes for the Great Barrier Reef? What factors influence disadoption of management practices in agricultural industries and are there examples from elsewhere on how to address it? [7.2, 7.2.1]

Roy Murray-Prior, Tracy Schultz, Peter Long

The synthesis of the evidence for **Question 7.2** was based on 106 studies published after 2000, including 102 undertaken in the Great Barrier Reef. The synthesis includes a *High* diversity of study types (29% mixed, 12% secondary data analysis, 17.5% quantitative, 15% qualitative, 9% review, 17.5% conceptual model) and has a *Moderate* confidence rating (based on *Moderate* consistency and *High* overall relevance of studies). Only four studies were found in Australia since 2000 that discussed disadoption of management practices in agriculture. None of these discussed the Great Barrier Reef and none measured the levels of disadoption or the factors that hinder or enable disadoption of management practices.

Summary of findings relevant to policy and management action

The factors that influence the uptake of management practices to improve water quality operate at various systems levels. These levels can be described as macro (governance, culture, media, economics, policy and legislation), meso (industry, research and development agencies and community), micro (individuals and relationships to people) and practice or behaviour characteristics. The macro context, including the enabling environment and governance systems, directs and moulds what occurs at each of these levels and hence influences efficiency and effectiveness. Landholder distrust and suspicion of certain groups including government and scientists involved in Great Barrier Reef research, program delivery organisations, program managers and delivery staff is a key factor hindering uptake of management practices. To overcome this distrust, management practices and programs for agricultural and urban land managers would be more efficacious if they were developed, tested, scaled, monitored and evaluated using collaborative processes that actively involve key actors in the relevant communities, value chains and innovation systems. Context and the processes used to engage with the land managers are critical to consider but factors identified that may be associated with improved uptake include levels of human and social capital, economies of size, presence of trusted advisors and bottom-up development of practices.

Supporting points

- Recent literature has identified several principles that can be used to help address the lack of trust, particularly active engagement of key actors from the planning stages onwards which can improve the design, implementation and scaling of management practices to improve water quality outcomes for the Great Barrier Reef.
- There has been extensive investigation of factors hindering and enabling the uptake of management practices at the practice, landholder and micro-level. Perceptions of these factors vary between researchers and farmers and within farming communities, creating a diversity of evidence about drivers of management practices. Options to address these factors need to be incorporated within the innovation processes (research, development & extension).
- While real and perceived economic factors are important to landholder decision making, even profitable practices can take time to be adopted because of the interactions within and between economic factors and landholders, research, extension, industry and community attitudes and systems. Less profitable practices are likely to take even longer and will require further development of approaches, supporting policies and instruments. Additionally, for all land uses, demonstrating links between practice change and improved water quality outcomes was identified as an important factor that could enable and hinder practice adoption. Other factors for major land uses include:
    - For sugarcane, social norms, costs of adoption, compatibility with farming systems, economies of size effects, and the interaction of technology characteristics and context were identified as factors that hinder and enable uptake.
    - For grazing, the interaction of weather and climate with property and decision-maker context, financial and other support over time, transaction costs and skills required.
    - For urban, social resilience, and innovative and adaptive capacity may be important but there were few studies to support this.
- Mixes of instruments (e.g., regulation, incentives) could be collaboratively designed, implemented and evaluated alongside or in coordination with extension approaches to improve their efficiency and effectiveness.
- Government policies and the introduction of regulations were mentioned by multiple authors as resulting in mistrust that hindered the uptake of recommended management practices to improve water quality outcomes beyond minimum standards. When these decisions didn't have the support of the target audiences (e.g., landholders or councils), they generated resistance and conflict that was supported and intensified by industry, media and politicians.
- Program evaluation from the micro to the macro levels is still weak and requires guidelines and funding that puts a greater focus on outcomes and impacts beyond the life of programs or projects. Ideally, evaluation would be part of the planning process, extend beyond the lifespan of the program, and include changes in behaviour, and human and social capital that may have ongoing benefits.
- Disadoption has not been studied in the Great Barrier Reef catchment area. However, there are two factors that need to be quantified to improve this understanding: 1) the number of landholders (as a portion of the landholder population) that adopt management practices which improve water quality and 2) those that then disadopt, noting that there may be very few that disadopt when compared with those that don't shift land use practices in the first instance. The factors influencing disadoption are also likely to vary in the same way that factors influencing initial uptake vary. Understanding disadoption does not require extra studies, rather it should be part of ongoing evaluations.

What are the critical success factors for greater Indigenous involvement in water quality decision making in the Great Barrier Reef region? [7.3]

Tom Espinoza, Sydney Collett, Conway Burns

The synthesis of the evidence for **Question 7.3** was based on 119 studies, undertaken in primarily colonial and settled nations (e.g., Australia, Canada) and published between 1990 and 2022. The synthesis includes a *Low* diversity of study types (30% primary studies, largely observational and 70% secondary studies primarily literature reviews and reviews of survey outcomes) and has a *Limited* confidence rating (based on

Moderate consistency and *Low* overall relevance of studies).

Summary of findings relevant to policy or management action

Determining the critical success factors for greater Indigenous involvement in water quality decision making and management for the Great Barrier Reef is difficult within the constraints of the Scientific Consensus Statement process that uses peer reviewed scientific evidence only. To fully address this question requires Indigenous knowledge and input. While recognising this limitation, several factors and learnings can be identified from national and international peer reviewed studies. Issues of communication, relationships, engagement and involvement of Indigenous people in natural resource management broadly, and water quality management specifically, are a global issue. Historic exclusion from natural resource management and decision-making precludes and impedes contemporary attempts to integrate cultural values. Improved understanding and collaboration across all sectors of natural resource management to recognise Indigenous connections to Country, the need for improved engagement frameworks specifically recognising social and cultural factors, and the socio-ecological benefits of Indigenous involvement in management and decision-making are identified as common needs for environmental programs globally. Critical factors and key learnings from national and international studies include increased understanding and knowledge of Indigenous culture and connection to Country, helping to establish trust and respect between all partners through relationship building, support for increased capacity to engage and become involved in programs, support for improved capability to collaborate and deliver across all aspects of planning and delivery, and adoption of an adaptive management approach to program delivery. Learnings from this synthesis should be accompanied by the development of meaningful relationships, policies and frameworks led by Traditional Owners to ensure delivery of sustainable and holistic outcomes for the Great Barrier Reef and its associated catchments.

Supporting points

- Several issues were identified for Traditional Owner engagement in water quality and broader natural resource management programs relevant to the Great Barrier Reef including: communication problems between contemporary management authorities and Indigenous people (31 studies); Indigenous exclusion from natural resource management and decision-making (23 studies); improved engagement with Indigenous people for improved natural resource management outcomes (40 studies); the need to direct resources towards capacity building of Indigenous organisations (16 studies); successful engagements or decision-making with Indigenous organisations (17 studies); Indigenous connections to Country and the benefits to communities from involvement in managing Country (32 studies); and recognition of the social dimensions of the issues and the need for social science expertise to be embedded in the solutions (21 studies).
- The outcomes from Indigenous-led decision-making including a description of successful engagements or successful outcomes are rarely published in the scientific literature. Key learnings identified to be most relevant to the Great Barrier Reef from national and international studies are:
    1. **Understanding:** Cultural awareness across western societies of Indigenous people's connections with the natural world are low and not conducive to acceptance that engaging and involving Indigenous people in natural resource management has global benefits. Support for education campaigns and engagements around cultural awareness that are designed and delivered by Indigenous people 'on Country' and target senior management staff is critical for success. Recognition of the social dimensions of the issues and solutions is a priority.
    2. **Respect:** Cultural awareness builds respect for Indigenous culture, land and sea management practices, and innate connections to Country held within Traditional Ecological Knowledge. Relationships built on trust, respect and understanding have shown best results in supporting Indigenous organisations on the pathway from exclusion to decision-making and self governance. Furthermore, Traditional Owners are not stakeholders to be consulted but rather decision-makers and as such, should be included from the start in relevant management roundtables.
    3. **Collaboration:** Collaboration is required at all levels of environmental decision-making including research, planning, policy, implementation, assessment and overall governance; and establishing relationships that are founded on respect, trust and mutual capacity-building is critical. Collaborative research that integrates different types of ecological knowledge has demonstrated great success in environmental outcomes and led to increased recognition of the awareness of the knowledge and wisdom held and contributed by Indigenous people.

4. **Capacity:** Contemporary Traditional Owner groups are expected to contribute effectively and efficiently across a vast scope of legislative, policy and planning frameworks. Development of resources focused on improving literacy of Traditional Owners to understand these frameworks in formats that are more meaningful for Traditional Owners, and the provision of more opportunities for individuals to gain experience with relevant management programs, are beneficial for the building of this capacity. Efforts should also be made to include Traditional Owners in all engagements to ensure improved capacity as decision-makers for the Great Barrier Reef.
5. **Capability:** Greater resources and effort to support Traditional Owner organisations to acquire the skills needed to govern, manage and deliver programs in terms of design, research, policy, planning, implementation, assessment and management have been shown to be beneficial. Effective self-governance of Traditional Owner organisations should be an endpoint which is supported by all western organisations involved with the management of the Great Barrier Reef.
6. **Adaptive management:** The critical success factors for greater Indigenous involvement should implicitly consider the critical success factors of greater Indigenous involvement. Integration of the steps above into policy and planning documents supported by fit for purpose Monitoring Evaluation and Reporting Strategies to measure success is necessary for continuous improvement and adaptive management.

- Consideration of these critical success factors can provide a useful foundation to build on and provide pathways for future engagement and involvement of Indigenous people in Great Barrier Reef water quality decisions and management.

What are the co-benefits e.g., biodiversity, carbon, productivity, climate change, and drought resilience, of land management to improve water quality outcomes for the Great Barrier Reef? [8.1]

Megan Star, Iain Gordon, Anne-Laurence Bibost

The synthesis of the evidence for **Question 8.1** was based on 97 studies undertaken in the Great Barrier Reef, nationally and internationally, and published between 1990 and 2023. The synthesis includes a *Moderate* diversity of study types (63% observational or experimental, 26% reviews and 11% modelling), and has a *Moderate* confidence rating (based on *Moderate* consistency and *Moderate* overall relevance of studies).

Summary of findings relevant to policy or management action

Co-benefits occur where a specific land management practice implemented to improve water quality for the Great Barrier Reef has additional positive on-farm secondary impacts such as improving economic and production outcomes, reducing carbon emissions, increasing biodiversity or improving soil health. Economic and production co-benefits and the ‘downstream’ effects of these co-benefits on Great Barrier Reef ecosystems were outside of the scope of this Question and are addressed elsewhere in the Scientific Consensus Statement. The potential direct co-benefits of water quality improvement practices in grazing, sugarcane, bananas, horticulture and cropping (primarily grains) were included in this review; non-agricultural land uses (such as urban), conservation areas and wetlands were not in scope. Indirect or ‘expected’ co-benefits such as reduced gully erosion as a result of ground cover management in grazing lands, was not within scope. While limited, the available literature clearly indicates there may be significant environmental and social co-benefits from land management practices designed to improve water quality in the Great Barrier Reef. For example, reducing grazing pressure and changing the timing of grazing can lead to increased vegetation cover, particularly of perennial grasses. Increased vegetation cover can improve water infiltration and reduce runoff, which can lead to improved soil health, higher levels of soil carbon and greater biodiversity. In sugarcane and grain cropping systems, nitrogen management strategies (type, timing, and quantity applied) implemented to reduce the amount of nitrogen entering the Great Barrier Reef can also reduce nitrous oxide and greenhouse gas emissions. The use of break-crops, rotations, controlled traffic farming and trash blanketing, all of which are used to reduce runoff and erosion, also has demonstrated benefits for soil health. Co-benefits associated with management practices to improve water quality can be complex, and therefore are not guaranteed and require careful planning and design. Contextual and site factors, the specific design and implementation of the management action and program design can influence the extent, magnitude and duration of a co-benefit. Further work is needed to understand the potential co-benefits associated with water quality improvement actions in the Great Barrier Reef catchment area, and to devise appropriate mechanisms to encourage adoption of practices with multiple benefits.

Supporting points

- There are existing policy mechanisms such as the Land Restoration Fund and Australian Carbon Credit Unit scheme that are relevant to supporting co-benefits (environmental, socio-economic and First Nations) flowing from Great Barrier Reef water quality management practices. While these existing mechanisms could offer opportunities for water quality benefits to be included with other co-benefits over the same area, differences in the guidelines, timelines, measurements and specific practices of the programs currently impede this.
- Key considerations for successful policy and program design for encouragement and greater adoption of practices yielding co-benefits include the specific co-benefit being sought, the capacity to accrue multiple benefits, the framework that is applied to measure it and to achieve additional co-benefits, the time expected to achieve co-benefits and the monitoring and maintenance required to demonstrate their achievement.
- The ways in which land management practices and climate warming interact will affect co-benefits. As an example, grazing practices that increase tree cover, ground vegetation cover and soil carbon are likely to trap more water on the property and thus improve vegetation productivity, reducing the impacts of droughts.

Grazing

- The relationship between grazing management strategies and soil organic carbon over the short and long term is complex. Stored soil organic carbon (to a depth of 30 cm) appears to be influenced by various combinations of grazing intensity, land condition, rainfall and land/soil type, and it is difficult to establish evidence for a strong link between livestock management and soil organic carbon content. Studies to date indicate that the benefits of maintaining ground cover and/or reducing stocking rates for soil health can take many years.
- Improved riparian and vegetation management in grazing (and cropping) lands has been shown to result in positive changes for a range of bird, insect and other invertebrate species, with evidence of increases in species richness, relative abundance and change in composition.

Sugarcane

- In sugarcane, a critical Paddock to Reef Water Quality Risk Framework management practice to reduce the risk of nutrient runoff is to reduce the amount of fertiliser applied to match industry recommended rates. Reducing the amount of fertiliser applied can also reduce emissions of the greenhouse gas nitrous oxide, however, there are still losses through other pathways including deep drainage and runoff. Nitrous oxide emissions vary with soil type, temperature, and soil water which also vary across sugarcane growing regions.
- Maintaining sugarcane trash on paddocks after harvesting, or green cane trash blanketing can both minimise soil erosion and runoff, and improve soil health. The use of soybean break-crops for inhibiting monoculture fungus and pests has also shown benefits for soil health. However, there is limited evidence that trash blanketing is beneficial for soil carbon. There is some evidence of downstream benefits to biodiversity from maintaining streambank vegetation in sugarcane areas.
- The methods for measuring outcomes of co-benefits in sugarcane vary between studies, with additional variability in temporal and spatial characteristics, making it difficult to compare benefits between studies.

Horticulture and bananas

- There was only one study specific to horticulture, but many of the principles, practices and outcomes are similar to those of other cropping systems. As with sugarcane, reducing the amount of fertiliser applied in horticulture and bananas reduces the risk of nutrient runoff and potentially, nitrous oxide emissions. Nitrous oxide emission rates linked to the amount of fertiliser applied have been compared among horticulture crops, with emissions varying across the plots. Increased monitoring will help to understand these potential co-benefits.

Grains

- There are potential improvements to soil health from crop rotations and fallow management, which reduce sediment erosion, break monoculture and reduce disease pressure.
- Grain cropping systems have the most long-term comprehensive datasets to assess the various co-benefits flowing from water quality improvement practices, and to understand the impacts of different climate cycles and climate change. However, these data do not necessarily align with different environmental benefits. For example, a number of soil carbon recordings are made at different depths from those required for credit by the Australian Carbon Credits Unit.

What are the key attributes of successful monitoring and evaluation programs to support coastal and marine water quality management, and what examples are there of innovative monitoring and evaluation frameworks, methods and approaches that are applicable to the Great Barrier Reef? [8.2]

Michelle Devlin, Amelia Wenger

The synthesis of the evidence for **Question 8.2** was based on 244 studies, undertaken in multiple locations and published between 1997 and 2023. The synthesis includes a *High* diversity of study types relating to monitoring and evaluation approaches (48% reviews, 32% observational, 15% experimental and 5% modelling) and has a *Moderate* confidence rating (based on *Moderate* consistency and *High* overall relevance of studies).

Summary findings relevant to policy or management action

Monitoring and evaluation of projects and programs of management actions to improve coastal and marine water quality is essential to assess environmental, social and management change, track progress towards program objectives and targets, and inform and improve current and future decision making. Monitoring is a critical element that involves the collection of data and information before, during and after implementation. Successful evaluation involves the systematic assessment of a project or program's design, its implementation, and outcomes to determine whether original objectives were achieved, identify lessons learned, deliver learning and demonstrate accountability. Across the studies included in this review, success was associated with the inclusion of holistic monitoring and evaluation approaches across multiple values, beneficiaries, and disciplines. Coastal and marine water quality monitoring and evaluation programs that have successfully driven positive change from management include those that adopt the system drivers, pressures, state, impact and responses (typically shortened to DPSIR) framework, recognise ecosystem services and marine natural capital, adopt multi-disciplinary frameworks and report on the interactions between environmental and human health, and support connections to people through the use of citizen science. The Reef 2050 Integrated Monitoring and Reporting Program and the Paddock to Reef Integrated Monitoring Modelling and Reporting programs are among the most comprehensive and integrated catchment to reef monitoring programs in the world. These programs recognise the links between drivers, pressures and state through the reporting of environmental, social and economic indicators. They also attempt to merge the complexities of the pressure-state response in user-friendly visual portals and report card formats, although the connections between environment and people, health and citizen science are not explored in great detail. Potential improvements drawn from the global evidence base include greater recognition and quantification of complex social, cultural, economic and environmental values and their interconnections, strengthening of multi-disciplinary frameworks to link to human health, and greater community engagement including direct participation in monitoring programs. A holistic ecosystem approach to Great Barrier Reef water quality management in the context of other major drivers such as climate change could also help to enhance the value of existing monitoring and evaluation programs.

Supporting points

- Successful monitoring and evaluation approaches were identified in this review from programs around the world that consider concurrent measures and indicators related to environment, economics and society. The primary integrated coastal and marine water quality monitoring and evaluation programs in the Great Barrier Reef are the Reef 2050 Integrated Monitoring and Reporting Program, the Paddock to Reef Integrated Monitoring Modelling and Reporting program and the monitoring and reporting conducted as part of the regional report card partnerships.

- Incorporation of natural capital into monitoring programs has been a successful way to bring together the system linkages between ecology, goods and services, and benefits to human wellbeing. Integrated approaches like the cross-sectoral and transdisciplinary One Health monitoring and evaluation framework, that emphasises the interconnections between the health of humans and ecosystems, are highly applicable to the Great Barrier Reef as a potential monitoring and evaluation approach. These holistic approaches also recognise the benefits of projects and programs that are relevant to a range of end-users.
- Monitoring and evaluation programs that contribute to positive changes through management actions include those that engage and represent the values of a diverse range of stakeholders that are impacted by the decision making. This is particularly true for local and regional stakeholders but can also extend to international partnerships, large conservation agencies and international frameworks.
- Greater engagement of the community in data collection, but also in evaluation and decision making, would enhance monitoring and evaluation programs for the Great Barrier Reef and potentially lead to greater acceptance and support of changed management arrangements.
- Measures of success across different scales (relevant to different audiences) from policy to community and multiple stakeholders are important and may deliver a more robust understanding of project and program outcomes.

Diver surveying coral reefs
Photo: R. Beeden.
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Appendix 1: Expert Groups for Consensus Process

Expert groups were designed to contain 7-9 experts, mostly the Lead Authors of Questions within each Theme, and some Contributors with relevant expertise.

Themes 1 and 2 – Values, condition and drivers of health of the Great Barrier Reef

Seven experts were included (all Lead Authors of SCS Questions) from two different institutions, James Cook University (JCU) and the Australian Institute of Marine Science (AIMS).

Question	Name	Role in SCS
1.1	Maxine Newlands (JCU)	Lead Author
1.2/1.3/2.1	Len McKenzie (JCU)	Lead Author
1.4	Aaron Davis (JCU)	Lead Author
1.4	Richard Pearson (JCU)	Lead Author
2.2	Katharina Fabricius (AIMS)	Lead Author
2.3	Stephen Lewis (JCU)	Lead Author
2.4	Sven Uthicke (AIMS)	Lead Author

Theme 3 - Sediments and particulate nutrients

Eight experts were included (six Lead Authors and two Contributors) from four different institutions, JCU, Griffith University (GU), University of Canberra (UC)/Independent and CSIRO. Contributors provided additional expertise in sediment distribution and delivery/transport processes (Z. Bainbridge) and wetlands (F. Adame).

Question	Name	Role in SCS
3.1	Stephen Lewis (JCU)	Lead Author
3.1	Zoe Bainbridge (JCU)	Contributor
3.2	Catherine Collier (JCU)	Lead Author
3.2	Fernanda Adame (GU)	Contributor
3.3	Ian Prosser (UC)	Lead Author
3.4	Scott Wilkinson (CSIRO)	Lead Author
3.5	Rebecca Bartley (CSIRO)	Lead Author
3.6	Andrew Brooks (GU)	Lead Author

Theme 4 - Dissolved nutrients

Nine experts were included (eight Lead Authors and one Contributor) from five different institutions, AIMS, JCU, GU, UC/Consultant and CSIRO, Alluvium and an independent consultant. An additional contributor provided expertise on the non-agricultural sections of Q4.6 and wetlands (T. Weber)

Question	Name	Role in SCS
4.1	Barbara Robson (AIMS)	Lead Author
4.2	Guillermo Diaz-Pulido (GU)	Lead Author
4.3	Ciemon F Caballes (JCU)	Lead Author
4.4	Ian Prosser (UC/Independent)	Lead Author
4.5	Michele Burford (GU)	Lead Author
4.6	Peter Thorburn (CSIRO)	Lead Author
4.6	Tony Weber (Alluvium)	Contributor
4.7, 4.9	Nathan Waltham (JCU)	Lead Author
4.8	Megan Star (Independent)	Lead Author

Themes 5 and 6 - Pesticides and other pollutants

Seven experts were included (four Lead Authors and three Contributors) from five different institutions, AIMS, JCU, UQ, and Macquarie University (MU), Queensland Government's DESI, and an independent consultant. Contributors provided additional expertise in marine and catchment pesticide risk (M. Warne), hydrology (M. Silburn), and economics of water quality management practices (M. Star).

Question	Name	Role in SCS
5.1	Andrew Negri (AIMS)	Lead Author
5.1	Michael St. J. Warne (UQ)	Contributor
5.2	Michelle Templeman (JCU)	Lead Author
5.3	Aaron Davis (JCU)	Lead Author
5.3	Mark Silburn (DESI)	Contributor
5.3	Megan Star (Independent)	Contributor
6.1	Anthony Chariton (MU)	Lead Author

Themes 7 and 8 - Human dimensions and emerging science

Eight experts were included (six Lead Authors and two Contributors), from three different institutions, UQ, CSIRO, Burnett Mary Regional NRM Group and four independent consultants. Contributors provided additional expertise in social dimensions of urban water management (T. Schultz) and Indigenous knowledge (C. Burns).

Question	Name	Role in SCS
7.1	Anthea Coggan (CSIRO)	Lead Author
7.2	Roy Murray-Prior (Independent)	Lead Author
7.2	Tracy Schultz (UQ)	Contributor
7.3	Tom Espinoza (Burnett Mary Regional Group)	Lead Author
7.3	Conway Burns (Butchulla Aboriginal Corporation)	Contributor
8.1	Iain Gordon (Independent)	Lead Author
8.1	Megan Star (Independent)	Lead Author
8.2	Michelle Devlin (Independent)	Lead Author

Appendix 2: Individuals involved in the 2022 Scientific Consensus Statement

The table below lists the individuals involved in different aspects of the design, development and delivery of the 2022 Scientific Consensus Statement including members of working groups, authors and contributors, and peer reviewers. To find out more about the different steps involved in developing the 2022 Scientific Consensus Statement, visit the Process section of the website.

Note: Two of the 63 peer reviewers for the syntheses of evidence requested anonymity so are not listed here.

Name	Role in the 2022 Scientific Consensus Statement
Aaron Davis	Lead Author (Q1.4 and Q5.3) Consensus Process (Summary and Conclusions)
Aaron Hawdon	Synthesis of evidence Reviewer
Abbie Rogers	Synthesis of evidence Reviewer
Aimee Brown	Co-author/Contributor (Q2.2, Q2.4, Q3.2 and Q4.1)
Al Songcuan	Co-author/Contributor (Q2.2)
Alana Grech	Co-author/Contributor (Q1.2/1.3/2.1)
Alistar Robertson	Synthesis of evidence Reviewer
Allan Dale	Synthesis of evidence Reviewer
Amanda Reichelt-Brushett	Synthesis of evidence Reviewer
Amelia Wenger	Co-author/Contributor (Q8.2)
Andrew Ash	Methods Working Group Consensus Process Working Group Reef Water Quality Independent Science Panel (ISP)
Andrew Brooks	Lead Author (Q3.6) Consensus Process (Summary and Conclusions)
Andrew Hughes	Synthesis of evidence Reviewer
Andrew Negri	Lead Author (Q5.1) Consensus Process (Summary and Conclusions)
Angela Arthington	Co-author/Contributor (Q4.2)
Angus Thompson	Co-author/Contributor (Q1.2/1.3/2.1)
Anne-Laurence Bibost	Co-author/Contributor (Q8.1)
Anthea Coggan	Lead Author (Q7.1) Consensus Process (Summary and Conclusions)
Anthony Boxshall	Consensus Workshop Facilitator
Anthony Chariton	Lead Author (Q6.1) Consensus Process (Summary and Conclusions)

Name	**Role in the 2022 Scientific Consensus Statement**
Barbara Robson	Lead Author (Q4.1) Co-author/Contributor (Q2.2 and Q2.4) Consensus Process (Summary and Conclusions)
Beth Fulton	Eminent Reviewer – Summary and Conclusions
Bianca Molinari	SCS Coordination Team Co-author/Contributor (Q2.4, Q4.7 and Q7.1)
Bill Venables	Reef Water Quality Independent Science Panel (ISP)
Bob Pressey	Evidence Synthesis Methods Reviewer
Bradley Moggridge	Synthesis of evidence Reviewer
Brandon Goeller	Synthesis of evidence Reviewer
Britta Schaffelke	Methods Working Group
Bronwyn Harch	Oversight and assurance of process, as Queensland's Chief Scientist (for part of the project)
Bruce Murray	Co-author/Contributor (Q3.4 and Q3.5)
Bruce Taylor	Synthesis of evidence Reviewer
Caleb Connolly	Co-author/Contributor (Q4.6)
Cameron Holley	Editor
Carla Wegscheidl	Co-author/Contributor (Q4.8)
Catalina Reyes-Nivia	Co-author/Contributor (Q4.2) Consensus Process (Summary and Conclusions)
Catherine Collier	Lead Author (Q3.2) Co-author/Contributor (Q2.2 and Q4.2) Consensus Process (Summary and Conclusions)
Catherine Lovelock	Co-author/Contributor (Q4.2 and Q4.9)
Catherine Neelamraju	Co-author/Contributor (Q5.1)
Cathy Foley	Oversight and assurance of process, as Australia's Chief Scientist
Christian Roth	Synthesis of evidence Reviewer
Ciemon F Caballes	Lead Author (Q4.3) Consensus Process (Summary and Conclusions)
Claudia Baldwin	Synthesis of evidence Reviewer
Colin Brown	Synthesis of evidence Reviewer
Conway Burns	Co-author/Contributor (Q7.3) Consensus Process (Summary and Conclusions)
Craig Johnson	Synthesis of evidence Reviewer
Craig Thornton	Synthesis of evidence Reviewer
Damien Burrows	Reef 2050 Independent Expert Panel (IEP)
Daniel Druckman	Consensus Process Working Group
Daren Harmel	Synthesis of evidence Reviewer
Darren Koppel	Synthesis of evidence Reviewer
David Obura	Synthesis of evidence Reviewer
Dayanthi Nugegoda	Synthesis of evidence Reviewer
Diane Jarvis	Co-author/Contributor (Q7.1)
Elizabeth Dinsdale	Synthesis of evidence Reviewer
Ella Schirru	Co-author/Contributor (Q7.1)

Name	Role in the 2022 Scientific Consensus Statement
Eva Abal	Reef Water Quality Independent Science Panel (ISP)
Fernanda Adame	Co-author/Contributor (Q3.2, Q4.2 and Q4.9) Consensus Process (Summary and Conclusions)
Francois Galgani	Synthesis of evidence Reviewer
Geoff MacFarlane	Editor
Gillian McCloskey	Co-author/Contributor (Q4.5)
Graeme Batley	Synthesis of evidence Reviewer
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Guillermo Diaz-Pulido	Lead Author (Q4.2) Co-author/Contributor (Q3.2) Consensus Process (Summary and Conclusions)
Hayley Kaminski	Co-author/Contributor (Q5.1)
Helene Marsh	Reef 2050 Independent Expert Panel (IEP)
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James Daley	Co-author/Contributor (Q3.6)
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Jenny Stauber	Reef Water Quality Independent Science Panel (ISP)
Jianyin (Leslie) Huang	Co-author/Contributor (Q4.5)
Jim Binney	Synthesis of evidence Reviewer
Joanne Burton	Co-author/Contributor (Q4.5)
Jochen Mueller	Synthesis of evidence Reviewer
John Bruno	Synthesis of evidence Reviewer
John Cook	Consensus Process Working Group
John Quiggin	Synthesis of evidence Reviewer
John Rolfe	Editor Reef Water Quality Independent Science Panel (ISP)
Joseph Guillaume	Synthesis of evidence Reviewer
Joy Zedler	Synthesis of evidence Reviewer
Kate Hodge	Theme Conceptual Models 2022 SCS website development
Katharina Fabricius	Lead Author (Q2.2) Co-author/Contributor (Q2.4 and Q3.2) Consensus Process (Summary and Conclusions)

Name	Role in the 2022 Scientific Consensus Statement
Katie Motson	Co-author/Contributor (Q4.7 and Q4.9)
Katie Sambrook	SCS Coordination Team Co-author/Contributor (Q4.3)
Keith Pembleton	Synthesis of evidence Reviewer
Kerrie Wilson	Consensus Process Working Group Methods Working Group Reef 2050 Independent Expert Panel (IEP) Note: Involvement in the project ended following appointment to Queensland Chief Scientist role.
Kerrylee Rogers	Synthesis of evidence Reviewer
Kirsten Verburg	Co-author/Contributor (Q4.6)
Laurence McCook	Synthesis of evidence Reviewer
Leanne Fernandes	Synthesis of evidence Reviewer
Len McKenzie	Lead Author (Q1.2/1.3/2.1) Consensus Process (Summary and Conclusions)
Malcolm McCulloch	Synthesis of evidence Reviewer
Mara Emmerling	Co-author/Contributor (Q7.1)
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Mark Stafford-Smith	Synthesis of evidence Reviewer
Matt Curnock	Synthesis of evidence Reviewer
Matthias Vanmaercke	Synthesis of evidence Reviewer
Maxine Newlands	Lead Author (Q1.1) Consensus Process (Summary and Conclusions)
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Michael Newham	Co-author/Contributor (Q4.5)
Michael Risk	Synthesis of evidence Reviewer
Michael St J Warne	Co-author/Contributor (Q5.1) Consensus Process (Summary and Conclusions)
Michele Burford	Lead Author (Q4.5) Consensus Process (Summary and Conclusions)
Michelle Devlin	Lead Author (Q8.2) Consensus Process (Summary and Conclusions)
Michelle Templeman	Lead Author (Q5.2) Consensus Process (Summary and Conclusions)
Mike Acreman	Evidence Synthesis Methods Reviewer
Mike Elliott	Synthesis of evidence Reviewer
Miles Furnas	Synthesis of evidence Reviewer

Name	Role in the 2022 Scientific Consensus Statement
Mohammad Bahadori	Co-author/Contributor (Q4.5)
Mohsen Kayal	Synthesis of evidence Reviewer
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Natalie Hejl	Co-author/Contributor (Q6.1)
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Name	Role in the 2022 Scientific Consensus Statement
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Steve Hamilton	Synthesis of evidence Reviewer
Stuart Bunn	Editor
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Sue Vink	Synthesis of evidence Reviewer
Suzanne Painting	Synthesis of evidence Reviewer
Suzie Greenhalgh	Synthesis of evidence Reviewer
Sven Uthicke	Lead Author (Q2.4) Co-author/Contributor (Q2.2 and Q4.1) Consensus Process (Summary and Conclusions)
Sydney Collett	Co-author/Contributor (Q7.3)
Syezlin Hasan	Co-author/Contributor (Q4.8)
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Tim Pietsch	Co-author/Contributor (Q3.6)
Tim Smith	Synthesis of evidence Reviewer
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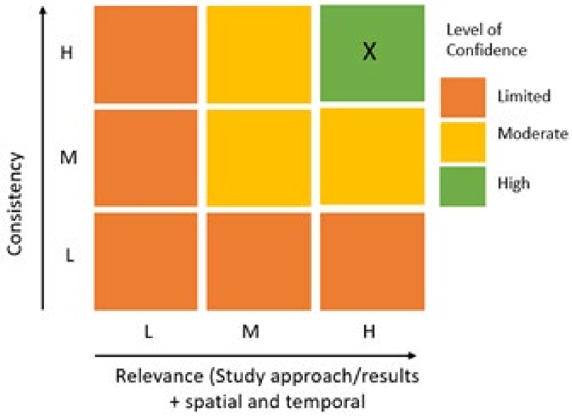
Tony Weber	Co-author/Contributor (Q4.6 and Q5.3) Consensus Process (Summary and Conclusions)
Tracy Schultz	Co-author/Contributor (Q7.2) Consensus Process (Summary and Conclusions) Project evaluation surveys
Trevor Ward	Consensus Process Working Group
Val Snow	Synthesis of evidence Reviewer
Vincent Pettigrove	Synthesis of evidence Reviewer
Virginia Marshall	Synthesis of evidence Reviewer
Wendy Craik	Eminent Reviewer – Summary and Conclusions
Zoe Bainbridge	Co-author/Contributor (Q2.3, Q3.1 and Q4.5) Consensus Process (Summary and Conclusions)

Appendix 3: Glossary

This glossary includes terms related to the convergence process and the synthesis of evidence, and a selection of terms that are widely used throughout this document. For a comprehensive glossary, visit the 2022 Scientific Consensus Statement website.

Bias	A preference for or against one idea, thing or person. In scientific research, bias is a systematic deviation between observations or interpretations of data and an accurate description of a phenomenon[1].
Body of evidence	All *evidence items* used to address a specific question.
Confidence in evidence	Level of trust in the *body of evidence* used to answer each question. For the 2022 Scientific Consensus Statement, the 'overall confidence' of a *body of evidence* was determined by the *relevance* of studies that constitute it and by the consistency of the *body of evidence*[2]. 
Consensus	In the context of the 2022 Scientific Consensus Statement, it was agreed that consensus is "A public statement on scientific knowledge on Great Barrier Reef water quality and ecosystem condition, drawn from multiple lines of evidence, that is generally agreed by a representative group of experts. The consensus does not necessarily imply unanimity."
Consistency of evidence	Level of convergence or agreement of findings between *evidence items*. This may be assessed as being consistent both in the direction and magnitude of effect.
Convergence	The process of moving towards a uniformity of view on the interpretation of the evidence.
Diversity of study types	The type of studies being used as sources of *evidence* i.e., observational, experimental, modelling, theoretical or conceptual, and secondary studies such as reviews or summaries. In the context of the 2022 Scientific Consensus Statement, also associated with 'multiple lines of evidence'[3].

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[1] How bias affects scientific research

[2] UK Department for International Development (2014) Assessing the Strength of Evidence: How to Note.

[3] Deriving guideline values using multiple lines of evidence

Evidence	Relevant information used in answering a question or hypothesis to determine its truth or validity.
Evidence item	An individual piece of *evidence* which may be a study, data or other documented evidence used to address a specific question.
Expert Group	Comprised of 7-9 Lead Authors & Contributors, refer to Appendix 1.
Great Barrier Reef catchment area	The natural drainage area upstream of a point that is generally on the coast. It generally refers to the 'hydrological' boundary and is the term used when referring to modelling in this document. There may be multiple catchments in a basin. In the context of the Great Barrier Reef, it refers to the 35 major drainage basins or the 6 natural resource management regions including Cape York, Wet Tropics, Burdekin, Mackay Whitsunday, Fitzroy and Burnett Mary.
Great Barrier Reef ecosystems	In the context of the Scientific Consensus Statement, it refers to marine (coral, seagrass, pelagic, benthic, and plankton communities), estuarine (estuaries, mangroves, saltmarsh), and freshwater (freshwater wetlands, floodplain wetlands) ecosystems within the Great Barrier Reef World Heritage Area.
Pollutant	Any contaminant above natural background which may or may not cause an adverse effect.
Quantity of evidence	A relative assessment of the size of the *body of evidence* used to address each Scientific Consensus Statement question based on the total number of *evidence items*. While it is not possible to quantify the number of studies that is adequate for answering specific questions, authors had to use their topic expertise to suggest whether the number of studies used is 'high', 'moderate' or 'low'.
Rapid review	A form of knowledge synthesis that follows the formal *Systematic Review* process (defined below), but parts of the process are simplified or omitted to produce information within specified resources, in a timely manner and to meet specific user needs[4].
Relevance of evidence	The extent to which the *evidence* is relevant to the question being asked. Relevance is often referred to as the 'external validity' of the study (i.e., whether it can be generalised from the original study to address the review question). For the 2022 Scientific Consensus Statement two aspects of relevance were assessed: 1) the relevance of the study approach and results to the question and 2) the spatial and temporal relevance to the question.
Single Draft Text Procedure	Effective way to facilitate creative, joint problem-solving whenever there are multiple stakeholders whose input to a decision or plan needs to be considered or whose support may be needed for implementation. This method places all drafting responsibility in the hands of a single drafter or drafting team. All other parties are involved in the process as critics who provide input. In this way, the inefficiencies of working with multiple drafts are minimised. Parties work together to iterate and improve a single, shared working draft. Parties are asked to note how and why the current draft version of the agreement is not acceptable or could be improved (in terms of technical content only, avoiding wordsmithing). The drafting team iterates between soliciting criticism and revising the draft until the predetermined maximum number of agreed iterations for making a decision is reached. At this point, the drafting team presents all parties with a final draft for acceptance[5,6].

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[4] Khangura S, Konnyu K, Cushman R, Grimshaw J, Moher D (2012) Evidence summaries: the evolution of a rapid review approach. Systematic Reviews, 1(1), 1–9.

[5] Overview of the one-text procedure

[6] Single-text negotiation

Strength of evidence	The use of a combination of information from several independent sources to give sufficient evidence to fulfil an information requirement. It depends on factors such as the quantity and quality of the data, consistency of results (including replicability and multiple lines of evidence), robustness, reliability, and relevance of the information[7].
Synthesis	Synthesis occurs when disparate data, concepts, or theories are integrated in ways that yield new knowledge, insights, or explanations[8]. Synthesis creates emergent knowledge in which the whole is greater than the sum of the parts. By engaging experts with multiple perspectives, synthesis is capable of vetting a vast body of information for use by other disciplines or by society in general[9].
Uncertainty	Refers to situations involving limited knowledge or unknown information where it is not possible to clearly describe the existing state, the processes occurring, a future outcome, or more than one possible outcome.
Water Quality	The physical, chemical, and biological characteristics of water and the measure of its condition relative to the requirements for one or more biotic species and/or to any human need or purpose[10].
Waterbodies	Marine waterbodies: Five distinct water bodies are defined for the Great Barrier Reef under the Great Barrier Reef Water Quality Guidelines 2010 – inshore [enclosed coastal + open coastal], midshelf, offshore and the Coral Sea. These are important context for the Scientific Consensus Statement when describing the extent of influence of water quality on the Great Barrier Reef.

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[7] Weight of evidence

[8] Pickett STA, Kolasa J, Jones CG (2007) Ecological understanding: The nature of theory and the theory of nature. 2nd ed. Academic Press.

[9] Carpenter SR, Armbrust EV, Arzberger PW, Chapin FS, Elser JJ, Hackett EJ, Ives AR, Kareiva PM, Leibold MA, Lundberg P, Mangel M, Merchant N, Murdoch WW, Palmer MA, Peters DPC, Pickett STA, Smith KK, Wall DH, Zimmerman AS (2009) Accelerate synthesis in ecology and environmental sciences, BioScience, 59 (8), 699–701.

[10] Australian and New Zealand Guidelines for fresh & marine water quality glossary of terms

Mulgrave-Russell flooded landscape, Far North Queensland
Photo: Dieter Tracey

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