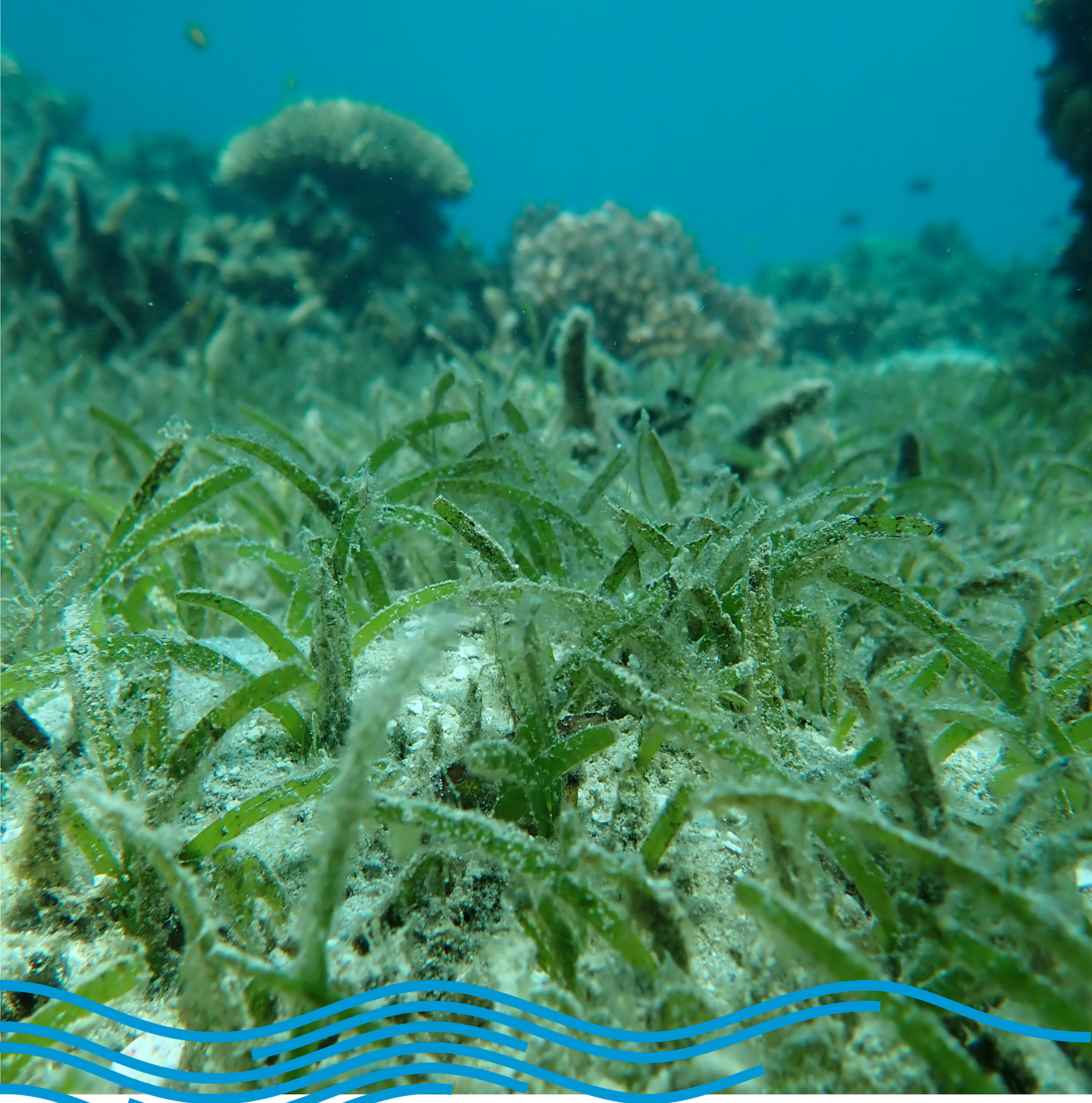

2022 Scientific Consensus Statement

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

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Cover image credit: Dieter Tracey.

Explanatory Notes for readers of the 2022 SCS Syntheses of Evidence

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

What is the Scientific Consensus Statement?

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

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

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

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

Method used to address the 2022 SCS Questions

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

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

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

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

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

Two methods were developed for the 2022 SCS:

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

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

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

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

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

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

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

Guidance for using the synthesis of evidence

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

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

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

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

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

Peer Review and Quality Assurance

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

Contents

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Executive Summary

Question

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

Background

The extent and condition of Great Barrier Reef (GBR) ecosystems are fundamental to the maintenance of the Outstanding Universal Value that underpin the GBR World Heritage Area (GBRWHA). However, the GBR marine ecosystems and the associated catchment area are part of a dynamic, interconnected system. Providing an up-to-date review of the state of knowledge relating to the conditions and trends of key GBR marine, estuarine and freshwater ecosystems, including current knowledge on threatening activities leading to pressures and impacts on these ecosystems, is essential to inform management efforts and policy.

Methods

- A formal Rapid Review approach was used for the 2022 Scientific Consensus Statement (SCS) synthesis of evidence. Rapid Reviews are a systematic review with a simplification or omission of some steps to accommodate the time and resources available[5]. For the SCS, this applies to the search effort, quality appraisal of evidence and the amount of data extracted. The process has well-defined steps enabling fit-for-purpose evidence to be searched, retrieved, assessed and synthesised into final products to inform policy. For this question, an Evidence Summary method was used.
- Search locations were Web of Science, Scopus, Google Scholar and Wetland*Info*.
- Main source of evidence: Studies derived within the GBR, as evidence from outside the GBR has very limited relevance to this question.
- From the initial keyword search, 1,746 studies were identified through online searches for peer reviewed and published literature. Five studies were added manually from citations in online search publications and personal collections, which represented <1% of the total evidence. In total, 100 studies were eligible for inclusion in the synthesis of evidence. No studies were unobtainable.

Method limitations and caveats to using this Evidence Summary

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

- Only studies written in English were included.
- Only two academic databases were searched.
- Only GBR derived studies were included. The review was restricted to peer reviewed journal publications as well as publications of the major government programs.
- Only studies published from 2016 onwards were included.

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

Key Findings

Summary of evidence to 2022

The literature was searched for peer reviewed publications and reports that reported extent, current condition or identified threats to GBR ecosystems (coral, seagrass, pelagic, benthic + plankton

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

communities, estuaries, mangroves, saltmarsh, freshwater wetlands, floodplain wetlands). In total, 100 eligible evidence items/studies were identified, all of which were published from 2016 onwards. Most studies (79%) were of an observational or modelled nature, and the majority (67%) of studies had a GBR wide scope.

Relatively few studies reported on the current condition (9%) or trend (16%) of ecosystems and less than half (41%) of those were observational. The majority (67%) of studies focused on coral reef ecosystems, while the remainder focused on the marine environment overall (13%), followed by seagrass meadows, estuaries and overall wetlands with one publication each. When reporting condition, the Wet Tropics, Burdekin and Mackay Whitsunday Natural Resource Management (NRM) regions received greater attention.

Overall, there is a strong body of evidence on threats to GBR ecosystems (collectively), covering multiple lines of evidence. The greatest proportion of studies focused on identifying/perceiving water quality pollution (39% of studies), closely followed by climate change (37%), cumulative impacts (19%) and the coral eating crown-of-thorns starfish (COTS, 6%).

Apart from overall water quality, the most reported water quality related threats were pesticides (26% of studies), followed by nutrients (15%), sediments (11%) and others (7%). Of the studies reporting on climate change threats, the majority identified rising water temperatures as the major stressor (77%), while the remaining studies reported on extreme events (12%) and ocean acidification (12%). The majority of studies identified human induced climate change as the greatest threat to GBR ecosystems. The ability/capacity of ecosystems (i.e., resilience) to resist and recover from damage associated with extreme climatic events is being undermined by poor water quality, which is primarily a consequence of land-based runoff of sediments, nutrients, pesticides and other pollutants. Marine ecosystems considered to be at greatest risk overall are those located in close proximity to the mainland.

Key conclusions from the body of evidence are that:

- The ability of GBR ecosystems to resist pressures, and their capacity to recover during periods of low disturbance, is affected by the cumulative impacts of climate change in concert with local disturbances (e.g., tropical cyclones) and pressures, such as land-based runoff.
- There are 24,094 km^2 of coral reefs mapped within the GBR.
- The condition of shallow coral reefs of the inshore GBR (Wet Tropics to Fitzroy region) has marginally declined since 2017 and between 2020 and 2021 was still rated Poor[6], although there were differences depending on the region.
- Hard coral cover on shallow midshelf and offshore reefs 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 (COTS) outbreaks between 2016 and 2019[7].
- The primary threats to corals throughout the GBR are rising sea surface temperature leading to marine heatwaves, tropical cyclones, outbreaks of COTS 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 km^2 of the GBR seafloor.
- Inshore seagrass meadows across the GBR declined from Moderate abundance and resilience in 2017 to Poor in 2020, and while overall condition improved in 2021 (to Moderate), there were continuing declines in the Fitzroy and Burnett Mary Regions. This was primarily a consequence of above-average discharges from some rivers and disturbance from tropical cyclones.

[6] Reef Water Quality Report Card 2020
[7] AIMS Long Term Monitoring Program

- The primary threats to GBR seagrass meadows are tropical cyclones, land-based runoff (particularly fine sediments and pesticides), and thermal stress from rising sea surface temperatures.
- Other components of the GBR 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.
- In general, dugongs and turtle populations of the GBR are in a Poor condition and in decline, although some populations are recovering (e.g., southern green turtle)[8].
- The greatest threats to dugong and turtle 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 GBR estuaries, there are 2,188 km^2 of mangroves and 1,757 km^2 of salt flats and saltmarshes. Apart from minor localised losses, they are stable and in Good condition[8]. The primary threats to mangroves and saltmarshes are climate change related, including extreme events such as storms, extreme sea-level variations, and heatwaves.
- In the GBR catchment area, the most recent assessment of wetland extent through the Paddock to Reef Program in 2017 reported 15,556 km^2 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 the extent of palustrine wetlands in the Wet Tropics and Mackay Whitsunday regions of ~49% and ~44% respectively, compared to pre-development estimates).
- The primary threats to GBR wetlands are historic wetland loss due to landscape modification including drainage and infilling, poor water quality, invasive species, changes in hydrological connectivity, and increasing temperature and salinity from climate change.
- In 2022 when this review was prepared, there was no new data on current extent of natural and near-natural wetlands since the 2017 SCS, as changes in wetland extent are assessed every 4-5 years. The next update is expected to be reported in 2024.

Recent findings 2016-2022

The strongest themes in the recent body of evidence are:

- A greater level of recognition of cross-shelf variation in coral assemblages, the influences of environmental conditions and threatening pressures (elevated temperatures), and the importance of constraints such as successful recruitment (particularly following bleaching events). This has been supported by improved reporting of inshore condition with the adoption of process-based indicators for coral recruitment (e.g., juvenile coral density), recovery rates (e.g., hard coral cover change), and competition (e.g., macroalgae cover) in the Marine Monitoring Program (MMP).
- Better understanding of seagrass ecosystem resilience, and the adoption of resilience indicators for reporting seagrass condition particularly in the Marine Monitoring Program reporting.
- Improved modelling on the effects of land-based runoff (current and future) on seagrass ecosystem condition. There is now closer agreement between modelling and observations which strengthens the confidence about sources of land-based runoff and management targets.
- Improved understanding of how weather-related events such as cyclones, extreme sea level variation and heatwaves can cause significant impacts to mangroves.

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[8] Great Barrier Reef Outlook Report 2019
[9] Reef Water Quality Report Card 2020

Significance for policy, practice, and research

Based on the number of studies across GBR ecosystems that identified ecosystem condition was worse when climate change pressures were coupled with additional water quality pressures, it is highly likely that continuation of the key management approaches in the Reef 2050 Long-Term Sustainability Plan can improve the resilience of GBR ecosystems. It therefore follows, that many of the issues raised in previous Scientific Consensus Statements remain relevant, but the body of evidence supporting them has increased. The significance of the findings identified in this current review for policy, practice and research include:

- Limited information exists on the resilience of estuarine ecosystems, including mangroves and saltmarshes, because their condition is not systematically monitored.
- As reporting on ecosystem condition and resilience has improved, there is now a need to quantify tolerance thresholds and tipping points in key freshwater floodplain, seagrass and coral reef species and communities in response to single, multiple and cumulative pressures.
- Ecological aspects of recovery in seagrass have been documented through monitoring, but recovery processes (e.g., triggers for seed germination, seed viability, seed bank thresholds, sediment conditions, species interactions) remain critical information gaps that preclude accurate prediction of recovery rates for GBR seagrass ecosystems.
- Recent research provides a greater evidence base on the response of resilience-related attributes to pressures such as increased temperatures and reduced water quality. However, there is a greater need to improve understanding of recovery processes of coral reefs and seagrass meadows as management focuses more on restorative actions.

Key uncertainties and/or limitations

Factors that lead to uncertainties or limitations of the evidence include:

- GBR wetland extent and condition is only assessed every 4-5 years. The last assessment was reported in the 2017 SCS. The next assessment is due for completion in mid-late 2023, therefore current wetland extent and condition is outdated.
- Deepwater seagrass habitats are not monitored, and therefore GBR seagrass condition is restricted to the inshore seagrass habitats only.
- Midshelf and offshore coral monitoring by the AIMS Long-Term Monitoring Program (LTMP) reports coral cover but not overall coral condition for the regions assessed. This limits GBR coral condition assessments to the shallow inshore coral monitoring reported through the GBR Marine Monitoring Program.
- Several eligible studies in the evidence base use results from the LTMP, and as a consequence there may be some double counting of evidence due to the inclusion of secondary analyses of these data. This has not been quantified.
- There are no data to assess temporal trends in inshore coral condition in the Cape York and Burnett Mary, indicating the need for implementation of monitoring in these regions.

Evidence appraisal

The overall confidence in the body of evidence was rated as High. This was due to a number of factors, including:

- The relevance of the study approach and study results was High overall, as knowledge about the extent and condition of GBR ecosystems, and threats to its health is a mature science.
- The relevance or generalisability of the spatial scale of studies was High, as the spatial scale of most studies cover the entire GBR, or at least several catchments/NRM regions.
- Relevance or generalisability of the temporal scale of studies was also High overall, with most studies covering multiple years, wet seasons, and/or various bleaching events. There were a few exceptions, (n=6 studies) that had a more limited temporal scale (i.e., single observation, or only one year or wet season of data).

1. Background

The Great Barrier Reef (GBR) is recognised as the world's largest coral reef system, covering an area of about 350,000 km^2 and spanning some 14° of latitude from the tip of Cape York Peninsula to just north of Hervey Bay (Figure 1). The GBR is one of the most prominent icons of Australia and was listed on the World Heritage Register in 1981. Underpinning the Outstanding Universal Values of the GBR is not only its beauty and extent, but the condition of its natural features, including ecosystems, habitats and species. Although the GBR's natural beauty and natural phenomena endure, increasing pressures are threatening the GBR's resilience, and signs of deterioration are becoming apparent.

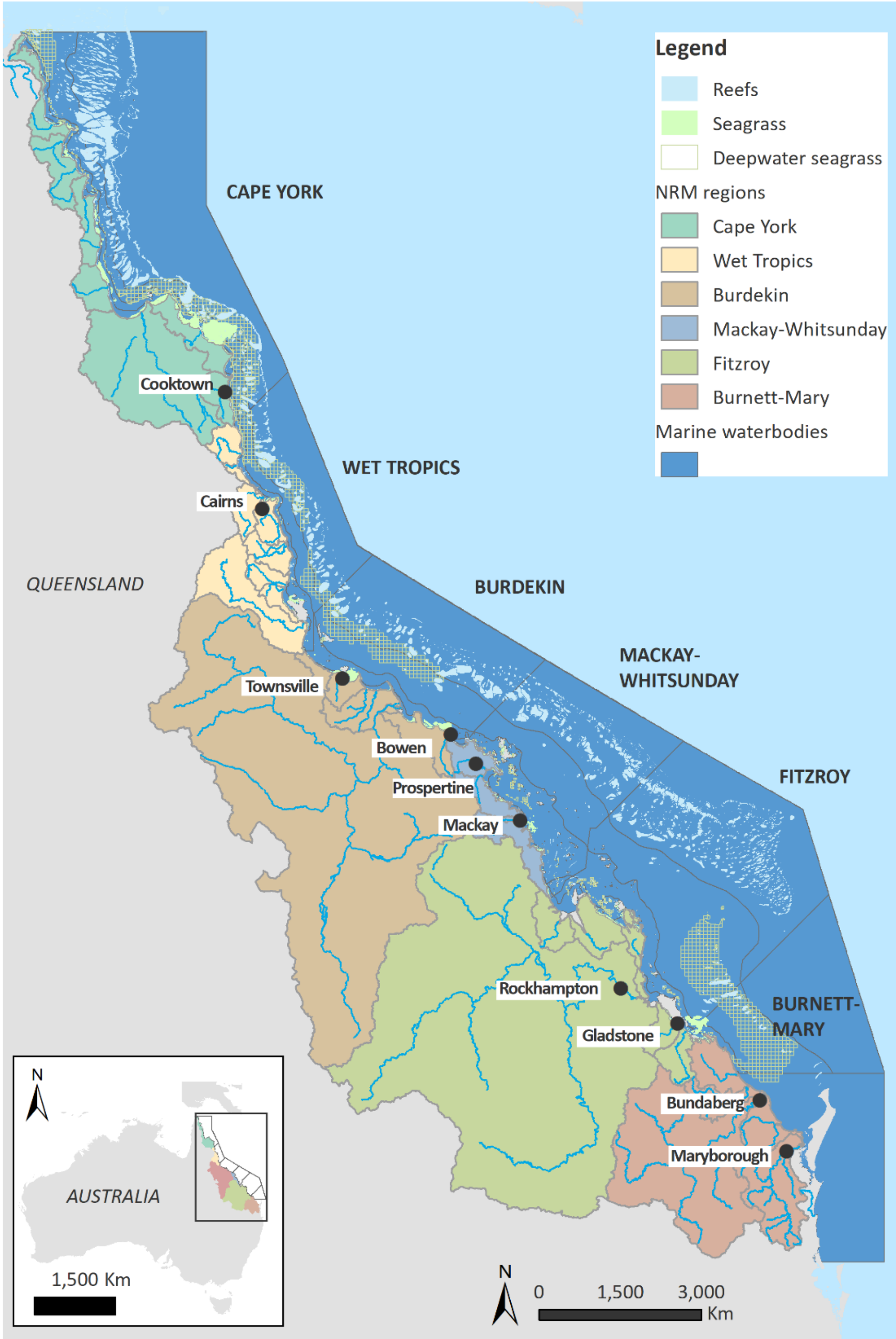


Figure 1. Map showing major Queensland Rivers and cities, GBR Natural Resource Management (NRM) regions and marine waterbodies, and the GBR coral reef and seagrass (deepwater seagrass shown as modelled grids) ecosystems.

A major component of the overarching consensus in the 2017 Scientific Consensus Statement (SCS) was that “key GBR ecosystems continue to be in poor condition. This was largely due to the collective impact of land runoff associated with past and ongoing catchment development, coastal development activities, extreme weather events and climate change impacts such as coral bleaching events” (Waterhouse et al., 2017). The aim of this review was to consider the recent evidence base in regard to any changes in the condition of GBR ecosystems since 2017 and identify the primary threats to their health.

1.1 Question

Primary question	**Q1.2/1.3/2.1** What is the extent and condition of Great Barrier Reef ecosystems, and what are the primary threats to their health?

The question covers the extent and condition (i.e., current, but also any significant changes documented in the evidence) of Great Barrier Reef ecosystems, including marine (coral, seagrass, pelagic, benthic and planktonic communities), estuarine (estuaries, mangroves, saltmarshes) and freshwater wetlands. The first part of the question highlights the importance of spatial aspects (position across the continental shelf, latitude), and captures significant trends in the condition of GBR ecosystems (linking to Question 1.4, Davis & Pearson, this SCS which discusses connections within and between the catchment and the GBR).

The second part of the question sets the context for the relative threats, drawing on the latest evidence on climate change, water quality and direct use, among others. Where possible, current threatening activities are discussed separately from future threats to assist in policy decisions and urgency. The relative risks for different pollutants are also discussed where the evidence was available. This part of the question aims to introduce the primary pollutants (fine sediments, nutrients, pesticides and other pollutants) and knowledge regarding the extent of the water quality influence (i.e., predominantly, inshore focus) to provide context for the scope of other SCS questions.

1.2 Conceptual diagram

A conceptual diagram (Figure 2) is provided to give context to the narrative synthesis (Section 4.1), illustrating the current and potential primary threats (shown with red text, with main impacting factor) which influence the health (condition and extent) of the GBR’s ecosystems (white boxes with black text, with examples of stressors). The primary pressures include climate change, water quality (i.e., land-based runoff), coastal development and direct use. Each of these pressures influence the health of each GBR ecosystem, albeit to different degrees. For example, climate change influences all ecosystems, however, it has a greater influence on offshore coral, estuarine and mangrove ecosystems than other ecosystems. Similarly, poor water quality, resulting from land-based runoff, has greater influence on those ecosystems downstream or adjacent (i.e., inshore) to modified catchments and populated areas.

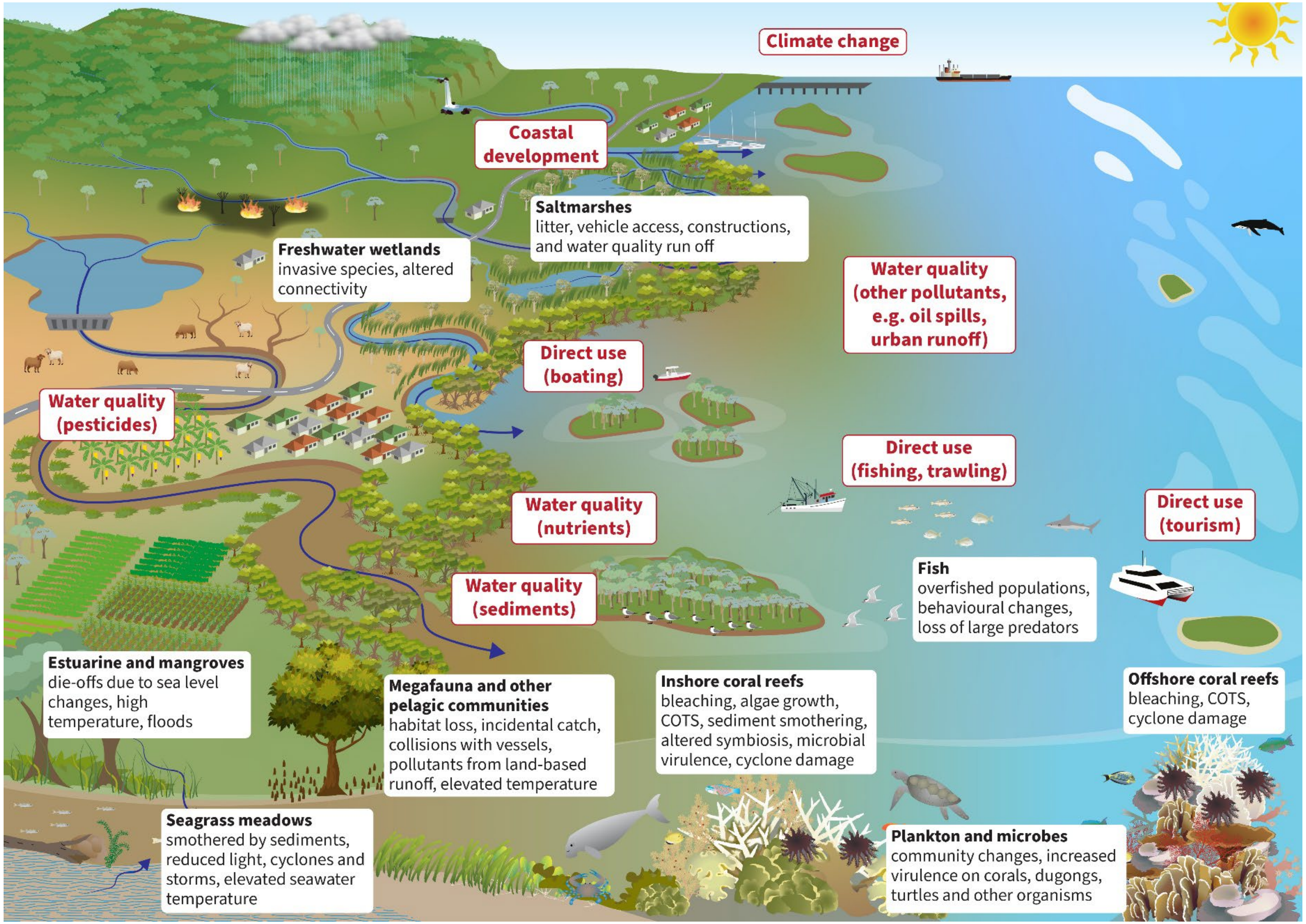


Figure 2. Conceptual model for Q1.2/1.3/2.1 on the extent and condition of Great Barrier Reef ecosystems (white boxes with black text, with examples of stressors), and the primary threats to their health (red text, with main impacting factor).

1.3 Links to other questions

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

Links to other related questions	*Link to the ecological values* **Q1.1** What are the socio-ecological, cultural, economic, and intrinsic values of the Great Barrier Reef? *Link to the connectivity of ecological processes* **Q1.4** 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? *Link to climate change and cumulative pressures* **Q2.2** What are the current and predicted impacts of climate change on Great Barrier Reef ecosystems (including spatial and temporal distribution of impacts)? **Q2.4** How do water quality and climate change interact to influence the health and resilience of Great Barrier Reef ecosystems? *Link to natural variability for sediments and nutrients* **Q3.1** What are the spatial and temporal distributions of terrigenous sediments and associated indicators within the Great Barrier Reef? **Q4.1** What is the spatial and temporal distribution of nutrients and associated indicators within the Great Barrier Reef? *Link to impacts of pollutants on GBR ecosystems* **Q3.2** 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? **Q4.2** What are the measured impacts of nutrients on Great Barrier Reef ecosystems, what are the mechanism(s) for those impacts and where is there evidence of this occurring in the Great Barrier Reef? **Q5.1** 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? **Q6.1** What is the spatial and temporal distribution and risk of other pollutants in Great Barrier Reef ecosystems, and what are the primary sources? *Link to biophysical drivers for anthropogenic sediments and nutrients delivery* **Q3.4** What are the primary biophysical drivers of anthropogenic sediment and particulate nutrient export to the Great Barrier Reef and how have these drivers changed over time? **Q4.5** What are the primary biophysical drivers of anthropogenic dissolved nutrient export to the Great Barrier Reef and how have these drivers changed over time?

2. Method

A formal Rapid Review approach was used for the 2022 Scientific Consensus Statement (SCS) synthesis of evidence. Rapid Reviews are a systematic review with a simplification or omission of some steps to accommodate the time and resources available[10]. For the SCS, this applies to the search effort, quality appraisal of evidence and the amount of data extracted. The process has well-defined steps enabling fit-for-purpose evidence to be searched, retrieved, assessed and synthesised into final products to inform policy. For this question, an Evidence Summary method was used.

2.1 Primary question elements and description

The primary question is: ***What is the extent and condition of Great Barrier Reef ecosystems, and what are the primary threats to their health?***

S/PICO frameworks (Subject/Population, Exposure/Intervention, Comparator, Outcome) can be used to break down the different elements of a question and help to define and refine the search process. The S/PICO structure is the most commonly used structure in formal evidence synthesis methods[11] but other variations are also available.

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

Table 1. Description of question elements for Question 1.2/1.3/2.1.

Question S/PICO elements	Question term	Description
Subject/Population	GBR ecosystems	As per definitions. The main focus are marine (coral, seagrass, pelagic, benthic + plankton communities), estuarine (estuaries, mangroves, saltmarsh), and freshwater (freshwater wetlands, floodplain wetlands) ecosystems within the Great Barrier Reef World Heritage Area (GBRWHA).
Intervention, exposure & qualifiers	Threats	A threat is anything (i.e., driver, activity, pressure or stressor) which has a potential adverse impact on the health of GBR ecosystems (e.g., climate change, land-based runoff, coastal development, or direct use). A threatening process is a sequence of events or activities that have the potential to cause an impact (e.g., land use change causing poor water quality through land-based runoff). A driver (driving force) is a natural or anthropogenic "superior complex phenomena" that governs the

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

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

		nature of ecosystem change (Oesterwind et al., 2016) (e.g., climate, economic growth). A pressure is the result of a driver-initiated mechanism (human activity/natural process) causing an effect on any part of an ecosystem that may alter the environmental state (Oesterwind et al., 2016), i.e., a specific source or cause of an environmental threat (e.g., climate change or land-based runoff). A stressor is any external abiotic or biotic factor that moves a biological system out of its normal operating range (Segner et al., 2014) (e.g., reduced available light for photosynthesis).
Comparator	Temporal	Current extent and condition of GBR ecosystems (2017-2022), but also any significant changes reported in the past (<2017).
Outcome & outcome qualifiers	Extent Condition Ecosystem Health	Current dimension (ha or km^2) of GBR ecosystems in the GBRWHA. The function of GBR ecosystems and their capacity to deliver goods and benefits (aka services). An ecological system is healthy and free from distress syndrome if it is stable and sustainable, i.e., if it is active and maintains its organisation and autonomy over time, and is resilient to stress (Costanza, 1992)[12].

Table 2. Definitions for terms used in Question 1.2/1.3/2.1.

Definitions	
Climate change	Climate change refers to long-term shifts in temperatures and weather patterns, mostly driven by human activities (i.e., burning fossil fuels like coal, oil and gas) since the 1800s. Climate change-related potential pressures in the context of the SCS include: increasing temperature, intensity and frequency of heatwaves, ocean acidification, altered extreme rainfall events (drought / floods), rising sea levels, and frequency and strength of tropical cyclones.
Condition	The state of GBR ecosystems and their capacity to deliver goods and benefits (aka services).
Current	Looking at the past five years, since the previous SCS published in 2017.
Drivers	A superior complex phenomena governing the direction of the ecosystem change, which could be both of human and natural origin (Oesterwind et al., 2016). Drivers can be anthropogenic (based on economic, social and political fundamental needs) or natural (majorly independent from anthropogenic causes).
Ecological function	The natural processes, products, or benefits that GBR ecosystems provide or perform.

[12] Costanza R (1992) Toward an operational definition of ecosystem health. In R Costanza, B Norton & B Haskell (Eds.), *Ecosystem health: new goals for environmental management* (pp. 239– 256). Island Press, Washington DC.

Extent	Current dimension (ha or km^2) of GBR ecosystems in the GBRWHA, including proportion within inshore, mid, and outer reef areas (or using the four main water bodies: enclosed coastal, open coastal, midshelf and offshore).
GBR ecosystems	Marine (coral, seagrass, pelagic, benthic + plankton communities), estuarine (estuaries, mangroves, saltmarsh), and freshwater (freshwater wetlands, floodplain wetlands) ecosystems within the Great Barrier Reef World Heritage Area.
Ecosystem health	An ecological system is healthy and free from distress syndrome if it is stable and sustainable, i.e., if it is active and maintains its organisation and autonomy over time, and is resilient to stress (Costanza, 1992).
Primary threat	A driver, activity, pressure or stressor which affects the majority of ecosystems and communities over a greater area and more frequently than other threats.
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.
Waterbody (marine)	Waterbodies are based on marine water types within which water quality is reasonably consistent, and reef biota distributions and geomorphology (i.e., shelf width) are similar (Beaman, 2010; De'ath & Fabricius, 2008; DEHP, 2009). • Inshore: Broadly corresponds to enclosed and open coastal water bodies including seaward part of estuaries, adjoining intertidal areas and habitats adjacent to the coast, and inshore from midshelf reefs. • Midshelf: Refers to midshelf waters and reefs between inshore areas and the outer shelf (offshore). • Offshore: Refers to waters east of the midshelf to the GBR Marine Park boundary, including reefs and habitats along the edge of the continental shelf and Coral Sea.

2.2 Search and eligibility

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

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

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

a) Search locations

Searches were performed in:

- Web of Science (WoS) core collection
- Scopus
- Google Scholar
- Wetland*Info* database

b) Search terms

Table 3 shows a list of the search terms used to conduct the online searches. The first set of search terms identified studies from the GBR and most GBR ecosystems. The next level of search terms was used to identify studies relating to the extent and condition of GBR ecosystems, followed by pressures and stressors affecting their current and future state.

Table 3. Search terms for S/PICO elements of Question 1.2/1.3/2.1.

Question element	Search terms
Subject/Population	'Great Barrier Reef', GBR, including freshwater wetlands
Exposure or Intervention	Threats, pressures, climate change, sea surface temperature, seawater temperature, SST, warming, thermal, cyclone, acidification, pCO*, CO2, sea level rise, water temperature, coastal development, agriculture, urban, aquaculture, port development, water quality, sediment, nutrient, pesticide, pollutants, light, irradiance, turbidity, direct use, fishing, boating, tourism
Comparator	Temporal, spatial, trend, pattern, region, cross-shelf, inshore, offshore, outer reef
Outcome	Extent, dimension, area, condition, 'potential capacity', health, state.

c) Search strings

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

Table 4. Search strings used for electronic searches for Question 1.2/1.3/2.1.

Search strings
Web of Science: TS = (("Great Barrier Reef" OR GBR) AND (coral* OR seagrass* OR mangrove* OR fish* OR "freshwater wetland" OR plankton* OR estuary* OR saltmarsh OR floodplain OR inshore OR offshore OR "outer reef") AND (condition OR health OR state OR stress OR threat OR pressure)) **989 (2017-2022)**
Scopus: TITLE-ABS-KEY (("Great Barrier Reef" OR gbr) AND (coral OR seagrass OR mangrove OR fish OR "freshwater wetland" OR plankton OR estuary OR saltmarsh OR floodplain OR inshore OR offshore OR "outer reef") AND (condition OR health OR state OR stress OR threat OR pressure)) AND PUBYEAR > 2016 **507 (2017-2022)**
Google Scholar "Great Barrier Reef" AND (condition OR health OR state OR stress OR threat OR pressure OR monitoring OR outlook) **2017-2022 – 23,200**

d) Inclusion and exclusion criteria

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

Table 5. Inclusion and exclusion criteria for Question 1.2/1.3/2.1 applied to the search returns.

Question element	Inclusion	Exclusion
Subject/Population	Great Barrier Reef	Studies outside of the GBR (or broader focus; not specific to the GBR).
Exposure or Intervention	Primary threats	Minor threats (e.g., physical damage to coral reefs by scuba divers and tourists if visitor numbers are low).
Outcome	Most up-to-date monitoring reports.	Monitoring or other reports superseded by more recent publications/data.
Language	English	Any other language
Study type	High-level studies and Review articles if possible, studies at the ecosystem level, field studies, monitoring reports, modelling studies, future scenarios or projections (for threats).	• Single-species studies, limited in scope (spatial and temporal). • Experimental or laboratory studies. • Non-peer reviewed, comments or reports or conference papers. • Papers beyond a paywall or inaccessible. • Paleontological studies (not current extent or condition). • Restoration/adaptation studies. • Studies with a focus on planning/ management. • Future scenarios or projections (for health and status). • Studies on values (more relevant to Question 1.1, Newlands & Olayioye., this SCS). • Studies on connectivity (more relevant to Question 1.4, Davis & Pearson, this SCS).

3. Search Results

A total of 1,746 studies were identified through online searches for peer reviewed and published literature (Table 6). Fifteen studies were identified manually through expert contact and personal collections, which represented <1% of the total evidence. One hundred studies were eligible for inclusion in the synthesis of evidence (Figure 3). No studies were unobtainable.

The only evidence base for the most recent condition of offshore coral on the GBR was the annual reporting of the Long-Term Monitoring Program (LTMP) of the Australian Institute of Marine Science (AIMS). The level of peer review of the annual web-based reporting of the status and trends of reef health, however, is unclear. In the authors' professional opinion, the overall confidence in the LTMP reporting is considered High and qualifies for inclusion in the body of evidence, based on the following:

- The LTMP is one of the world's longest running and most comprehensive coral reef monitoring programs, having documented the status and trends of GBR coral and reef fish assemblages since 1985 (i.e., mature methodology).
- The LTMP uses standard operating procedures to determine reef condition and provide critical and reliable information about the status of the GBR (Emslie et al., 2020) (i.e., peer reviewed methodology).
- The data reported by the LTMP underpins a large body of peer reviewed literature, which are the primary data reported in the current review by six of the eligible studies including: Castro-Sanguino et al., 2021; Cheal et al., 2017; Jonker et al., 2019; MacNeil et al., 2019; Mellin et al., 2019a; 2019b; Smith et al., 2020.
- The 2021-22 period reported on the condition of 87 reefs surveyed between August 2021 and May 2022, spread from the northern to the southern reaches of the GBR (AIMS, 2022) (i.e., representative).
- AIMS is an Australian Government statutory authority established in 1972, and thereby LTMP outputs should qualify as a publication from a major government program.

The evidence base for the most recent condition of marine pelagic, benthic and planktonic communities was similarly limited, with condition only provided from the 2019 GBR Outlook Report (GBRMPA, 2019).

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

Date (d/m/y)	Search strings	Sources	
A) Academic databases		Web of Science	Scopus
12/01/2023	*("Great Barrier Reef" OR GBR) AND (coral* OR seagrass* OR mangrove* OR fish* OR "freshwater wetland" OR plankton* OR estuary* OR saltmarsh OR floodplain OR inshore OR offshore OR "outer reef") AND (condition OR health OR state OR stress OR threat OR pressure)* *(Date restriction: 2017-2022)*	*126 of 989*	*106 (89 duplicates) of 507*
B) Search engine (Google Scholar)			
23/01/2023	*"Great Barrier Reef" AND (condition OR health OR state OR stress OR threat OR pressure OR monitoring OR outlook)* *(Date restriction: 2017-2022) (selection of new items only)*	*29 of 23,200 (first 250)*	

	Total items online searches	***1,746 (99.1 %)***
C) Manual search		
Date/time	Source	Number of items added
13/08/2023	*Third party submissions*	*11*
	Mendeley shared library	*2*
	Personal collections	*2*
	Total items manual searches	***15 (0.9 %)***

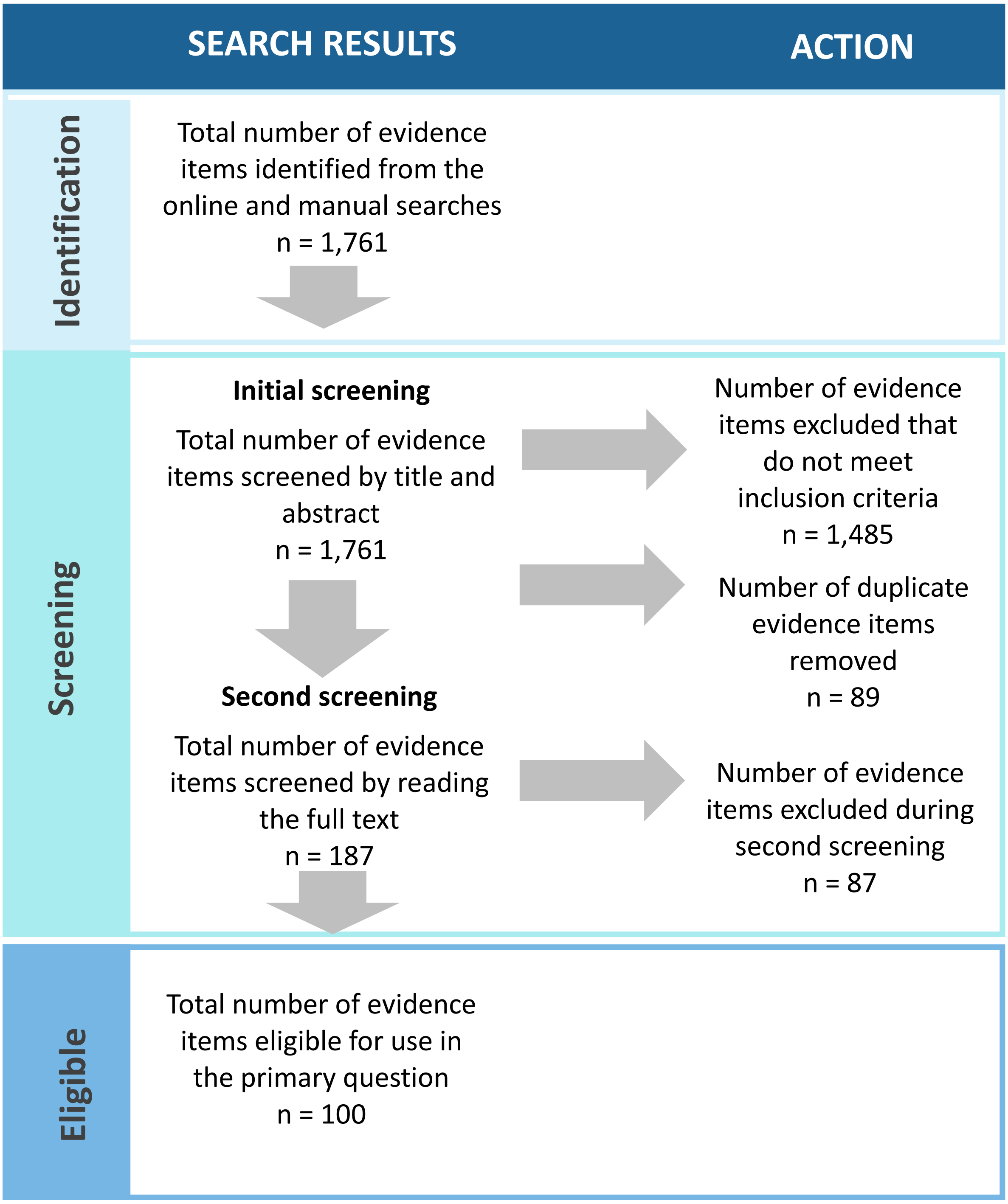


Figure 3. Flow chart of results of screening and assessing all search results for Question 1.2/1.3/2.1.

4. Key Findings

4.1 Narrative synthesis

4.1.0 Summary of study characteristics

A total of 100 eligible studies were found for the period 2017 to 2022. Nearly a quarter of studies were published in 2019 (22%), with the number of studies declining until reaching the lowest in 2022 (12%). Some of these publications represent the most recent in a series (e.g., annual updates), and therefore superseded publications were excluded during the initial screening. Fifty six percent of the studies focused on coral reefs (including coral, algae, fishes and mobile invertebrates), followed by the marine environment overall (18%), megafauna (7%) and seagrass (5%) with all other ecosystems in less than 5% of studies (Table 7). The least reported studies were on microbial communities, which is a key knowledge gap.

Table 7. Summary of the primary characteristics evaluated for each of the GBR ecosystems, indicating the number of studies in each category. Note: individual studies can include several of the primary characteristics evaluated.

Ecosystem	Extent	Condition/Trend	Threats	Total
Coral reef (coral, algae, fishes and mobile invertebrates)	2	38	40	56
Seagrass	2	3	3	5
Pelagic		3	1	4
Planktonic		1	2	3
Marine environment (overall)		7	14	18
Estuaries	1	1	1	2
Wetlands (overall)	1	1	2	3
Microbial communities		1	0	1
Megafauna		4	6	7
Freshwater & marine environment (overall)		1	1	1
Total	**6**	**60**	**70**	**100**

The majority of studies (66%) reported on the ecosystems across the entire GBR, however, of the remaining studies the most examined region was the central GBR (Wet Tropics, Burdekin and Mackay Whitsunday) (53%), and the least was the far northern GBR (north of Bathurst Bay within the Cape York Natural Resource Management (NRM) region) (5%).

Studies were classed as primary (experimental, observational or modelled), or secondary (reviews, systematic reviews or meta-analysis) or mixed (e.g., involve a mixture of experimental, modelled and/or observational studies and reviews). The majority of studies were of an observational or modelled nature (52% and 27%, respectively), while the remaining were either review (19%) or theoretical/conceptual (2%). Only 6% of studies presented evidence on spatial extent (Table 7).

Of the 60 studies/documents published between 2017 to 2022 which included ecosystem condition and/or trend information, relatively few reported on current condition (9%) or trend (16%). Less than half (41%) the studies reporting current condition were observational, while the remainder were either modelled (39%) or review (20%). Sixty-seven percent of studies reporting condition focused on coral reef ecosystems, while the remainder focused on the overall marine environment (13%), followed by seagrass, estuaries and overall wetlands with one publication each.

Just under three quarters (70%) of studies reported on ecosystem threats. Of these studies, water quality pollution was identified/perceived as the greatest threat (39% of studies), closely followed by climate change (37%), cumulative impacts (19%) and crown-of-thorns starfish (COTS, 6%). Apart from overall water quality, the most reported water quality related threats were pesticides (26% of studies), nutrients (15%), sediments (11%) and others (7%). Of the studies reporting on climate change threats, most identified rising water temperatures as the major stressor (77%), while the remaining studies reported on extreme events (12%) and acidification (12%).

4.1.1 Summary of evidence to 2022

Extent and condition of Great Barrier Reef ecosystems

Covering an area of about 350,000 km^2 on the north-eastern Australian continental shelf, the Great Barrier Reef (GBR) is a vast and globally significant marine biome of interconnected ecosystems (Figure 1). The GBR's natural beauty and natural phenomena endure, but increasing pressures are threatening the GBR's resilience, and signs of deterioration are becoming apparent. In the 2009 Outlook Report, the GBR was considered to be at a crossroads between a positive, well-managed future and a less certain one (GBRMPA, 2009). In 2014, it was seen as an icon under pressure, with continued efforts needed to address key threats. Since then, the GBR has further deteriorated and in 2019 was classified as changed and less resilient (GBRMPA, 2019).

Natural values of the GBR include species, habitats and ecosystem processes (refer to Question 1.1, Newlands & Olayioye, this SCS, for additional information on GBR values). Individual ecosystem conditions are presented in Table 9, however, it should be noted that the assessment approach, measurable characteristics and use of indicators is not consistent across all ecosystems, with the exception of reporting for ecosystems assessed through the GBR Marine Monitoring Program (MMP). Nevertheless, losses, degradation and alteration have occurred in a number of areas across most ecosystems in the long-term, substantially affecting populations of some dependent species. For example, the significant and large-scale impacts from record-breaking sea surface temperatures have resulted in loss of corals across many areas of the GBR, although recent recovery has been observed (AIMS, 2022). Not all habitats have been equally affected and their condition varies across the length and breadth of the GBR. For instance, coral reefs that have escaped impacts of bleaching, cyclones and COTS outbreaks remain in good condition (AIMS, 2022; Thompson et al., 2022). Some critical ecosystem functions have also deteriorated since 2014, mainly due to declines in ecological processes, such as symbiosis and recruitment, and deterioration of some physical processes, such as sea temperature and light. Some processes important to replenishment and recovery of species and habitats, such as currents, connectivity and primary production, remain in Good to Very Good condition (refer to Question 1.4, Davis & Pearson, this SCS, for additional information on the connectivity of key GBR ecosystem processes) (GBRMPA, 2019).

The pressures influencing inshore GBR dynamics differ slightly from those influencing more offshore ecosystems. Tropical cyclones, heatwaves and COTS are recognised as the major pressures threatening offshore ecosystems (Bozec et al., 2022). Inshore ecosystems are additionally influenced by land-based runoff (Castro-Sanguino et al., 2021; Thompson et al., 2022).

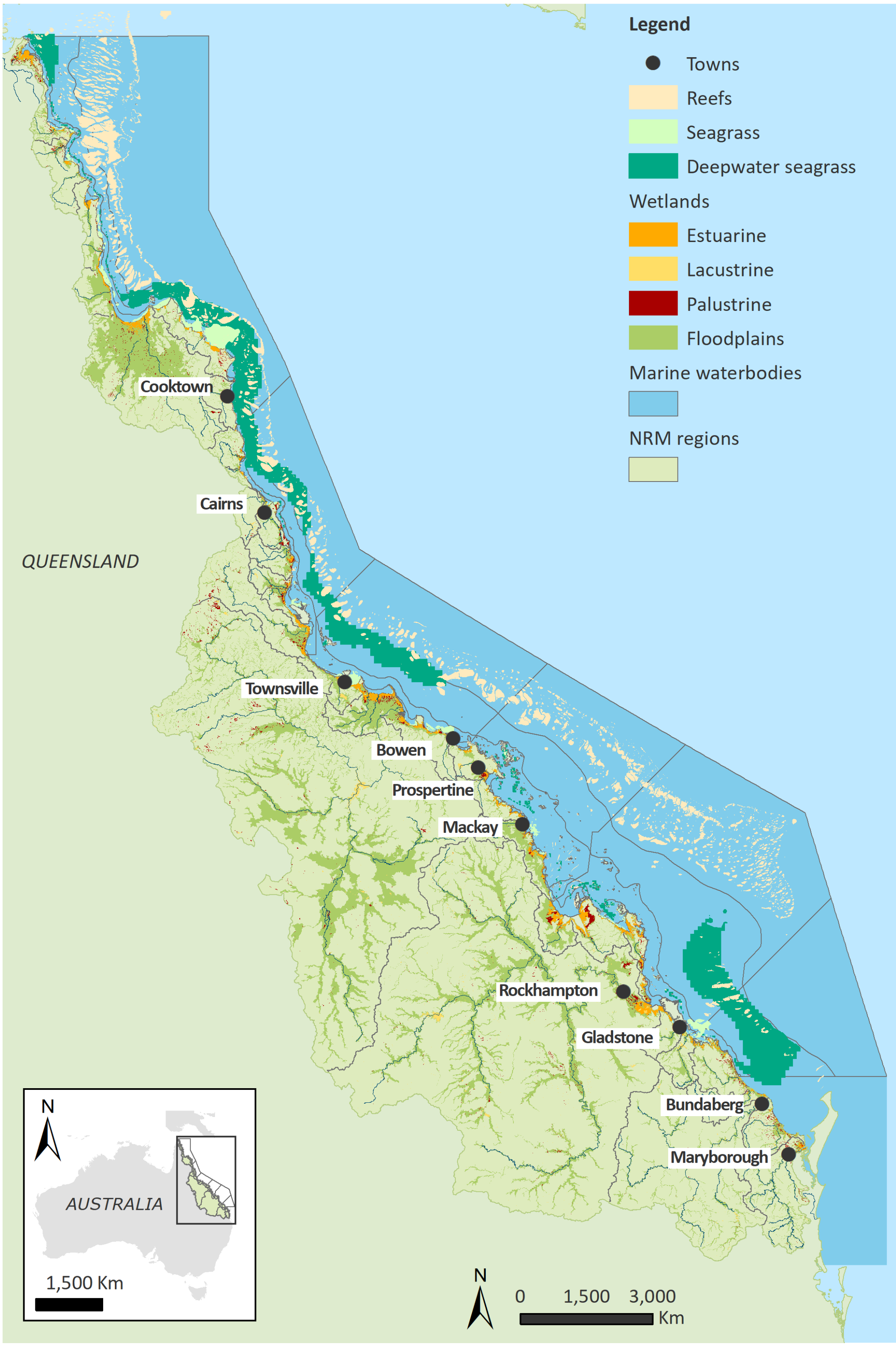


Figure 4. General map showing major Queensland Rivers and cities, GBR Natural Resource Management (NRM) regions, marine waterbodies and floodplains, and marine habitats including seagrass, coral reef and inland wetlands (estuarine, lacustrine and palustrine wetlands).

Table 8. Extent of GBR ecosystems, presented by NRM region and GBR waterbody in km^2. Sum of regional areas may not equal Total due to regional rounding. From north to south: CY = Cape York, WT = Wet Tropics, B = Burdekin, MW = Mackay Whitsunday, F = Fitzroy and BM = Burnett Mary NRM regions.

GBR ecosystems	Total extent (GBRWHA)	By NRM region (km^2)	By waterbody (km^2)			References
			Inshore	Midshelf	Offshore	
Marine- Coral	24,094 km^2 Inshore: ~760 reefs Offshore: ~2,200 reefs	CY 10,354 WT 2,427 B 2,965 MW 3,212 F 4,855 BM 283	296 78 31 279 173 6	2,212 74 206 58 445 277	7,846 2,275 2,728 2,875 4,237 -	Moran et al., 2022
Marine- Seagrass	35,679 km^2	CY 11,594 WT 4,872 B 6,127 MW 502 F 6,036 BM 6,548	2,884 409 660 502 676 243	5,214 1,780 3,050 - 5,360 6,220	3,496 2,683 2,417 - - 85	McKenzie et al., 2022a,b[†]
Estuarine	3,946 km^2 Mangroves (M) 2,188 km^2 Salt flats and saltmarsh (S) 1,757 km^2	CY M 572 S 489 WT M 345 S 43 B M 269 S 390 MW M 325 S 123 F M 512 S 641 BM M 164 S 71				DES, 2019[#]

GBR ecosystems	Total extent (GBRWHA)	By NRM region (km^2)			By waterbody (km^2)			References
					Inshore	Midshelf	Offshore	
Freshwater wetlands	Riverine (R) 6,739 km^2 Palustrine (P) 2,881 km^2 Lacustrine (L) 252 km^2	CY	R	459				DES, 2019#
			P	603				
			L	59				
		WT	R	387				
			P	374				
			L	5				
		B	R	3,269				
			P	678				
			L	91				
		MW	R	153				
			P	103				
			L	2				
		F	R	1,761				
			P	811				
			L	85				
		BM	R	706				
			P	298				
			L	6				
Wetlands(overall)	15,556 km^2	CY		2,188				DES, 2019#
		WT		1,257				
		B		5,248				
		MW		797				
		F		4,532				
		BM		1,534				

*Area calculations were performed in the GDA 1994 Australia Albers Equal Area projection. Data provided by the Great Barrier Reef Marine Park Authority and the Queensland Government.
†Area calculations were performed in the GDA 1994 MGA Zone 55 projection; temporal composite of seagrass extent includes modelled data (probability ≥50%, pixel size of 5 km^2, from Coles et al., 2009).
#Area calculations were performed by Wetland*Info* in the GDA 1994 Australia Albers Equal Area projection. Data from https://www.data.qld.gov.au/dataset/wetland-data-version-5-queensland-series, GBR river basin/catchment boundaries from https://qldspatial.information.qld.gov.au/catalogue/custom/detail.page?fid={C3E7CB1D-5881-4EB4-A9C1-9DADABA0E10B}.

Table 9. Summary of the current condition of GBR ecosystems, indicating long-term trends by NRM region. Where condition categories are assigned, they relate to reported condition assessed on the basis of multiple indicators. For example, inshore coral and seagrass condition are based on multiple indicators including resilience indices reported by the Marine Monitoring Program (MMP). From north to south: CY = Cape York, WT = Wet Tropics, B = Burdekin, MW = Mackay Whitsunday, F = Fitzroy and BM = Burnett Mary NRM regions.

GBR ecosystems	Current condition	Long-term trends (2005 – 2021)	Regional current condition and trend since 2017	References
Inshore coral	Poor	WT – no change B – no change MW – decline F – no change	WT – moderate (stable) B – moderate (declined) MW – poor (stable) F – poor (declined)	Thompson et al., 2022
Offshore coral	(Condition not categorised) 46% reefs: ≤30% hard coral cover. 32% reefs: 30-50% hard coral cover. 22% of reefs: >50% hard coral cover.	CY – increase WT – no change B – increase MW – increase F – no change BM – increase	Condition not categorised CY – increase WT – increase B – increase MW – increase F – no change BM – increase	AIMS, 2022
Marine - Inshore seagrass	Moderate Declined since 2017, but slight uptick in 2020-21.	CY – decrease WT – no trend B – no trend MW – decrease F – decrease BM – no trend	CY – moderate (improved) WT – moderate (improved) B – moderate (improved) MW – poor (declined) F – poor (declined) BM – poor (declined)	McKenzie et al., 2022a
Marine - Pelagic, benthic and planktonic communities	Plankton and microbes - Good	Deteriorating		GBRMPA, 2019
Mangroves	Mangroves – Excellent-Good	Mangroves – stable		Brodie & Waterhouse, 2018; GBRMPA, 2019
Estuaries & saltmarshes	Good	Under pressure-stable		Brodie & Waterhouse, 2018; GBRMPA, 2019
Freshwater wetlands	Moderate	Stable		Australian & Queensland Government, 2022

GBR ecosystems	Current condition	Long-term trends (2005 – 2021)	Regional current condition and trend since 2017	References
Wetlands (overall)	Moderate	Stable		Adame et al., 2019
Megafauna	Dugongs and Turtles - Poor	Dugongs and turtle populations are in decline – some populations are recovering (e.g., southern green turtle)		Brodie & Waterhouse, 2018; GBRMPA, 2019

Coral reefs

Shallow coral reefs account for a relatively small area (7%) of the GBR (Figure 4, Table 8), but are the predominant focus of research, monitoring, and management. There are several distinct types of coral reefs which broadly correspond to their cross-shelf position: i) inshore fringing reefs adjacent to the mainland or high continental islands; ii) midshelf platform reefs; and iii) offshore barrier reefs arrayed along the edge of the continental shelf. The composition of coral reef assemblages on individual reefs depends on their cross-shelf position. Shallow offshore reefs are dominated by fast-growing, thermally sensitive corals such as *Acropora* and *Pocillopora* species which are strongly photoautotrophic. Conversely, inshore reefs become progressively dominated by corals with a strong capacity for feeding on particulate matter and that are better adapted to turbid/low light habitats (DeVantier et al., 2006; Mellin et al., 2019a; Mellin et al., 2019b). In addition to cross-shelf patterns, the biological and physical structure of coral reefs on the GBR varies with latitude (Pratchett et al., 2019a).

The greatest extent (83%) of shallow coral reefs is located within the GBR's offshore waterbody area, while the smallest (4%) is located inshore (Table 8). Regionally, Cape York contains the greatest area of coral reefs (43%), followed by Fitzroy (20%), Mackay Whitsunday (14%), Burdekin (12%), Wet Tropics (10%), and Burnett Mary with the least (1%) (Table 8). Improved mapping in deeper areas surrounding 2,164 shallow offshore reefs, based on depth, geomorphic and benthic composition has increased the known area of coral reef habitat within the GBRWHA. Roelfsema et al., (2021b) estimate that ~10,600 km^2 (8,696–11,828 km^2, 95% Confidence Interval) of reef area (~57% of shallow offshore reef area) is covered by hard substrate suitable for coral growth. Additionally, a further 25,600 km^2 of submerged banks between 20 and 200 m isobaths has been identified using a bathymetric model (Roelfsema et al., 2021b). Overall, the southern reefs had the highest estimates of coral habitat concentrated in the outermost reefs, while the central region, specifically between Cairns and Townsville, had the lowest (Roelfsema et al., 2021b). The distance of coral reefs from the continental mainland similarly varies latitudinally (Figure 5). This is a consequence of the shape of the continental shelf on which coral reefs have developed.

Variation in coral assemblages across the continental shelf in the GBR reflect the cross-shelf gradient of environmental conditions, such as exposure to terrestrial runoff inshore (refer also to Questions 3.2, Collier et al., and 4.2, Diaz-Pulido et al., this SCS) and influence of wave exposure and proximity to the Coral Sea offshore (Jonker et al., 2019; Mellin et al., 2019b). Higher rates of increase in coral cover have been reported for outer shelf coral communities (characterised by *Acropora* spp. and exposed to lower seasonal variations in salinity and sea surface temperature), while lower rates of coral cover increase occur for inshore communities that are more frequently exposed to reduced water quality (Mellin et al., 2019a; Waterhouse et al., 2021; refer also to Questions 3.1, Lewis et al., and 4.1, Robson et al., this SCS). However, branching coral annual linear extension rates (Burn et al., 2018) and fecundity in some species of *Acropora* have been reported to be similar on inshore and offshore reefs (Pratchett et al., 2019b). Lower rates of recovery of coral cover on inshore reefs, will in part reflect the lower representation of fast growing species on many inshore reefs where other constraints such as lack of successful recruitment, increased incidence of disturbances, or higher levels of chronic stress reduce survivorship of specific corals in these environments (Pratchett et al., 2019b).

Coral communities are naturally dynamic, progressing through periods of recovery following mortality after acute disturbances such as cyclones. For example, between 2002 and 2018 coral cover at Heron Island (Fitzroy region) fluctuated from highs in 2004 (42.7 ±3.3%) to lows in 2006 (12.8 ±1.3%), followed by a gradual increase at reef scale to 2016, after which it decreased again (Roelfsema et al., 2021a). Despite the well-documented effects of bleaching on coral abundance in the GBR over the last decade (Dietzel et al., 2020; Hughes et al., 2017; refer also to Question 2.2, Fabricius et al., this SCS), there is still considerable uncertainty regarding how loss of cover translates to loss of species as reporting is limited to higher taxonomic grouping because of the challenges of coral species identification. Recent taxonomic research using molecular techniques has indicated that the current coral taxonomy does not accurately reflect coral species diversity (Cowman et al., 2020; Kitahara et al., 2016; Ramírez-Portilla et al., 2021). For example, Richards et al. (2021) reported fluctuations in scleractinian coral species diversity at Lizard Island between 2011 and 2020 (decline 2011 to 2017 and recovery 2017 to 2020) and identified that up to 16% of the local species pool was possibly at risk of local extinction or local range reduction. However, the risk may have been underestimated as a result of the morphological techniques applied. Ongoing taxonomic research aimed at resolving the taxonomic diversity and biogeography of corals on the GBR provides an opportunity to better understand population trajectories of corals (Cowman et al., 2020; Ramírez-Portilla et al., 2021). However, existing monitoring data for corals, which is typically collected at the taxonomic resolution of genus does enable tracking of any high-level changes in taxonomic, or alternatively functional, diversity of corals assemblages. This information may provide a clearer understanding of habitat provisioning and ecological functioning underpinning ecosystem resilience (Hughes et al., 2018a).

Overall, the shallow coral reefs of the inshore GBR are generally in a poor condition with degradation continuing (Table 9; Thompson et al., 2022). GBR-wide, coral cover declined from 45-55% in 1960 (for offshore reefs), to 28% in 1986, and 14% in 2011 (with similar declines in inner reefs) (Brodie & Waterhouse, 2018; Pratchett et al., 2019a). Both modelling and long-term monitoring covering the 2008-2020 period show the strongest relative losses for the inshore reefs (63–73%), the northern midshelf (58%), and southern outer shelf (44%) regions (Bozec et al., 2022, Table 9). Reconstructed coral cover trajectories between 1996 and 2017, predicted a mean annual coral loss of -0.67% per year (Mellin et al., 2019a). These declines have also been accompanied by changes to coral assemblages. For example, a 91-year study in the Low Isles (Wet Tropics region) identified a systematic decline in richness and diversity of corals, specifically, massive corals replacing branching corals, and soft corals becoming much more abundant (Fine et al., 2019).

Trends in coral cover published annually by the Australian Institute of Marine Science (AIMS, 2022; Emslie et al., 2020; Thompson et al., 2022) demonstrate the ongoing recovery potential in many areas of the GBR, when corals are spared from severe impacts associated with large scale climatic events or outbreaks of COTS. Ultimately however, the long-term trend in condition of coral communities will be due to the balance between the cumulative impacts of acute and local pressures and the continued maintenance of the life history processes that enable recovery of coral communities (Bozec et al., 2022). The Coral Index (Thompson et al., 2022), used to assess the condition of inshore coral communities as ‘poor' in 2021 (Thompson et al., 2022) (Table 9), explicitly incorporates process-based indicators for coral recruitment, recovery rate, and competition (macroalgae). Such an indicator framework has yet to be developed for offshore reefs.

The current poor condition of inshore coral communities demonstrates that since 2005, the frequency and severity of disturbances has exceeded the capacity of inshore communities to recover (Thompson et al., 2022). This is further supported by reports that the rate of decline in coral calcification in the GBR has accelerated in the past two decades, with calcification falling by up to 1.5% $year^{-1}$ relative to baseline values, as of the late 2000s (Davis et al., 2021). In fact, the results of a global meta-analysis indicated that coral reef ecosystems around the world are experiencing a shift in their essential metabolic processes of calcification and photosynthesis, and could become net dissolving worldwide around 2054 (Davis et al., 2021).

Regardless of their dynamic nature, cumulative pressures since 2016 contributed to a period of decline for corals over much of the GBR. Marine heatwaves, tropical cyclones, and outbreaks of COTS variously reduced coral cover at many mid- and offshore reefs before a noted rebound in 2021-22 (AIMS, 2022). Similarly, inshore reefs are predominantly influenced by acute disturbance events, such as storms, however, the contributions of other pressures such as land-based runoff, disease, and macroalgae abundance, vary between regions (Lam et al., 2018). In the southern catchments, flooding has also been associated with negative trends in inshore live coral cover. Corals exposed to low salinity floodwaters died (Thompson et al., 2022), with high loads of fine sediments and nutrients delivered by floods likely to intensify chronic stressors associated with poor water quality across the inshore GBR more generally (Fabricius et al., 2016).

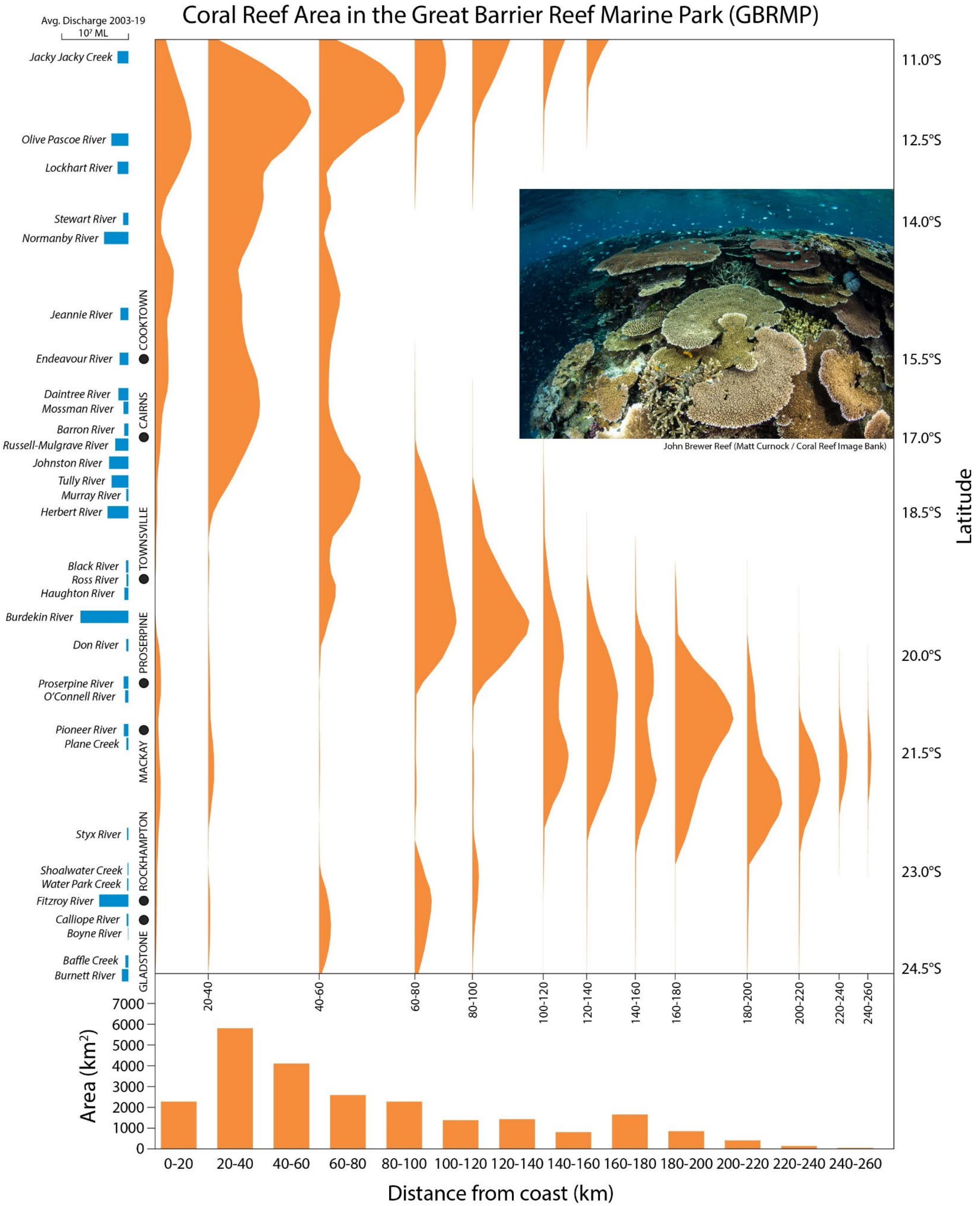


Figure 5. Distribution of coral reefs within the Great Barrier Reef Marine Park (GBRMP), showing extent of coral reef across latitudes, distance from the mainland coast and annual discharge volume from adjacent basins.

The condition of coral communities has follow-on effects to the myriad of species reliant on coral reefs as habitat. For example, while differences in the assemblage structure of herbivorous coral reef fishes across the GBR shelf has been linked to environmental parameters such as water quality, exposure to wave energy, and connectivity that may govern larval supply, herbivorous fishes are also sensitive to structural habitat for the provision of settlement sites and protection from predation (McClure et al., 2019). While distinct cross-shelf assemblages can remain following environmental disturbances, habitat damage has been linked to reduced richness of herbivorous fishes and this group of fishes may also be more vulnerable to chronic localised stresses (McClure et al., 2019). Homogenisation of GBR fish assemblages, with shifts towards predominance of small-bodied, algal-farming, habitat generalists, has been reported following the 2016-2017 mass coral bleaching event at Lizard Island (Richardson et al., 2018). Pelagic fishes associated with reefs (such as sharks) depend less on benthic habitat, but may decline in response to changes in their reef-associated prey if fishery impacts are precluded (Heupel & Simpfendorfer, 2014).

Seagrass meadows

The GBR's seagrass meadows are reported to occupy approximately 10% of the seafloor (Figure 4, Table 8). Seagrass meadows are a key ecosystem of the GBR, providing critical goods and benefits. Fifteen seagrass species are reported within the GBR (Coles et al., 2015), distributed from just above mean sea level to 76 m deep (Carter et al., 2021). They occur in 12 habitat types based on water quality types (estuary, coastal, reef, and offshore) and water depth (intertidal, shallow subtidal <15 m, and deep subtidal >15 m) (Udy et al., 2018).

Mapping the GBR's seagrass meadows is challenged not only by the size of the GBR, but also the optically complex waters, and the variety and dynamic nature of seagrass communities and habitats (McKenzie et al., 2022a; 2022b). Intertidal and shallow subtidal seagrass meadows occur predominantly within 20 km of the mainland coast (Figure 6a) and contribute to around 15% of the GBR's overall seagrass extent (Table 8). The most extensive areas of seagrass within the GBR occur in the deep subtidal habitats (>15 m depth; Table 8), however, due to the challenges of distinguishing meadow boundaries, extents are modelled; based on field validation points, water depth, sediment grain size and water clarity (Coles et al., 2009). Regionally, Cape York contains the greatest area of seagrass overall (32%), followed by Burnett Mary (18%), Burdekin (17%), Fitzroy (17%), Wet Tropics (14%), and Mackay Whitsunday with the least (2%) (Table 8). The seagrass meadows in Mackay Whitsunday are also the most restricted in cross-shelf distribution, only occurring in inshore (Table 8). The occurrence of deepwater meadows varies latitudinally and with distance from the coast; a consequence of the GBR's offshore water body being located closer to the mainland north of approximately 17°S and increasing further from the coast in higher latitudes (Figure 6b). The cross-shelf seagrass distribution decreases in depths greater than 35 m, and there is a consistent tendency for higher species diversity closer to the mainland coast (Coles et al., 2009). In contrast to cross-shelf distributions, large spatial scale discontinuities in deepwater seagrass presence occur north of Princess Charlotte Bay and immediately south of Mackay (Figure 6b), suggesting that biophysical parameters (e.g., tidal ranges and velocities, nutrient limitation) and biological constraints (e.g., recruitment limitation) may influence distribution (Coles et al., 2009).

a)

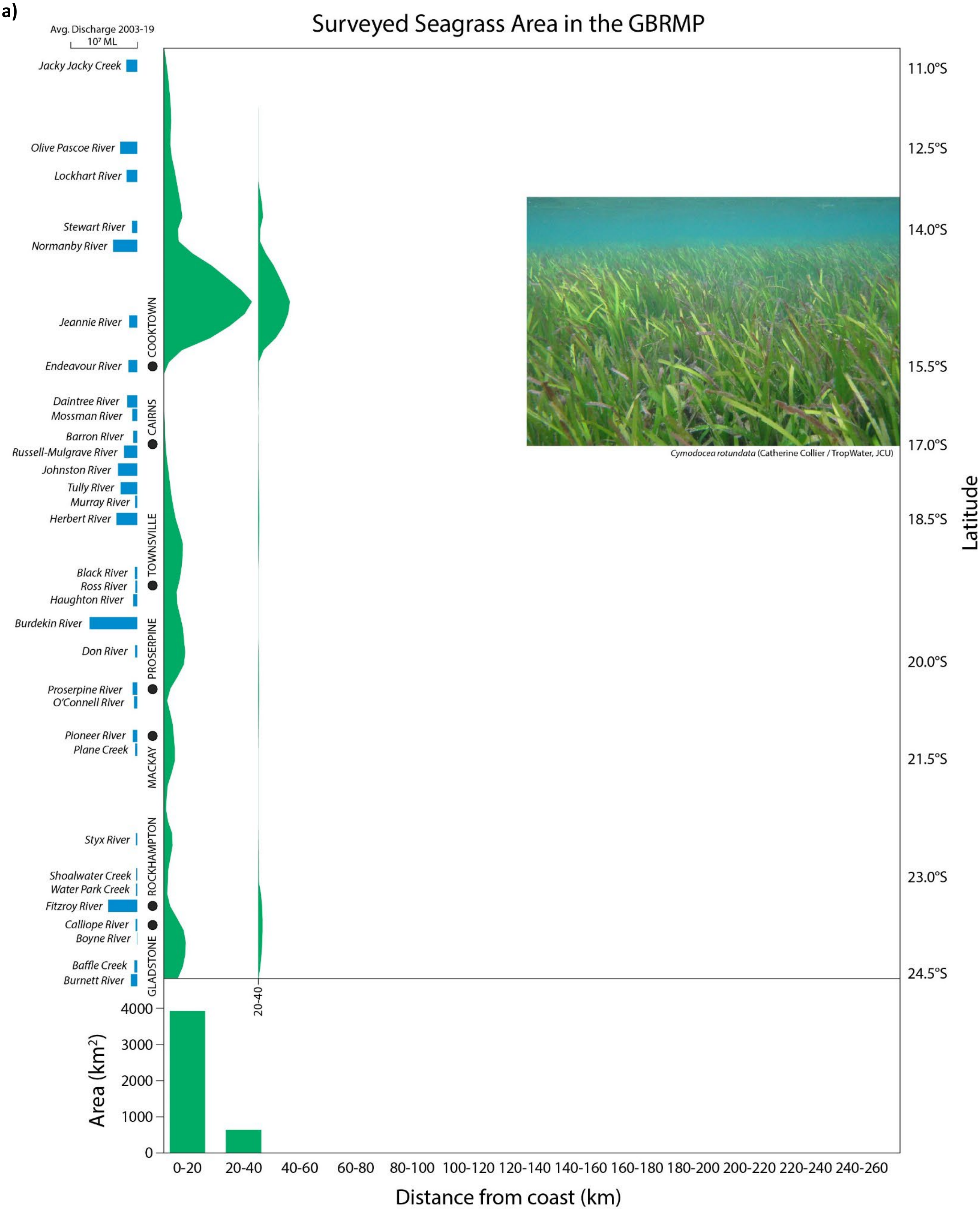


Figure 6a. Distribution of surveyed seagrass meadows in the GBR, showing meadow extent across latitudes, distance of meadows from mainland coast and annual discharge volume from adjacent basins.

b)

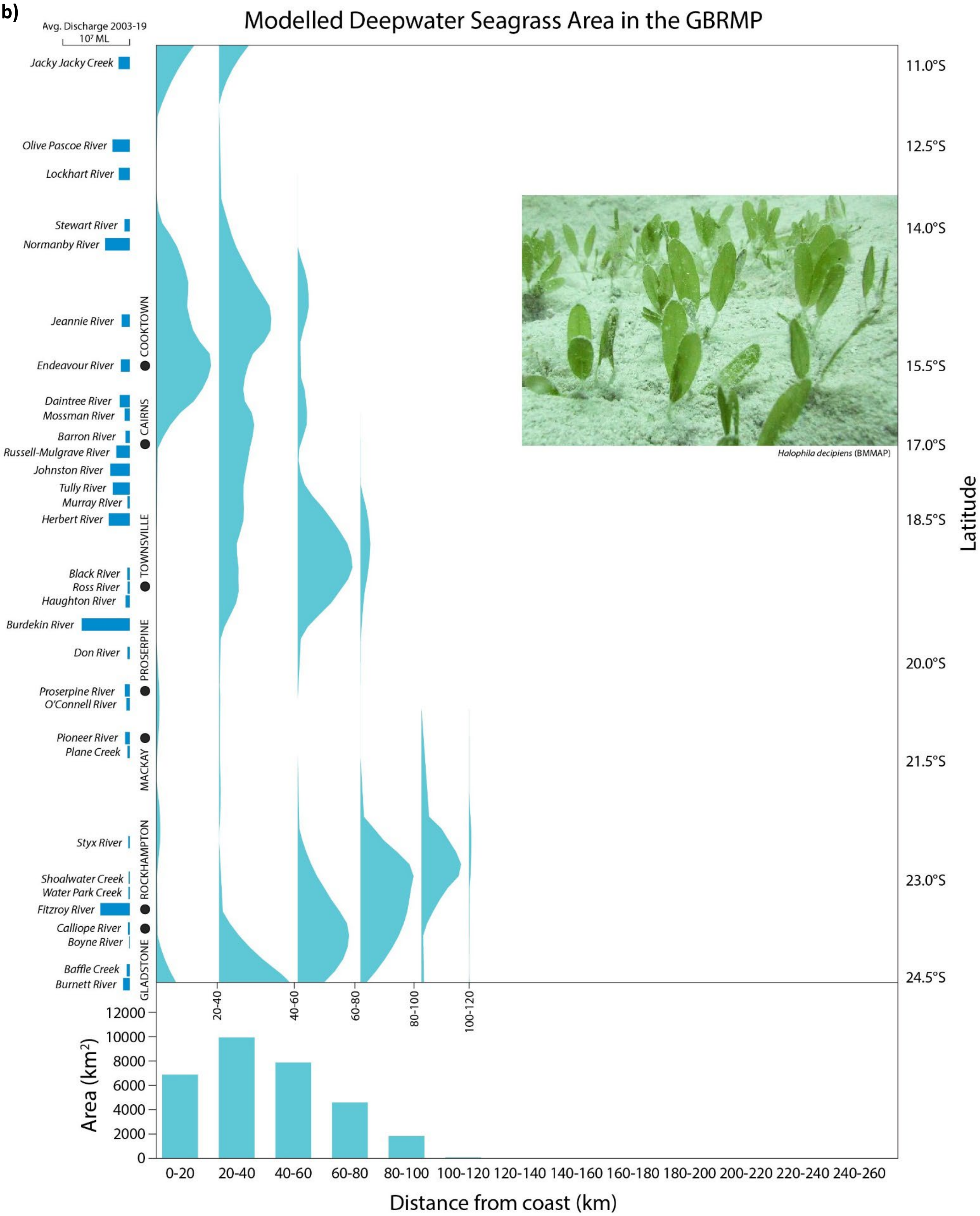


Figure 6b. Distribution of modelled seagrass meadows in the GBR, showing meadow extent across latitudes, distance of meadows from mainland coast and annual discharge volume from adjacent basins.

Deepwater meadows are relatively sparse, structurally smaller, highly dynamic, composed of colonising species (*Halophila* spp.), and less productive than shallower seagrasses (Campbell et al., 2007; Coles et al., 2009; York et al., 2015). Intertidal and shallow subtidal seagrass meadows are generally denser and composed of more foundational species (McKenzie et al., 2022a; McKenzie et al., 2022b). However, these inshore meadows are significantly influenced by major pressures such as seasonal and episodic pulses of sediment-laden and nutrient-rich land-based runoff (Carruthers et al., 2002; Grech et al., 2012; Petus et al., 2016). Cyclones, severe storms and large rainfall events, wind and waves, elevated seawater temperatures and desiccation, as well as macrograzers (e.g., fish, dugongs, and turtles) and direct anthropogenic activities (e.g., catchment and coastal development, boating and dredging) also influence all seagrass habitats along the breadth of the GBR to varying degrees (Carruthers et al., 2002; Grech et al., 2012). The most critical stressor for seagrass is light limitation (Collier et al., 2016), which can be exacerbated with the cumulative impacts of additional stressors, such as elevated seawater temperature, resulting in reductions in seagrass abundance/biomass (Adams et al., 2020; Collier et al., 2012; refer also to Question 3.2, Collier et al., this SCS).

Seagrass condition is variable in space and time across the GBR. In the past, seagrass declines have been associated with severe cyclones and large river flood events, which resulted in decreased meadow extent, reduced seagrass abundance and compromised resilience (Brodie & Waterhouse, 2018; Coles et al., 2015; McKenzie et al., 2022a; Rasheed et al., 2014). Overall, the inshore seagrass habitats of the GBR are in a moderate condition, improving slightly in 2020-21 (McKenzie et al., 2022a) (Table 9). The Seagrass Index used to assess the condition of inshore seagrass habitats incorporates abundance and resilience indicators (McKenzie et al., 2022a). However, such an indicator framework has yet to be implemented for deepwater meadows, which are not currently assessed. Inshore seagrass condition improved to a moderate grade in the northern NRM regions (Cape York, Wet Tropics and Burdekin), while condition deteriorated in the southern regions (Mackay Whitsunday, Fitzroy and Burnett Mary), with the grade declining to poor (McKenzie et al., 2022a). The poorer conditions in the southern regions appear either a legacy of recent (past 3 – 4 years) extreme events (e.g., cyclones) or localised disturbances (e.g., sediment and bank movement) which may render the seagrass more vulnerable to adverse or severe disturbances in the near future (McKenzie et al., 2022a).

Other benthic communities

The GBR includes extensive inter-reef soft bottom habitats which support a diversity of benthic invertebrates ranging in size from microscopic to macroscopic. Excluding seagrass meadows, these soft-bottom habitats and associated communities extend throughout the lagoon to beyond the outer barrier reefs to depths of 200 m. These ecosystems play an important role in primary production, nutrient cycling, carbon sequestration and sediment trapping. Sediments in these inter-reef habitats range from fine mud near the mouth of rivers to calcareous sands, and largely determine floral and faunal species composition. Inter-reef areas are generally a mosaic of sediments and more isolated patches of sponges, gorgonians and molluscs (e.g., bryozoan reefs) that provide habitat for many mobile species, including fish (Hutchings et al., 2007). A major component of offshore sediments is disaggregated *Halimeda* segments which can accumulate as thick bank-like structures or bioherms, covering 6,167 km^2 of the GBR; spanning the entire northern section and a smaller area in the Swain reefs to the south (McNeil et al., 2016). These *Halimeda* bioherms are a complex habitat that hosts higher average species richness and diversity of both plants and invertebrates than the surrounding inter-reef (non-coral reef) benthos, i.e., an inter-reef biodiversity hotspot (McNeil et al., 2021).

Apart from sediment composition, it is likely that inter-reef soft bottom ecosystems are influenced by the available light, water currents, water temperature, salinity and nutrient availability (Hutchings et al., 2007). Pressures such as climate change, land-based runoff, and to a lesser extent bottom trawling, are likely to significantly impact ecosystem condition and biodiversity (Hutchings et al., 2007; McNeil et al., 2021). In general, their location in deeper waters may buffer some disturbance events, however, cyclone impacts have been recorded down to 65 m in the central section of the GBR and increased sea temperatures recorded down to 40 m (Bongaerts et al., 2013; Frade et al., 2018). Since the 2003-2006 GBR-wide assessment of these ecosystems (Pitcher et al., 2007), there has been no follow-up to assess the current ecological condition. With a number of severe cyclones and heatwaves impacting the GBR over the last decade, it is highly likely that the condition of inter-reef soft bottom ecosystems has deteriorated (GBRMPA, 2019).

Pelagic and planktonic communities

The pelagic environment (water column) is the largest, by volume, ecosystem of the GBR. The GBR has a total water volume of around 7,200 cubic kilometres, and serves as the main habitat for many species of fish, cetaceans, dugong, turtles, invertebrates and microbes (Johnson & Marshall, 2007). Almost all marine organisms spend some part of their life history in the water column.

Plankton and microbes: Plankton and microbes are suspended (drifting or weakly self-propelled) pelagic organisms that are highly abundant and diverse within the GBR. They include single-celled plants, free-living bacteria, viruses, zooplankton (radiolarians, foraminiferans, dinoflagellates, cnidarians, crustaceans, chordates, and molluscs) and animal larvae. Plankton and microbes are critical to overall ecosystem health and functioning, providing the basis of pelagic food chains and food for benthic filter feeders. Plankton and microbes respond relatively quickly to changes in the surrounding waters, such as lowered salinity, temperature increases and nutrient increases (i.e., chlorophyll concentration and turbidity) (Glasl et al., 2019). Stressors affecting these communities are elevated temperature, elevated nutrients and reduced pH (for plankton with carbonate skeletons), all of which are occurring in the GBR (GBRMPA, 2019).

Nekton: Nekton are highly mobile pelagic animals, including cephalopods, bony fishes, elasmobranchs, marine reptiles, cetaceans and sirenians. Although the majority are GBR residents, many are temporary visitors, depending on the time of year and the conditions they experience. The diversity and abundance of pelagic animals varies across the GBR and is influenced by the connectivity between habitats and other ecosystems. Conversely, large predators from the pelagic environment affect other environments and generate complex trophic links. Trophic cascades in pelagic ecosystems, however, are likely to be strongly bottom-up with strong linkages between phytoplankton, zooplankton and fish populations. For example, the structure of planktivorous damselfish assemblages across the continental shelf reflected cross-shelf gradients in coral habitat and zooplankton availability (Emslie et al., 2020).

Pelagic animals of the GBR are also influenced by water depth, which has been found to be a strong predictor of fish assemblage composition. For example, in the central GBR, fish species richness and abundance decreased steeply between 100 and 260 m, with commercially-valuable Lutjanidae species (from *Pristipomoides* and *Etelis* genera), absent from shallower depths (Sih et al., 2017). The condition of fish across the GBR is considered good, however, the condition of sharks and rays is uncertain but likely to be poor (GBRMPA, 2019). Declines in sawfish and river shark populations are known to have occurred since 1970 across the inshore GBR (GBRMPA, 2019).

Apart from sharks, rays and fish, other highly mobile megafauna in the GBR include marine mammals and reptiles. At least 30 species of marine mammals, 6 species of sea turtles and 14 species of sea snake spend some part of their lives in GBR waters (Marsh et al., 2019). Marine megafauna play critical roles across the GBR's ecosystems, although their presence and abundance varies depending on food availability, habitat condition, and threatening activities (e.g., fishing). For example, declining seagrass condition can have severe flow-on negative effects on seagrass dependent megafauna e.g., dugongs and turtles (Meager & Limpus, 2012a, 2012b; Wooldridge 2017). Turtles foraging in coastal areas are also exposed to a range of anthropogenic pollutants derived from the adjacent coastal catchment areas, as demonstrated by higher concentrations of metals in turtles foraging at coastal seagrass sites relative to more offshore/remote sites (Gallen et al., 2019a; Wilkinson et al., 2022). Trace element exposure (in particular, cobalt) is having an impact on the health of coastal sea turtle populations, although the exact effects and their extent require closer examination using targeted diagnostics (Gaus et al., 2019; Villa et al., 2017).

Overall, there has been recovery of the southern green turtle populations (Hof et al., 2017). However, there are growing concerns for the future of loggerhead, hawksbill and the northern green turtle populations due to a number of external pressures, including climate change and overseas fishing mortality (GBRMPA, 2019). In particular, the northern green turtle population is extremely female-biased and complete feminisation of this population is possible in the near future due to increasing incubation temperature effects on egg mortality and sex ratios of hatchlings (Booth et al., 2020; Jensen et al., 2018). Although the GBR's dugong population exhibits an overall long-term decline, there has been some recent recovery for the urban coast dugong population since 2014 (GBRMPA, 2019).

Estuaries and freshwater wetlands

Wetlands are vital for sustaining the health and resilience of the GBR, and they cover 15,556.2 km^2 (~4%) of the overall GBR catchment. Within the GBR wetlands, riverine wetlands comprise most (43.3%) of the area, followed by estuarine (25.4%), palustrine (vegetated swamp) (18.4%), and lacustrine (lakes) (1.6%) (DES, 2019) (Figure 4, Table 8). Regionally, the Burdekin contains the greatest area of wetlands (34%), followed by Fitzroy (29%), Cape York (14%), Burnett Mary (10%), Wet Tropics (8%), and Mackay Whitsunday with the least (5%) (Table 8). Artificial and highly modified wetlands comprise 11.3% of wetland area and are greatest in the Fitzroy region and the least in Cape York.

The GBR's estuarine tidal wetlands include mangroves, salt flats and saltmarshes. Mangroves and related tree communities cover 55% of estuarine wetlands, with the greatest extent in Cape York and the least in Burnett Mary (Table 8). Mangroves of the GBR are a functionally diverse group of at least 44 species and hybrids (Duke & Larkum, 2019), which play a vital role in the coastal ecosystem by supporting ecologically diverse communities of flora and fauna and providing important ecosystem services (Pearson et al., 2021). Mangroves along the entire GBR coast are generally in excellent condition and relatively stable, with only small losses reported, mostly associated with port and urban development (Brodie & Waterhouse, 2018). However, weather-related events can cause significant impacts, in particular: cyclones, extreme sea level variation and heatwaves (Duke et al., 2022; GBRMPA, 2019).

Salt flats and saltmarshes are coastal ecosystems that occur in the upper intertidal area of estuaries (where saltwater inundation occurs less frequently), at the interface of marine and terrestrial environments. Salt flats and saltmarshes cover 45% of estuarine wetlands (Table 8), with approximately 32 species reported to occur in the GBR (Johns, 2019). The greatest extent of salt flats and saltmarshes occurs in the Fitzroy region, while the least extent is in the Wet Tropics (Table 8). The GBR's saltmarshes are vulnerable to anthropogenic pressures (such as direct use through construction of ponded pastures, salt ponds, urban development, vehicles, and illegal dumping), as well as climate change, excess nutrient, fine sediment and pesticide loads (GBRMPA, 2019; Pearson et al., 2021).

Freshwater wetlands of the GBR include lacustrine (lake) and palustrine (vegetated swamp) habitats located on coastal lowlands and floodplains (Figure 4) characterised by seasonal inundation. Riverine wetlands connect marine, estuarine, lacustrine and palustrine wetlands, and include those systems contained within channels (e.g., river, creek or waterway) and their associated streamside vegetation. Freshwater wetlands overall, provide essential functions and services, including the maintenance of natural inputs of water and suspended/dissolved materials to estuaries, coastal and marine ecosystems, in addition to reducing the impacts of floods, retaining sediment, absorbing and transforming pollutants and providing nurseries for fish and other freshwater and marine species (Pearson et al., 2021). This is discussed in further detail in Question 4.9 (Waltham et al., this SCS). The greatest overall freshwater wetland extent (41%) is located in the Burdekin region, while the smallest (3%) is within the Mackay Whitsunday region (Table 8).

In 2022 when this review was prepared, there was no new data on current extent of natural and near-natural wetlands since the 2017 SCS, as changes in wetland extent are assessed every 4-5 years. The next update expected to be reported in 2024. Historical losses provide important context for these assessments. Recent estimates suggest that the loss of wetlands (all types) in the GBR catchment area since European settlement are: 15% of saltmarshes, with around 30% of those remaining affected by bund walls; 19% of freshwater wetlands, but with variable condition; and 42% of forested floodplain (open forests and woodlands on drainage lines or low-lying areas that intermittently flood) (GBRMPA, 2019; Pearson et al., 2021). However, these figures vary between wetland types and NRM regions with substantial declines in some areas. The loss of wetlands has been most significant in the Wet Tropics (30.5%) and Burnett Mary (28.5%) regions. The greatest losses are in palustrine wetlands across all regions (except Cape York), particularly in the Wet Tropics and Mackay Whitsunday regions (approximately 49% and 44% loss respectively). Riverine wetlands are also showing greater losses, ranging between approximately 10% and 36% (excluding Cape York). Currently, natural wetlands (lakes, swamps and estuaries) in the GBR catchments have low rates of area loss (<0.1%, 2013-2017; DES, 2021) and are generally well protected (Adame et al., 2019). However, losses have been reported in the Fitzroy and Mackay Whitsunday NRM regions. For example, between 2004-2017 (14 years), decreases in extent of mangroves (1,146 ha), estuarine wetlands (1,495 ha), and saltmarsh grass areas (1,546 ha) occurred in the Plane Creek Basin catchment, Mackay Whitsunday region (Chamberlain et al., 2020). The mangrove decline was the result of changes in sediment profiles, defoliation, and inundation from a coastal cyclone, while reduction in estuarine wetland was primarily due to the alteration of natural flow regimes through stream regulation. The degradation of saltmarsh over time, was possibly due to climatic factors such as recent cyclonic activity, sea level variability, and prolonged inundation (Chamberlain et al., 2020).

Primary threats to the health of Great Barrier Reef ecosystems

Threats to the GBR are multiple, cumulative and increasing. A threat can be a driver, activity, pressure or stressor which has a potential adverse impact on the health of GBR ecosystems, whereas a threatening process is a sequence of events or activities that have the potential to cause an impact. The ten threats identified in the 2014 and 2019 Outlook Reports as presenting a very high risk to the GBR's ecosystem and heritage values related mostly to climate change, land-based runoff (water quality), and fishing, affecting values on a GBR-wide scale (GBRMPA, 2019). Primary threats are those which affect the majority of ecosystems and communities over a greater area more frequently.

A driver (driving force) is a natural or anthropogenic "superior complex phenomena" that affects how society functions and interacts with the built and natural environment, and can act independently or in combination (Oesterwind et al., 2016). Economic and population growth, technological developments and societal attitudes are key drivers that affect the nature and intensity of the four primary pressures influencing the GBR (climate change, unsustainable coastal development, declining water quality and direct use). Other key pressures threatening the diversity of marine life in the GBR include shipping, unsustainable fishing, disease, invasive species and marine debris (Richards & Day, 2018). The 2017 SCS concluded that the impacts of land-based runoff associated with past and ongoing catchment development, coastal development activities, extreme weather events, and climate change, are collectively contributing to the poor condition of the GBR (Waterhouse et al., 2017).

Climate Change

Anthropogenically induced climate change is internationally recognised as one of the biggest threats to global marine ecosystems, including the GBR. Gradual sea temperature increases, ocean acidification, sea level rise and extreme events, such as marine heatwaves and storms, are the most immediate threats and pose the highest risk.

For the last few years, coral bleaching, due to ocean warming associated with climate change, has impacted coral reefs worldwide (Hughes et al., 2017). Mass coral bleaching events occur during extended periods of elevated sea surface temperatures (in combination with high solar radiation) (Baird et al., 2018; Lewis & Mallela, 2018; Zhao et al., 2021) and have the potential to result in significant and widespread loss of coral, and flow on effects to fish and invertebrate communities (Baird et al., 2018; Hoogenboom et al., 2017). Mass bleaching events have been reported across the GBR in 1998, 2002, 2016, 2017, 2020 and 2022 (AIMS, 2022; McWhorter et al., 2022; Thompson et al., 2022). These reports demonstrate that since 2016 the majority of the GBR has been exposed to Degree Heating Week values in excess of 8, at which point severe coral mortality is likely (McWhorter et al., 2022). At the worst affected reefs, extreme levels of coral mortality (upwards of 67% mortality) occurred (Hughes et al., 2017; Hughes et al., 2018c; Pratchett et al., 2019a). On inshore reefs, 15% of observed coral cover losses recorded between 2006 and 2022 have been attributed to coral bleaching (Thompson et al., 2022), while modelling reported by Bozec et al. (2022) suggested that by 2020 bleaching was the dominant cause of coral mortality accounting for an estimated 48% of annual coral mortality rates.

Climate-related increases in sea temperature are not only causing increased coral bleaching and mortality, but also transforming coral reef assemblages in the GBR. For example, following the 2016 bleaching event, a regional-scale shift in the composition of coral assemblages was reported, reflecting markedly divergent responses to heat stress by different taxa (Hughes et al., 2018b). Fast-growing staghorn and tabular corals suffered a catastrophic die-off, transforming the three-dimensionality and ecological functioning of 29% of the GBR (Hughes et al., 2018b). Additionally, increases in sea temperature may also be hindering growth rates of branching corals in the GBR. For example, slower growth rates in *Acropora muricata* were reported for Davies Reef in 2012-2014, compared to 1980-1982 (Anderson et al., 2018), and significant differences in growth patterns for both the branching *Isopora palifera* and the massive *Porites* spp. were reported over an 11-year study period at Myrmidon Reef (Razak et al., 2020). Another consequence of mass bleaching and mortality of adult corals is impaired capacity for recovery. Following the 2016 and 2017 bleaching event, for example, larval recruitment declined by 89% in 2018 compared to historical levels, highlighting the multifaceted processes that underlie the global decline of coral reefs (Hughes et al., 2019). Overall, cumulative bleaching events are likely undermining systemic resilience of the GBR, by reducing (up to 80-100%) larval supply across the majority of bleached reefs (Cheung et al., 2021; Ortiz et al., 2018).

Extreme temperatures, such as those experienced during mass bleaching events in the GBR, not only caused reductions in live coral, but consistent declines have also been reported in coral-feeding fishes, at the most heavily affected reefs (Stuart-Smith et al., 2018). Changes in coral cover have also resulted in community-wide trophic restructuring of reef fishes and invertebrates, with a weakening of strong pre-existing latitudinal gradients in the diversity of fishes, invertebrates and their functional groups (Stuart-Smith et al., 2018). In particular, fishes that scrape algae from reef surfaces, considered to be important for recovery after bleaching, declined on northern reefs following the 2016 bleaching event, whereas other herbivorous groups increased on southern reefs (Stuart-Smith et al., 2018). These changes vary geographically, and may be particularly acute at locations where many fishes and invertebrates are close to their thermal distribution limits (Stuart-Smith et al., 2018). The spatial footprint of recent mass bleaching events presents an unprecedented threat to the connectivity, recovery and long-term resilience of coral populations, and those of other reef organisms (Dietzel et al., 2021).

Seagrass meadows are similarly impacted by thermal stress, in particular intertidal and shallow water seagrass, and this will impact the ecosystems and communities that depend on the goods and benefits they provide. Inshore seagrasses on the GBR experience water temperatures well above ambient, and at times over 40°C (McKenzie et al., 2022a). At these extremes, seagrass photosystems become impaired, plant energy balances go into deficit and leaves visibly burn (Campbell et al., 2006; Collier et al., 2017). This can cause plants to draw down on energy reserves and shed leaves to balance energy budgets (Collier & Waycott, 2014), resulting in reduced seagrass abundance. This may be exacerbated by cumulative stress caused by low light levels (e.g., turbidity) (Adams et al., 2020; Collier et al., 2016). This combination of stressors (high temperature and low light) also contributes to the senescent season, when late in the tropical wet season, seagrass declines. With a changing climate, there is a risk of this occurring earlier in the season and resulting in greater loss with rising sea surface temperature.

As well as water temperature increases in the GBR, an increase in air temperature is also a concern. This is significant for ecosystems and communities exposed to air, such as mangroves, intertidal seagrass, intertidal mud/sand flats and cays. Many habitat-forming species and the species that live in these habitats are sensitive to changes in air temperature, particularly extremes of temperature (e.g., marine turtles and seabirds) (Congdon et al., 2007; Hamann et al., 2007; Jensen et al., 2018).

Extreme Climate Events (ECEs) that impact marine habitat-forming communities are already occurring and are likely to become more severe and extensive in the relatively near future. For example, coral bleaching occurred across much of northern Australia due to marine heatwaves (MHWs) affecting different regions in 2011, 2013, 2016, and 2017 (Babcock et al., 2019). The emergence of summertime MHW hotspots (i.e., extreme, localised thermal anomalies, nested within broader increases in sea surface temperature), can result in distinct molecular, cellular and microbial responses in corals, driving rapid large-scale coral mortality and decay in atypical timeframes (Fordyce et al., 2019).

Some species of massive reef-building corals (e.g., *Porites*) appear to be acclimatising to consecutive heatwaves, as demonstrated by the decreasing presence of 'stress bands' (indicative of past bleaching) within the coral's skeleton cores, following successive bleaching events in the 21st century, despite increasing exposure to heat stress (DeCarlo et al., 2019). Similarly, high-frequency temperature variability (i.e., daily temperature range) is reported from field observations as the most influential factor in predicting bleaching prevalence, with a clear mitigation effect, for instance, a 1°C increase in daily temperature range could reduce the odds of more severe bleaching by a factor of 33 (Safaie et al., 2018).

Alternatively, the existence of potential thermal refugia within the GBR, that avoid significant warming more than expected by chance, have been suggested. For example, based on field observations, deeper areas of GBR could provide a refuge (i.e., 13% of the GBR) from mass bleaching for some taxa (Baird et al., 2018; Cheung et al., 2021). Coral connectivity is likely to become increasingly disrupted given the predicted escalation of climate-driven disturbance effects on larval production and recruitment, but the existence of thermal refugia, may provide pockets of systemic resilience in the near-term (Cheung et al., 2021; Hock et al., 2017). Nevertheless, the protection afforded could be very transient and limited, at the broad ecological scale, as severe bleaching was observed on deep reefs in the northern GBR during the 2016 mass bleaching event (Frade et al., 2018). In addition, the advantage of any potential climate refugia on the GBR may fail if global warming exceeds 3°C, based on projections by McWhorter et al. (2022).

Ocean warming under climate change threatens marine ecosystems not only directly through fatal heat stress, but also indirectly, by boosting the energy of cyclones and storms that cause habitat destruction and loss of associated organisms. Cyclone intensity is predicted to increase globally, causing more frequent occurrences of the most destructive cyclones with potentially severe consequences for GBR ecosystems. In the GBR, increases in cyclone intensity predicted for this century are sufficient to greatly accelerate degradation (Cheal et al., 2017).

Apart from the physical impact of severe cyclones and storms, the frequency and severity of associated rainfall and river flood plumes can significantly impact the GBR's ecosystems. Floodwaters can cause flood plumes, reducing the salinity of reefs and the light availability for photosynthetic habitat-forming species. During the anomalously high rainfall events in 2011, seagrass ecosystems were impacted on both east and west tropical coasts. Mangrove forests experienced high mortality during the 2016 El Niño across coastal areas of northern and north-Western Australia due to severe water stress driven by drought and anomalously low mean sea levels. Predictions from ecosystem models suggest that the widespread mortality of habitat-forming taxa will have long-term and, in some cases, irreversible consequences, especially if they continue to become more frequent or severe. The abrupt ecological changes that are caused by ECEs could have greater long-term impacts than slower warming that leads to gradual reorganisation and possible evolution and adaptation. ECEs are an emerging threat to marine ecosystems and will require better seasonal prediction and mitigation strategies (Babcock et al., 2019; Ortiz et al., 2018).

Due to increasing anthropogenic carbon dioxide (CO_2) in the atmosphere, the world's oceans are absorbing more CO_2 which is resulting in chemical changes in the ocean, including a decrease in oceanic pH (i.e., ocean acidification). Progressive seawater acidification (seawater CO_2 fugacity, i.e., partial pressure), has been recorded at two monitoring stations on the GBR's continental shelf, ~28% higher than 60 years ago (i.e., increasing trend of > 2.0 ± 0.3 µatm yr^{-1}) (Fabricius et al., 2020). The similarity in the decadal CO_2 trends at both stations to the atmospheric CO_2 changes suggested these CO_2 trends are largely determined by atmospheric forcing and indicate that carbonate dissolution from the seafloor is currently unable to buffer the GBR against ocean acidification (Fabricius et al., 2020). The implications of ocean acidification for calcifying organisms could be profound.

Globally observed coral reef calcification rates are declining (at 4.3 ± 1.9% yr^{-1}), with 0 net calcification rates estimated worldwide by approximately 2054 (Davis et al., 2021). Ocean acidification alone has caused 13 ± 3% decline in the skeletal density of massive *Porites* corals on the Great Barrier Reef since 1950 (Guo et al., 2020). Coral reef calcification is influenced by aragonite saturation levels (i.e., Ω_{ar}, a proxy of ocean acidification), depth, benthic calcifier cover and changes in water temperature. Spatial declines in mean aragonite saturation across and along the GBR have been reported to be associated with monotonic declines in coral juvenile densities (1.3-fold) and crustose coralline algae (up to 3.1-

fold), while non-calcifying macroalgae greatly increase (up to 3.2-fold). These three key groups of organisms are important proxies for coral reef health. Results also suggest a tipping point at Ω_{ar} 3.5–3.6 for these coral reef health indicators (Smith et al., 2020).

Although higher temperatures can facilitate higher calcification rates, the overall effect of ocean warming and heatwaves will likely counteract those benefits when temperatures rise above thermal bleaching thresholds (Davis et al., 2021).

Refer to **Question 2.2** (Fabricius et al., this SCS) for further information on the current and predicted impacts of climate change on GBR ecosystems.

Land-based runoff resulting in poor water quality

Land-based runoff comprises freshwater flows from the terrestrial environment and what is carried with it into receiving waterbodies, including fine sediments, nutrients, pesticides and other pollutants. Activities, such as the application of fertilisers, deforestation, livestock management, pest control, stormwater and sewage management, aquaculture, mining and fracking, and earthworks can all affect the resulting water quality. Diffuse source land-based runoff occurs naturally and has always delivered sediments and nutrients to the GBR lagoon. However, changes in land use within the catchment since European settlement have increased the loads of sediments, nutrients, pesticides and other pollutants (including heavy metals and plastics) entering the GBR (refer to **Question 2.3,** Lewis et al., this SCS, for further information on changes in land-based runoff from pre-development in the GBR) (Abessa et al., 2018; GBRMPA, 2019; Pratchett et al., 2019a). These pollutants pose a risk to GBR coastal and marine ecosystems, and there is a considerable body of evidence indicating that water quality is a major anthropogenic threat to GBR health and resilience (Schaffelke et al., 2017).

Primary pollutants in the GBR catchments are total suspended sediment (TSS), dissolved inorganic nitrogen (DIN), Photosystem II (PSII) herbicides and organic runoff. Recent estimates have indicated that since European settlement (c. 1850), the mean annual TSS delivery through river systems of the GBR catchments has increased 1.4 to 5-fold and doubled for DIN (McCloskey et al., 2021), and at least 30 t year^{-1} of herbicides are exported to the GBR (Davis et al., 2017). Anthropogenic sediment originates mainly from hillslope, gully and streambank erosion. Since European settlement, the predominant form of nitrogen that is delivered to the GBR catchments has also shifted from dissolved organic nitrogen (DON), typical of undisturbed landscapes, to DIN, derived from crop fertiliser, grazing animal urine, soil mineralisation, sewage wastes, and to particulate nitrogen (PN) derived from soil erosion. Increased phosphorus (P) loading has not attracted the same attention as nitrogen, because phosphorus fertilisers are not extensively used in the GBR catchments. However, phosphorus is applied in some sugarcane agriculture, and mean annual total phosphorus load has increased by 8.9 times since European settlement. Most of the commonly detected herbicides originate from sugarcane and grain cropping, with a limited suite from the grazing and plantation-forestry industries. Recent monitoring of pesticide residues across the GBR catchments has shown widespread contamination of rivers and streams by a range of pesticides, with frequent exceedances of Australian water-quality guidelines, by up to 50-fold (Davis et al., 2017). Bacterial metabolism of organic runoff from agriculture, along with nutrient-derived eutrophication, can cause severe hypoxia in lentic water bodies and fish kills (Davis et al., 2017).

Since the release of the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP) in 2018, actions and progress towards Reef 2050 WQIP targets are assessed annually. The whole-of-GBR water quality targets in the Reef 2050 WQIP to be achieved by 2025 include: 1) at least a 60% reduction in anthropogenic end-of-catchment dissolved nitrogen loads; 2) a 20% reduction in particulate nutrient loads; 3) a 25% reduction in fine sediments; and 4) to protect at least 99% of aquatic species at the end-of-catchment from pesticides. Since then, inshore water quality has improved in the Wet Tropics and Mackay Whitsunday NRM regions (stable in the Burdekin), and in 2020-21 was considered moderate overall (Moran et al., 2022). However, the improvements have been slow and broad reaching and sustained improvements in the marine water quality of the inshore reef have not been observed yet (Moran et al., 2022). Poor water quality continues to affect many inshore areas of the GBR. The rate of reduction of pollutant loads has been slow, reflecting modest improvements in agricultural land management practices (GBRMPA, 2019).

It is not only individual pollutants which can affect GBR health, but the cumulative impact of pollutants and other pressures (refer also to Question 2.4, Uthicke et al., this SCS). For example, excessive sediment delivery to the marine environment is one component in a series of threatening processes to coral that include coral bleaching, damage by storms, and COTS. Sediment and the pollutants they carry can cause marine ecosystem declines and adversely impact recovery following disturbance by other pressures. Significantly, a portion of the nitrogen (N) species carried by fine sediment in the freshwater system is released in the marine environment, thereby perturbing marine ecology. Available controls on sediment and pollutant delivery are decreasing the rates in hillslope erosion, gully and streambank erosion, sediment deposition in sediment sinks including footslopes, floodplains, and water reservoirs, and the application rates of pesticides and fertilisers. By reducing sediment fluxes through the combined strategies of erosion control and deposition enhancement, near- and offshore impacts can be reduced. Gully erosion is a more significant source of fine sediment than hillslope and streambank erosion. Fertiliser and non-fertiliser N and pesticides carried by sediment play an important role in coral reef degradation (Hairsine, 2017).

- *Sediments and particulate nutrients (refer also to Questions in Theme 3)*
  Since European settlement, fine sediments entering the GBR lagoon are estimated to have increased five-fold, and in some regions up to eight-fold. The Burdekin region is the major contributor (approximately 40%) of the total anthropogenic sediment load to the Region, followed by the Fitzroy (18%), Wet Tropics and Burnett Mary regions (15% each) (GBRMPA, 2019) (refer also to Question 3.3, Prosser and Wilkinson, this SCS).

  The main source of sediment loads from land are from grazing lands, and include erosion on hillslopes and subsurface erosion from gullies and streambanks. Sediments from urban areas and port developments (including maintenance/capital dredging and associated disposal of dredge material) can be important, but at local scales (GBRMPA, 2019). A study reconstructing land uses changes on GBR river catchments from long-term coral Barium/Calcium (Ba/Ca) records, documented a tripling of flood plume suspended sediment loads delivered by the Burdekin River to the GBR lagoon relative to 'natural' pre-development baseline levels (D'Olivo & McCulloch, 2022).

  Mining and the increased runoff variability in the latter half of the 19th century are the likely sources of the original excess sediment that was used to build the bench features in these catchments. Grazing also contributed to increased bench sedimentation prior to 1900, however, the contribution of grazing was likely more significant in the second half of the 20th century and continues to be a dominant land use contributor today. Grazing is also likely to be exacerbating any damage done by mining and slowing landscape recovery. Therefore, managing both current, and legacy, sediment sources, will be critical for improving water quality to the GBR (Bartley et al., 2018).

  Sediment loads are exacerbated by highly variable rainfall patterns across the various river catchments. Sediments delivered from flood plumes settle relatively close to river mouths (within 50 km). However, fine sediment is carried further in suspension. Delivery and resuspension of new sediments from runoff and dredging, and resuspension of existing sediments, combine to affect water quality condition, and potentially impact on inshore marine ecosystems (GBRMPA, 2019; Howley et al., 2018) (refer also to Question 3.1, Lewis et al., this SCS).

  Regarding particulate nutrients (which often bind to sediments), the largest loads of particulate nitrogen originate from the Wet Tropics (27%) and Fitzroy (20%) regions. Particulate nitrogen primarily comes from land used for grazing. The largest phosphorus loads come from the Fitzroy (33%) and Burdekin (22%) regions. In the Wet Tropics and Mackay Whitsunday regions, the main source of phosphorus is sugarcane farming. Grazing activities contribute the most in other regions (GBRMPA, 2019).

  Refer to **Question 3.1** (Lewis et al., this SCS) for further information on the spatial and temporal distribution of terrigenous sediments in the GBR.

- *Nutrients (refer also to Questions in Theme 4)*
  Nutrients occur naturally in the GBR environment in relatively low concentrations. They include dissolved inorganic and organic nutrients (such as nitrogen, phosphorus and carbon) and particulate nitrogen (PN) and phosphorus (PP). Modelling indicates that total DIN loads exported to the GBR via land-based runoff have more than doubled since European settlement, from approximately 20,000 to 46,500 t yr^{-1}. This is largely due to land use changes in the catchment, particularly fertiliser use in agriculture (predominantly sugarcane) (McCloskey et al., 2021) (refer also to Question 4.4, Prosser and Wilkinson, this SCS). The rivers which contribute the most and pose the greatest total DIN exposure risk to coral are reported to be the Burdekin and Tully (Waterhouse et al., 2017; Wolff et al., 2018). Urban areas also contribute small amounts of nutrients to inshore waters, such as through wastewater discharges, which are important at a local scale (GBRMPA, 2019). Other sources of nutrients include wind-resuspension of fine sediments, dust storms, upwellings and the growth of the cyanobacteria *Trichodesmium.* Naturally occurring in the GBR, *Trichodesmium* is recognised as a significant source of N to the GBR, and although its growth has increased significantly since 2002 in the southern GBR, more research is needed to identify its relative importance and potential impacts (Bell, 2021).

  Similar to suspended sediments, most nutrient concentrations decrease along a gradient from the upper catchment to the flood plume. However, dissolved nutrients within flood plumes stimulate phytoplankton blooms that can inundate offshore coral reefs, with the exact area affected determined by flood magnitude, wind direction and wind speed (Howley et al., 2018). The dynamics of nutrients, together with those of phytoplankton, zooplankton and water clarity on the GBR are influenced by seasonal variation in coastal and oceanic conditions, and anthropogenic inputs (Skerratt et al., 2019). For example, during La Niña climatic events, DIN, primary production and phytoplankton biomasses are generally higher in inshore and midshelf waters, while there is little difference in offshore waters (Skerratt et al., 2019). Cross-shelf nutrient gradients are also reflected in bacterial assemblages, with nutrient dynamics and temperature explaining 41.4% of inter-seasonal and cross-shelf variation (Frade et al., 2020).

  Refer to **Question 4.1** (Robson et al., this SCS) for further information on the spatial and temporal distribution of nutrients in the GBR.

- *Pesticides (refer also to Questions in Theme 5)*
  Pesticides, including insecticides, herbicides, fungicides, miticides and rodenticides are widely used in Australian agriculture, by local councils and in smaller volumes in urban situations (GBRMPA, 2019). Australia has a long history of using pesticides and as a result, pesticide contamination is widespread across both rural and urban areas. Where monitoring exists in waterways, pesticide residues are detected widely and at concentrations often above Australian guidelines (Spilsbury et al., 2020), and commonly above published effect levels, especially in intensive cropping situations (Brodie & Landos, 2019; Spilsbury et al., 2020).

  A large number of individual pesticides used mainly in agriculture are lost from farming operations and discharged into streams and the GBR (refer also to Question 5.2, Templeman and McDonald, this SCS). The largest group present in relatively high concentrations are herbicides (many are PSII types) such as diuron and triazine types (Spilsbury et al., 2020), with more than a dozen known to present some risk to GBR coastal, estuarine, and lagoonal habitats and species (Brodie & Landos, 2019). Fifty-nine different types of pesticides and pesticide metabolites have been detected in the GBR catchments (Vandergragt et al., 2020). Pesticides are found throughout the GBR lagoon following river discharge events, but the highest areas of concern are in coastal wetlands, estuarine and coastal waters where pesticides are regularly found above Australian water quality guideline concentrations (refer also to Question 5.1, Negri et al., this SCS). Insecticides are also of some concern especially the neonicotinoid insecticides such as imidacloprid, which is widely used in sugarcane cultivation to control cane grubs and commonly found in streams draining sugarcane lands (Brodie & Landos, 2019).

The current Reef 2050 WQIP pesticide target aims to protect at least 99% of aquatic species from all pesticides, as measured at the end-of-catchments. Initially, pesticide reduction focused mainly on reducing the loads of five PSII herbicides (ametryn, atrazine, diuron, hexazinone and tebuthiuron). However, with advances in understanding of the toxicity of a broader range of pesticides, the assessment expanded to 22 pesticides (PSII herbicides, other herbicides and insecticides) with a focus on reducing concentrations (that directly relate to species protection) rather than loads of pesticides (Gallen et al., 2019b).

Since 2009, there has been no clear reduction in nearshore marine pesticide concentrations linked to improved land management practices (Brodie & Landos, 2019), indeed concentrations appear to have increased (Taucare et al., 2022, see also Question 5.1, Negri et al., this SCS). Diuron, atrazine and hexazinone are the most consistently detected and abundant PSII herbicides at most nearshore marine locations assessed, reflecting land use in sugarcane, horticulture and grain cropping industries. The concentrations of pesticides in marine waters of the GBR, however, remains generally low (Gallen et al., 2019a; 2019b). The highest pesticide concentrations are found in the Mackay Whitsunday region (in particular Flat Top island, Repulse Bay and Sandy Creek) (Thai et al., 2020), although low maximum pesticide risk was reported for all these inshore sites in 2019-20 and 2020-21 (Moran et al., 2022) (refer also to Question 5.1, Negri et al., this SCS). The spatial pattern of pesticide concentrations in the marine environment reflects the dominant land use in the adjacent catchment, and highest concentrations are found closest to the source. Sugarcane cropping contributes more than 95% of the total load of PSII herbicides entering the GBR and is the dominant land use in the Wet Tropics. The cumulative effects of long-term exposure to the mixture of pesticides is not well understood, and there is the potential that exposure may reduce resilience of inshore seagrass and coral habitats (GBRMPA, 2019; Spilsbury et al., 2020; Thai et al., 2020).

Refer to **Question 5.1** (Negri et al., this SCS) for further information on the spatial and temporal distribution of pesticides in the GBR, and the ecological impacts and risks to GBR ecosystems.

- *Other pollutants (refer also to Theme 6)*
  Other pollutants (such as alternate pesticides, antifouling paint components, coal particles, petroleum hydrocarbons, heavy/trace metals and metalloids, nanomaterials, marine debris including microplastics, pharmaceuticals and personal care products) occur in the marine environment, however, little is known about their sources, role and fate in the GBR (Kroon et al., 2020). All these other pollutants pose a risk to marine ecosystems, however, further research is required before that risk can be effectively evaluated at the scale of the GBR (Kroon et al., 2020).

  Marine debris (marine litter), in particular plastic, causes environmental, economic, aesthetic and human health impacts. The most common marine debris found in the GBR are plastic remnants (including lids, wrappers and containers), rope and net scraps, cigarette butts and rubber footwear (Kroon et al., 2020). The distribution and volume of marine debris are highly influenced by the amount washed into the GBR, the size and buoyancy of the debris, and the effects of currents, winds and the shape of the coastline and offshore islands. Marine debris enters the GBR from the catchment (from industrial and urban sources) and from local and international ocean-based activities (ship-sourced waste, abandoned fishing gear from recreational and commercial fisheries, and recreational uses and tourism). Marine debris from rivers in the GBR catchments is estimated to travel an average of 19 km from its source, whereas marine debris from shipping is estimated to travel approximately 225 km (GBRMPA, 2019). Additionally, small microplastics <300 µm have been reported to be abundant in water samples from the Whitsunday Islands region (Carbery et al., 2022).

  Other pollutants, including heavy/trace metals and metalloids, antifouling paints, coal dust and particles, petroleum hydrocarbons, pharmaceutical, veterinary, and personal health care products (PVPs) (such as cosmetics and soaps) can be found in the marine ecosystems of the GBR. Chronic contamination from antifouling paints and exposure to personal care products has been assessed as a risk in regions south of Cape York. These pollutants are associated with land-based runoff and high levels of human occupation locally and globally. Wastewater is one of the most significant sources of PVPs pollution, and the risk is greatest around urban centres.

Pharmaceuticals and personal care products have been found in treated sewage (for example, paracetamol in the Fitzroy region), although monitoring information on spatial and temporal variation of these pollutants is limited (GBRMPA, 2019; Kroon et al., 2020; Pratchett et al., 2019a). Evidence of PVPs in GBR waters is limited, with 26 pharmaceuticals in wastewater effluent from the Burdekin region being reported in the sub-µg L^{-1} range, including venlafaxine, hydrochlorothiazide, and citalopram, demonstrating the substantial dilution that occurs (Gallen et al., 2019a). A study of 73 sites from 19 waterways across Queensland reported that caffeine, paracetamol and salicylic acid were detected in 60% of samples, followed by carbamazepine (27%) and triclosan (25%). At least 50 wastewater treatment plants are operational within the GBR catchment area and discharge effluent into the environment. As the population increases over the coming decades, chemicals associated with urban and industrial uses may become of greater concern to coastal environments and wildlife (Gallen et al., 2019a).

Refer to **Question 6.1** (Chariton and Hejl, this SCS) for further information on the spatial and temporal distribution of other pollutants and their associated risks in the GBR.

Direct Use

Direct use of the GBR includes commercial marine tourism, defence activities, fishing, recreation, research and educational activities, ports, shipping and the traditional use of marine resources. The eight identified direct uses of the GBR expose the GBR's values to a variety of impacts at a local scale and cumulatively. When coupled with the highest and most immediate threats to the GBR (such as sea temperature increase and altered weather patterns), the impact of direct use is amplified. Some activities (tourism, defence, ports and research) tend to be localised, while other uses (fishing, recreational use and shipping) are more widespread (GBRMPA, 2019).

- *Fishing*
  Fishing is the largest extractive use of the GBR. Trawl, net, line and pot remain the most significant commercial fishing methods. Recreational fishing remains one of the most popular activities on the GBR and in estuaries. Threats from fishing include high risk bycatch of coastal dolphin, sawfish, dugong and turtle in the inshore fin fish fishery; and overfishing, resulting in collapse of the scallop fishery, unsustainable harvest of snapper, pearl perch and Spanish mackerel fisheries. Illegal fishing (recreational and commercial) persists as an issue. No-take zones are exhibiting a variety of benefits for fisheries' sustainability and ecosystem health (GBRMPA, 2019).

- *Shipping*
  Shipping traffic through the GBR is relatively limited compared with busier international locations, although the number of cruise ships transiting the GBR is increasing. Advances in technology, regulation, inspections and the level of monitoring of shipping traffic have improved shipping safety. Shipping and its impacts in the GBR have remained constant since 2014. However, knowledge and management gaps remain around the impact of ship anchoring, resuspension of sediments from ship propellers and light pollution from ships at anchor (GBRMPA, 2019).

- *Ports*
  While port operations and their impacts have remained constant since 2014, regulatory changes for ports in 2015 have reduced some threats and increased management effort. Port maritime development has slowed since that time (GBRMPA, 2019).

- *Recreation*
  Recreational use (not including fishing) is one of the major direct uses of the GBR. It encompasses short trips to the beach through to longer journeys to the outer GBR. Between 2014 and 2018, the number of recreational vessel registrations in the GBR was the highest recorded. The broad cultural value of the GBR has significantly increased for residents since 2013, despite coral condition decreasing (GBRMPA, 2019).

- *Defence activities*
  Defence activities, specifically training, are expected to be maintained or increase in frequency and intensity. While modern defence training activities have negligible impacts on the GBR, balancing defence activities with conservation in sensitive habitats remains a high priority (GBRMPA, 2019).

- *Traditional use of marine resources*
  Traditional use of marine resources is a key part of the GBR's Indigenous heritage and the ongoing connection of Traditional Custodians and Owners to their Land and Sea Country. Since 2014, new Traditional Use of Marine Resource Agreements (TUMRA) have been accredited bringing the cumulative area covered by these agreements to approximately a quarter of the GBR's coastline (GBRMPA, 2019).

- *Tourism*
  Commercial marine tourism remains the highest contributing GBR-dependent industry to the GBR's economy. Since 2014, the number of visitors to the GBR has generally increased (with the exception of the travel restrictions as a consequence of the COVID-19 pandemic in 2020 and 2021). The GBR Marine Park Authority's (GBRMPA) high standard tourism program remains in place, although uptake has slowed. Interpretive products about the GBR's values and training for GBR tourism guides have increased (GBRMPA, 2019).

- *Research and educational activities*
  Research and educational activities occur in many parts of the GBR, often in the vicinity of research stations or urban centres. Understanding of cumulative effects of the impacts associated with research and educational activities remains limited (GBRMPA, 2019).

Others

- *Coastal development*
  Coastal development includes all development activities, construction and land uses along the coastline as well as inland areas within the GBR and development on islands. The broad range of intensive land use in the catchments exerts individual and cumulative pressures on coastal and inshore ecosystems (GBRMPA, 2019).

- *Invasive species*
  Invasive species include plants, animals, and other living organisms (e.g., microbes) which have been introduced (i.e., non-native) and have negative consequences on the GBR. Introductions of non-native species to the GBR are the result of human activities, such as shipping (ballast water and fouling), mariculture and ornamental trade.

  On the GBR, marine invasives include animals such as the Asian green mussel (*Perna viridis*) and Caribbean tubeworm (*Hydroides sanctaecrucis*), both of which can grow quickly and cover underwater walls, boat hulls and intake pipes and compete with native fauna. However, some of the biggest threats are in the catchments and freshwater wetlands of the GBR.

  Invasive plants such as grasses and water hyacinth, introduced as ponded pasture species or ornamentals, can invade rivers and wetlands, particularly those disturbed by riparian vegetation loss and elevated nutrients (Pearson et al., 2021). They compete with native vegetation, cover open water and mud flats, depleting invertebrate, fish and bird assemblages. They can also reduce effective stream width, causing deepening and loss of habitat, create barriers to animal movement and cause hypoxia and fish kills (Pearson et al., 2021).

  Feral stock animals, including pigs, cattle and horses, may damage waterway habitats and reduce water quality. For example, feral pigs severely disrupt wetland habitats and fauna (Pearson et al., 2021). Invasive aquatic species include many fishes accidentally or wilfully introduced to waterways, including aquarium, ornamental and consumable species (Pearson et al., 2021). These species tend to be most abundant in disturbed waters, with mixed or unknown impact on native species (Pearson et al., 2021).

- *Crown-of-thorns starfish (refer also to Question 4.3)*
  Crown-of-thorns starfish (COTS, A*canthaster* sp.) are notorious for their destructive consumption of live coral that decimates tropical coral reefs, an attribute unique among tropical marine invertebrates. Their populations can rapidly increase from 0–1 COTS ha^{-1} to more than 10–1,000 individuals ha^{-1} in a short time period causing a drastic change to benthic communities and reducing the functional and species diversity of coral reef ecosystems (Deaker & Byrne, 2022). Population outbreaks were first identified to be a significant threat to coral reefs in the 1960s. However, the factors influencing outbreaks remain elusive (e.g., increased nutrients and water quality, larval connectivity, fishing pressure, abiotic conditions) (Deaker & Byrne, 2022; Matthews et al., 2020). What is becoming increasingly clear is that the success of COTS is tied to their inherent biological traits, especially in early life. Survival of larval and juvenile COTS is likely to be enhanced by their dietary flexibility and resilience to variable food conditions as well as their phenotypically plastic growth dynamics, all magnified by the extreme reproductive potential of COTS. These traits enable COTS to capitalise on anthropogenic disturbances to reef systems as well as endure less favourable conditions (Deaker & Byrne, 2022).

  There have been four documented outbreaks of COTS on the GBR, commencing in approximately 1962, 1979, 1993, and 2009 (Pratchett et al., 2019a) and there is currently an ongoing outbreak in the southern GBR (AIMS, 2022). The next outbreak predicted in the 'initiation area' between Cairns and Lizard Island, is predicted to begin between 2025 and 2027 (Babcock et al., 2020). Using newly developed tools and understanding, COTS densities can now be detected and controlled through targeted culling. Pre-outbreak aggregations can be predicted in low-density COTS populations using both conventional surveys (e.g., manta tows) and now with genetic methods (eDNA), there is a better understanding of where to find post-settlement COTS (Babcock et al., 2020).

  Refer to **Question 4.3** (Caballes et al., this SCS) for further information on the drivers of COTS population outbreaks in the GBR.

Cumulative pressures

Ecosystems and species rarely respond to pressures in isolation, and the greatest changes or declines occur as a result of disturbance history as well as present threats. The interactions and feedbacks among multiple pressures can produce additive, synergistic or antagonistic effects. For example, loss of coral cover on inshore reefs is driven by acute disturbances, most notably cyclones and marine heatwaves (Ceccarelli et al., 2020; Thompson et al., 2022). However, changes in coral cover at local scales result from different combinations of sea surface temperature, nutrient and turbidity parameters, exposure to high turbidity (primary) floodwater, depth, grazing fish density, farming damselfish density, and management zoning (Ceccarelli et al., 2020). In contrast, the recovery of coral communities following coral loss is influenced by environmental conditions, with recovery reduced by poor water quality (Bozec et al., 2022; Castro-Sanguino et al., 2021). Other research has shown that suspended sediments can act as additive stressors to seawater acidification on coralline algae, macroalgae and coral juveniles along the GBR (Smith et al., 2020).

Overall, the cumulative impact of multiple acute stressors (e.g., heatwaves and cyclones), and to a lesser extent chronic poor water quality, are the greatest contributors to the overall degradation of specific coral groups in the GBR (Castro-Sanguino et al., 2021). Similarly, a history of cumulative pressures facing the GBR's inshore seagrass meadows (including cyclones, floods, or thermal anomalies), are evident in current seagrass condition and the ongoing need for improved recovery (McKenzie et al., 2022a). Also, the effects of pollutants may combine with other anthropogenic impacts (such as fishing, climate change, habitat loss, and ocean acidification) to increase pressures to ecosystems (Abessa et al., 2018).

Understanding cumulative pressures is critical for effective management actions to reduce degradation of the GBR. For example, modelling that incorporated the cumulative pressures of tropical cyclones, coral bleaching, predation, and competition between corals, identified that a moderate level of catchment restoration would improve median inshore coral cover by 2%, but when combined with enhanced protection of COTS predators, coral cover improved by 14% suggesting that combining interventions may be highly effective (Condie et al., 2021). Although rapidly escalating climate change impacts are the largest threat to coral reefs of the GBR and globally, these findings suggest that proactive management actions that effectively reduce chronic stressors at local scales should contribute to improved reef resistance and recovery potential following acute climatic disturbances (Ceccarelli et al., 2020).

Refer to **Question 2.4** (Uthicke et al., this SCS) for further information on cumulative impacts on GBR ecosystems.

Relative risks for ecosystems

A comprehensive relative risk assessment across GBR ecosystems (sensu GBRMPA, 2019) is beyond the scope of this Rapid Review, however, across the body of evidence, climate change and acute impacts (i.e., cyclones/storms) are generally considered the most severe threats to GBR ecosystems, and declining water quality is undermining resilience and hindering recovery. Resilience underpins the sustainability of ecosystems and is defined as the capacity to withstand and recover from threatening processes. Although these threats are common across GBR ecosystems, how individual ecosystems are affected and how they respond differs.

Corals

Ocean warming, cyclones, and widespread coral mortality due to increasingly frequent and severe coral bleaching events are degrading coral reefs. GBR-wide simulations over a 13-yr period reported that annual rates of coral mortality (annual absolute cover loss –0.74% yr^{-1}) were mostly influenced by bleaching (48%), ahead of cyclones (41%) and COTS predation (11%) (Bozec et al., 2022). Other authors have reported that acute impacts (i.e., storms) have the greatest explanatory power in coral loss and changes in community composition, regardless of shelf position (Mellin et al., 2019b), and that impacts from intense chronic stress are difficult to identify due to unclear mechanisms (Lam et al., 2018).

Chronic pressures imposed by water quality are most evident in the recovery of coral communities following acute events. For example, coral resilience is reported to be negatively related to the frequency of river plume conditions (Mellin et al., 2019a), and the greatest influence on coral recovery on inshore and midshelf reefs has been identified as water quality (suspended sediments), which can delay recovery at 25% of inshore reefs (Bozec et al., 2022), a result supported by Castro-Sanguino et al. (2021). Suppression of coral recovery also appears in proportion to contaminant loads delivered from local catchments (Thompson et al., 2020). However, gradients in nutrients and turbidity from inshore to offshore across the GBR had minimal effect on the severity of bleaching in relation to the 2015-2016 bleaching event (Hughes et al., 2018c).

The scientific literature shows that across the GBR there are many causes of coral decline, often quite reef-specific, and how reefs respond to pressures varies spatially and depends on the resilience of the coral assemblage and the history of disturbance. Some coral communities live under extreme environmental conditions (i.e., low pH, low oxygen, and variable temperature), such as those within some GBR mangrove lagoons, which suggests high resilience to stressors and highlights the need to study unfavourable coral environments to better resolve mechanisms of stress tolerance (Camp et al., 2019). Further work is also needed to unpack the cumulative impacts of acute and chronic pressures on coral reefs. Nevertheless, reducing chronic stressors at local scales, such as mitigation of high sediment and nutrient loads through improved water quality, will support inshore and midshelf reefs to maintain resilience in an increasingly disturbed future (Ceccarelli et al., 2020; Good & Bahr, 2021; MacNeil et al., 2019; Morgan et al., 2017).

Seagrass

Severe climatic events (e.g., cyclones) causing physical damage and degraded light regimes from increased turbidity are the principal factors of declining seagrass abundance (Brodie & Waterhouse, 2018; Lambert et al., 2021; McKenzie et al., 2022a). Apart from the intensifying pressures of climate change (e.g., rainfall, river discharge and tropical storms), the greatest threat to seagrasses along the GBR coast comes from agricultural runoff, followed by urban and industrial runoff, urban port and infrastructure development, dredging, shipping accidents, bottom trawling, boat damage, and other fishing methods (Grech et al., 2011). Cumulative impacts from elevated sea water temperatures and reduced light availability (due to increased sediments and nutrients), in combination with herbicide exposure that runs off agriculture land, are threatening seagrass health, although there is a scarcity of studies testing the interactions of these pressures (King et al., 2021). The seagrass meadows identified at greatest risk of cumulative impacts are all adjacent to population centres or areas of farmland, in sheltered north facing bays, and are all located in the populated southern half of the GBR. Industrial ports are also located in sheltered bays and although heavily regulated, contribute to pressures on seagrass meadows (Coles et al., 2015).

The capacity for seagrass ecosystems to cope with disturbances (seagrass resilience) varies depending on the plant communities' ability to resist disturbances (through physiological processes and modifications to morphology), and recover following loss (by regeneration from seed and through plant growth) (McKenzie et al., 2022a). Seagrass species vary in their dependence on resistance and recovery strategies. The species are classed as 'colonising', 'opportunistic', or 'persistent' with increasing dependency on 'resistance' and reduced dependency on 'recovery' strategies through these groups (Kilminster et al., 2015). Seagrass meadows of the GBR are often multi-species and dominated by fast growing colonising and opportunistic species (McKenzie et al., 2022a). The predominance of species, however, varies spatially and temporally within and between habitats. In general, estuarine and coastal seagrass habitats of the GBR are dominated by opportunistic species, reef habitats by persistent and opportunistic species, and deepwater by colonising species. When seagrass meadows are exposed to prolonged or severe levels of stress they can shift to a non-vegetated habitat i.e., disappear. Most meadows can recover, to at least some degree, however, this depends on the nature of external stressors on the system and the availability of a seed bank and viable propagules. The transitory or enduring nature of meadows depends on their species composition and environmental factors, such as exposure. For example, transitory meadows tend to be dominated by colonisers (e.g., *Halophila*) and enduring dominated by opportunistic and persistent species (e.g., *Zostera* and *Thalassia*, respectively) (Kilminster et al., 2015). Therefore, the type of meadow and the resilience features of the species present are critical to the management strategies that can be adopted to protect or enhance resilience.

Seagrass condition is strongly influenced by pressures acting on the GBR, the rate of recovery (i.e., resilience) and time since disturbances (McKenzie et al., 2022a). This is particularly so in the dynamic estuarine and coastal habitats where seasonal and inter-annual variability in pressures force changes, and where declines and localised losses in meadows have occurred (McKenzie et al., 2022a). Climate change is the most significant threat to the GBR's long-term outlook and is likely to intensify pressures and increase the need for meadow resilience. Securing a future for GBR seagrass ecosystems will require an increased need to maintain and build meadow resilience. Water quality improvements to catchment runoff are expected to provide some relief from these impacts and improve meadow condition and resilience, but further options for enhancing resilience need to be explored such as focused restoration efforts using seed-based approaches, active environmental engineering to improve habitat suitability by mitigating limiting factors (e.g., wave energy, erosion) or creating new habitat (McKenzie et al., 2022a).

Wetlands

Major threats to GBR wetlands include historic wetland loss due to landscape modification including drainage and infilling (DES, 2021), water pollution (runoff of fine sediments, nutrients, pesticides and other pollutants that flush into wetlands through surface runoff and groundwater drainage), invasive species, altered hydrological connectivity due to agricultural and urban development, and increasing temperature and salinity from climate change (Adame et al., 2019). Cumulative pressures on freshwater wetlands' ability to function efficiently continue to come from poor water quality and changes in hydrology, including dams. Human-induced pressures include: expanding urban land uses and transport infrastructure (roads); the introduction and spread of aquatic and terrestrial invasive species; and intensive land use for grazing, agriculture, horticulture, and mining (Adame et al., 2019; Pearson et al., 2021). A changing climate is a significant threat to wetlands, potentially altering wetting and drying cycles, increasing fire frequency and intensity, and raising sea levels (GBRMPA, 2019; Pearson et al., 2021; Tibby et al., 2019).

Excessive nutrients in the GBR catchments, coupled with elevated temperatures, have deteriorated water quality, caused excessive growth of algae and aquatic weeds, influenced phytoplankton composition, enhanced decomposition of organic material and decreased macroinvertebrate and fish diversity (Pearson et al., 2021). Excess nitrogen has contributed to dieback of mangrove forests during periods of low rainfall (Adame et al., 2019). Increased sediment has resulted in the loss of native freshwater moray (*Gymnothorax polyuranodon*) habitat (Ebner et al., 2016), and increased turbidity has possibly decreased the diving duration of freshwater turtles. Some invertebrate species in lowland streams of the catchments, however, have shown resistance to high levels of suspended sediments, at least in the short-term (Adame et al., 2019). In estuarine wetlands, excessive sedimentation can increase mangrove areas in some locations, but also cause the death of trees in other areas where sediment buries seedlings and roots (Lovelock & Ellison, 2007). Pesticides are also a significant source of stress for wetlands in the GBR catchments. The most regularly reported herbicides are PSII inhibitors including atrazine, ametryn, hexazinone, tebuthiuron and diuron. Herbicides can affect the whole food chain, for example by reducing growth in benthic microalgae, modifying diatom community composition, and causing osmoregulatory disturbances in amphibians and fish (Adame et al., 2019; Kroon et al., 2015).

Wetland degradation caused by nutrient runoff and hydrological alteration favours the establishment of invasive non-native macrophytes, which reduce oxygen levels in the water column. Hypoxia events during summer months can cause extensive fish kills. Other non-native species impacting wetlands include cane toads, several fish species, pigs, cattle, and horses (Adame et al., 2019; Pearson et al., 2021). In the GBR catchments, barriers such as tidal exclusion bunds, dams, weirs, roads, rail crossings, urban infrastructure, weirs, and aquatic plant blockages have also altered hydrological connectivity (Adame et al., 2019).

Human-induced climate change is the major long-term threat to the condition of the GBR wetlands, as increased temperatures and changes to flow regimes may have consequences for fundamental ecosystem processes (Pearson et al., 2021). As temperatures increase, oxygen concentrations in the water column decrease, causing asphyxiation of aquatic animals which are unable to surface, respire, or escape. Increased temperature can cause both acute and chronic exposure effects in aquatic biota. Climate change is also varying the timing, frequency, and intensity of precipitation. A decrease in precipitation could change river flow patterns, which may decrease connectivity, increase salinity, and decrease sediment supply. Tropical storms cause defoliation, abrasion, stem breakage, uprooting and sediment smothering of wetlands. Sea level rise will also impact wetlands, especially coastal wetlands (Adame et al., 2019; Pearson et al., 2021).

Megafauna

Direct use (e.g., incidental catch, collisions with vessels) is the greatest threat to megafauna of the GBR, however pollutants from land-based runoff and habitat loss are also significant pressures. Loss of habitats, such as seagrass meadows and coral reefs, are primarily a consequence of climate change (rising temperatures, increasing frequency of severe storms and associated rainfall) and land-based runoff. Habitat losses have had profound consequences for megafauna, in particular dugong and sea turtle, by causing starvation and associated impacts such as delayed breeding. Pollutants from land-based runoff, such as trace elements (e.g., metals and organochlorines), are impacting coastal sea turtle and inshore dolphin populations (e.g., Australian humpback and snubfin) in the central and southern GBR (Cagnazzi et al., 2020; Gaus et al., 2019; Villa et al., 2017). Elevated seawater temperature is also influencing physiological condition, development rate, growth rate, swimming ability, reproductive performance, and behaviour of megafaunal fishes (including sharks and rays) (Johnson & Marshall, 2007).

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

Some of the most recent findings from studies published since the 2017 SCS, include:

- Improved understanding about the factors that contribute to the resilience of the GBR's key ecosystems and habitats, and how they recover after loss.

- Better understanding of cross-shelf variation in coral assemblages, the influence of environmental conditions and threatening pressures (elevated temperatures), and the importance of constraints such as successful recruitment (particularly following bleaching events). This has been helped by improved inshore condition reporting with the adoption of process-based indicators for coral recruitment, recovery rate, and competition.
- The incorporation of shifts in the composition and functional traits of coral assemblages in condition assessments to provide a clearer understanding of habitat provisioning and ecological functioning underpinning ecosystem resilience.
- Better understanding of seagrass ecosystem resilience, and the adoption of resilience indicators for reporting seagrass condition particularly in the Marine Monitoring Program reporting.
- Improved modelling on the effects of land-based runoff (current and future) on seagrass ecosystem condition. There is now closer agreement between modelling and observations which strengthens the confidence about sources of land-based runoff and management targets.
- Better understanding of the effects of increasing sea temperatures on megafauna, including feminisation of the northern GBR green turtle population. Improved understanding of how weather-related events can cause significant impacts to mangroves, in particular: cyclones, extreme sea level variation and heatwaves.

4.1.3 Key conclusions

The key conclusions from this review include:

- Overall, there is a strong body of evidence on most GBR ecosystems, covering multiple lines of evidence, from a wide range of GBR catchments, and addressing each element of the question.
- There are 24,094 km^2 of coral reefs mapped within the GBR. The condition of shallow coral reefs of the inshore GBR (Wet Tropics to Fitzroy NRM regions) has marginally declined since 2017 and between 2020 and 2021 was still rated poor, although there were differences depending on the region.
- Hard coral cover on shallow midshelf and offshore reefs increased overall since 2017, showing fast recovery from Cooktown to Bundaberg after experiencing losses from repeated mass coral bleaching and/or COTS outbreaks between 2016 and 2019.
- The primary threats to GBR corals are rising sea surface temperature and heatwaves, tropical cyclones, outbreaks of COTS 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 km^2 of the GBR seafloor. Inshore seagrass meadows across the GBR declined from Moderate abundance and resilience in 2017 to Poor in 2020, 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 GBR seagrass meadows are tropical cyclones, land-based runoff (particularly fine sediments and pesticides), and thermal stress from rising sea surface temperatures.
- Other components of the GBR marine ecosystems (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.
- In the GBR catchment area, the most recent assessment of wetland extent in 2017 reported 15,556 km^2 of mapped wetlands (artificial/highly modified, lacustrine, palustrine, riverine and estuarine), estimated at around 85% of pre-development extent, in stable and Moderate condition. However, the extent varies between wetland types and regions with substantial declines in some areas (e.g., significant losses in extent of palustrine wetlands in the Wet Tropics and Mackay Whitsunday regions of ~49% and ~44% respectively, compared to pre-development estimates). In 2022 when this review was prepared, there was no new data on current extent of

natural and near-natural wetlands since the 2017 SCS, as changes in wetland extent are assessed every 4-5 years. The next update is expected to be reported in 2024.

- There are 2,188 km^2 of mangroves and 1,757 km^2 of salt flats and saltmarshes within GBR estuaries, and apart from minor localised losses, they are stable and in good condition.
- Primary threats to mangroves and saltmarshes are climate change related, in particular extreme events such as tropical cyclones and storms, extreme sea level variation and heatwaves.
- Although some regional populations of dugongs and turtles are recovering (e.g., southern green turtle), populations of the GBR are in Poor condition and in decline. The greatest threats to dugong and turtle 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.
- The ability of GBR ecosystems to resist pressures, and their capacity to recover during periods of low disturbance, is affected by the cumulative impacts of climate change in concert with local disturbances (e.g., tropical cyclones) and pressures, such as land-based runoff.

4.1.4 Significance of findings for policy, management and practice

There is now even stronger evidence than in earlier Scientific Consensus Statements that ecosystem condition is worse when climate change pressures are coupled with water quality pressures, such as increasing loads of fine sediments, elevated nutrients and persistent pesticides. Continuing to follow the key management approaches in the Reef 2050 Long-Term Sustainability Plan is highly likely to improve the outcome and resilience of GBR ecosystems. It therefore follows, that many of the issues raised in previous Scientific Consensus Statements remain relevant, but the evidence supporting them has increased. The significance of the findings identified in this current review for policy, practice and research include:

- Limited information exists on the resilience of estuarine ecosystems, including mangroves and saltmarshes, because their condition is not systematically monitored.
- As reporting on ecosystem condition and resilience has improved, there is now a need to quantify tolerance thresholds and tipping points in key freshwater floodplain, seagrass and coral reef species and communities in response to single and multiple pressures.
- Ecological aspects of recovery in seagrass have been documented through monitoring, but recovery processes (e.g., triggers for seed germination, seed viability, seed bank thresholds, sediment conditions, species interactions) remain critical information gaps that preclude accurate prediction of recovery rates for GBR seagrass ecosystems.
- Recent research provides more information on the response of resilience-related attributes, however there is a greater need to improve understanding of recovery processes of seagrass meadows and coral reefs as management focuses more on restoration actions.
- The most severe threat to tropical coral reef ecosystems is ocean warming and widespread coral mortality due to increasingly frequent and severe coral bleaching events. However, reducing chronic stressors at local scales should contribute to improved reef resistance and recovery potential following acute climatic disturbances. This highlights the relative importance of water quality impacting coral recovery (Bozec et al., 2022; Ceccarelli et al., 2020).

4.1.5 Uncertainties and/or limitations of the evidence

Factors that lead to uncertainties or limitations of the evidence include:

- GBR wetland extent and condition is only assessed every 4-5 years. The last assessment was reported in the 2017 Scientific Consensus Statement. The next assessment is due for completion in mid-late 2023, therefore current wetland extent and condition is outdated.
- Deepwater seagrass habitats are not monitored, and therefore overall GBR seagrass condition is restricted to the inshore seagrass habitats only.
- Midshelf and offshore coral monitoring by the AIMS Long-Term Monitoring Program (LTMP) reports coral cover but not overall coral condition for the regions assessed. This limits GBR coral

condition assessments to the shallow inshore coral monitoring reported through the GBR Marine Monitoring Program.

- Several eligible studies in the evidence base use results from the LTMP, and as a consequence there may be some double counting of evidence due to the inclusion of secondary analyses of these data. This has not been quantified.
- There are no data to assess temporal trends in inshore coral condition in Cape York, indicating the need to introduce monitoring in the region.
- The challenges of selecting appropriate indicators and ability to distinguish natural influences on ecosystem condition versus anthropogenic influences.

4.2 Contextual variables influencing outcomes

Table 10. Summary of contextual variables for Question 1.2/1.3/2.1.

Contextual variables	Influence on question outcome or relationships
Climate & hydrology	The GBR catchment area covers 423,144 km^2 and includes 35 river basins, including dry tropics, wet tropics and sub-tropics. Hydrological regimes reflect the seasonal rainfall and evapotranspiration rates. The average rainfall of the GBR catchments ranges from less than 500 mm yr^{-1} at its inland, semi-arid boundaries, to 8,200 mm yr^{-1} in the wet tropics. Typically, 90% of annual rainfall in the dry tropics occurs during the summer wet season from November to April, with little falling during the cooler months of May to October. In the wet tropics, rainfall is more evenly distributed through the year, but is still strongly seasonal. The interaction between water quantity and quality is complex and depends strongly on the characteristics of individual catchments. River flow in the GBR catchments is highly variable among years and in the degree of intermittency over the dry season, except in the wet tropics. The seasonal flow regime defines the following key periods of water-quality risk over the annual hydrological cycle for diverse GBR catchment ecosystems: initial 'pre-flush' flows during the transition from the dry to the wet season; early wet season 'first flush' flows; peak wet season flood flows; and sustained base flow or periods of disconnection during the dry season (Davis et al., 2017).
Climate change	Changes to rainfall to 2050 are projected to be small compared to the current high annual variability of rainfall. Thus exports will continue to be dominated by climate and flood variability. If there is a future increase in flood variability it would be expected to lead to increased exports (Alluvium, 2019).

4.3 Evidence appraisal

Relevance

The overall relevance of the body of evidence was rated as being High. The relevance of each individual indicator was High for the relevance of the study approach and reporting of results, High for spatial relevance, and High for temporal relevance to the question. Of the 100 studies included in the review, 72% were given a 'High' score for the overall relevance to the question, while 28% had Moderate overall relevance to the question. Similarly, 74% had a High spatial relevance score, and 26% a Moderate spatial relevance score. In terms of temporal relevance, 61% had a High score, 15% was Moderate, and 6% had a Low temporal relevance score. This was due to a number of factors, including:

- The relevance of the study approach and study results was High overall, as knowledge about the extent and condition of GBR ecosystems, and threats to its health is a mature science.

- The relevance or generalisability of the spatial scale of studies was High, as the spatial scale of most studies covered the entire GBR, or at least several catchments/NRM regions.
- Relevance or generalisability of the temporal scale of studies was also High overall, with most studies covering multiple years, wet seasons, and/or various bleaching events. There were a few exceptions, (n=6 studies) that had a more limited temporal scale (i.e., single observation, or only one year or wet season of data).

The majority of studies found (n= 55) related to coral ecosystems, with a high proportion (74%) relating to impacts affecting those ecosystems. Few studies found related to other components of the conceptual model such as pelagic ecosystems.

Consistency, Quantity and Diversity

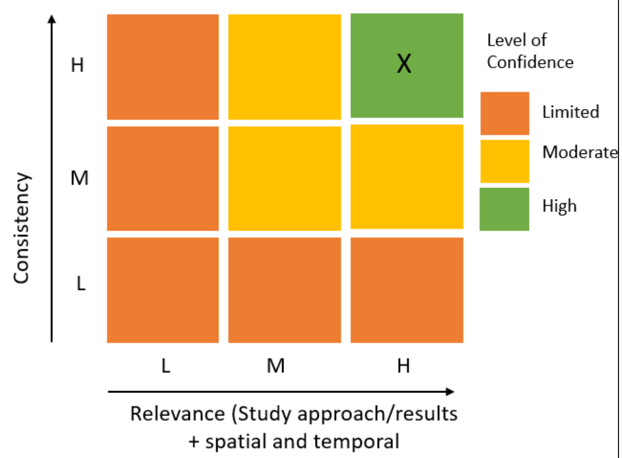
There were 100 peer reviewed journal papers and studies that directly addressed the question. Two academic databases were searched as well as Google Scholar and, in the Authors' professional opinion these searches resulted in the vast majority of peer reviewed published work being captured. These studies represented multiple lines of evidence (52 observational studies, 27 modelling, 19 review and 2 theoretical or conceptual) with High consistency on the agreement within the studies, and High spatial and temporal generalisability to address the question.

Confidence

The overall confidence in the body of evidence for the question was rated as High, as a result of the High consistency and spatial and temporal relevance of a large number of studies (Table 11). 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, including High diversity of study types (observational, modelling and reviews), and with a High confidence rating (based on High consistency and High overall relevance of studies).

The knowledge base on condition and pressures has contributed strongly to GBR management programs for nearly two decades now with some major improvements in understanding over that time and it is well placed to continue to support management if the monitoring and modelling programs are maintained and well-targeted future research is supported.

Table 11. Summary of results for the evidence appraisal of the whole body of evidence used in addressing Question 1.2/1.3/2.1. The overall measure of Confidence (i.e., Limited, Moderate and High) is represented by a matrix encompassing overall relevance and consistency.

Indicator	Rating	Overall measure of Confidence
Relevance (overall)	High	
-To the Question	High	
-Spatial	High	
-Temporal	High	
Consistency	High	
Quantity	High (100 studies)	
Diversity	High (52 observational, 27 modelling, 19 review and 2 theoretical or conceptual)	

4.4 Indigenous engagement/participation within the body of evidence

There was limited Indigenous engagement or participation described in the body of evidence. However, Indigenous participation has been critical in the collection of ecosystem condition evidence in remote regions of the GBR (e.g., Cape York and Fitzroy NRM regions) and megafaunal assessments.

- First Nations groups and Indigenous rangers are engaged within the MMP inshore seagrass component through both contributory and collaborative data collection approaches. After training and capacity building, some First Nations groups (e.g., Girringun) through the Seagrass-Watch Global Seagrass Observing Network, consent to the data they have collected in their Sea Country to be integrated into the MMP, to enable reporting on seagrass condition more widely in the GBR. Other groups accompany scientists in the field and assist with data collection (e.g., Wuthathi, Kuuku Ya'u, Yuku Baja Muliku, Darumbal) (McKenzie et al., 2022a).
- Similarly, as part of the Cape York Water Monitoring Partnership, Lama Lama Rangers and Yuku Baja Muliku rangers, accompany scientists in the field and assist with water quality data collection in their Traditional Sea Country (Moran et al., 2022).
- As a result of a green sea turtle project in Edgecumbe Bay (central GBR), Gudjuda and Girringun Aboriginal groups are now trained in the principles of turtle research methods and in data collection, which has built capacity and helped raise awareness about marine turtles and their habitat. As a core part of their work program, they also now engage junior rangers and promote their turtle research work through education. This project has provided the Gudjuda and Girringun Traditional Owners with an important ownership role in managing and protecting marine turtles on their traditional Sea Country (Hof et al., 2017).

4.5 Knowledge gaps

Table 12. Summary of knowledge gaps for Question 1.2/1.3/2.1.

Gap in knowledge	Possible research or Monitoring & Evaluation (M&E) question to be addressed	Potential outcome or Impact for management if addressed
Lack of a condition indicator for midshelf and offshore coral condition.	Develop an indicator framework similar to the process-based indicators for coral recruitment, recovery rate, and competition (macroalgae) used by the inshore coral monitoring for the GBR MMP.	Improved reporting on overall GBR coral condition and trends.
Lack of condition and trend reporting for deepwater seagrass habitats.	Implement monitoring of deepwater (>15m depth) seagrass habitats across the GBR. Develop indicators similar to those used for the shallow subtidal coastal and reef seagrass habitat monitoring for the GBR MMP.	Improved reporting on overall GBR seagrass condition and trends.
Increasing the maintenance and building of GBR seagrass meadow resilience.	Protection alone is unlikely to result in sufficient recovery of seagrass as pressures rise. Active interventions will be required to maintain seagrass resilience. Conduct research and development on methods for growing seagrass propagules (shoots and/or seeds), seagrass	Enhance resilience of seagrass meadows to resist pressures and stop declining trajectories. Implementing restoration and securing a future for GBR seagrass ecosystems.

Gap in knowledge	Possible research or Monitoring & Evaluation (M&E) question to be addressed	Potential outcome or Impact for management if addressed
	culture methods and seed storage protocols. Develop criteria for restoration, including how to prioritise restoration sites, and investigate ecological engineering options (creation of new habitats).	
Improved predictions of regional seawater conditions and their influences (Fabricius et al., 2020).	Ongoing support for a global network of fCO_2 (seawater CO_2 fugacity) and carbon chemistry monitoring sites.	Improved understanding about impact of acidification on coral reefs.
Long-term coral reef monitoring initiatives could be enhanced by incorporating assessments of microbial communities in seawater (Glasl et al., 2019).	Adding timely integration of microbial sampling into current coral reef monitoring initiatives.	Diagnostic value of microorganisms to environmental perturbations.
Spatial patterns of microbial communities across surface waters of the GBR (Frade et al., 2018).	To establish microbial observatories along GBR environmental gradients.	To facilitate robust assessments of microbial contributions to reef health and inform tipping-points in reef condition.
Better understanding of the ecological effects of contaminants, especially impacts on species diversity and ecosystem function, as well as thresholds for lethality, normal breeding and feeding activity and other sublethal stresses, for GBR freshwater wetlands and associated communities (Davis et al., 2017).	Increased ability to predict the effects of novel impacts or combinations of impacts as currently limited. Improved models are needed to explain interactions among environmental stressors, especially regarding changes in climate and future land use. Moreover, there is a need to link models of water quality more explicitly to target species and to ecosystem processes.	More useful and ecologically relevant water quality measures.
Need to quantify the cumulative and/ or interactive effects of multiple stressors for coastal ecosystems, and in particular for seagrass and marine microalgae systems (King et al., 2021).	It is recommended that potential mitigative physiological responses be investigated further through experimental studies that assess varying levels of PSII-inhibiting herbicides and light reduction over acute and chronic exposure periods.	To develop predictive models that can inform management of interactive stressors in seagrass and marine microalgae.
The relative contribution of known and likely sources to the Contaminants of Emerging Concern (CEC) and the associated risks these potential threats pose to the receiving environments,	Due to lack of (available) monitoring data, it is recommended: 1) that all relevant environmental data are included into integrated	Improved ecological risk assessments of these CECs to the GBR marine environments.

Gap in knowledge	Possible research or Monitoring & Evaluation (M&E) question to be addressed	Potential outcome or Impact for management if addressed
remains largely unknown (Kroon et al., 2020).	databases for building marine baselines for the GBR. 2) that the implementation of local, targeted monitoring programs is informed by predictive methods for risk prioritisation.	
Within GBR freshwater wetlands and estuaries, there is a need for a clearer understanding of basic ecology, impacts and appropriate application of management methods (Pearson et al., 2021).	Major needs in research and application include studies of: • Physical and biological processes and impacts in ground waters, large rivers and estuaries. • Ecological effects of pesticides. • Management and mitigation for invasive species and climate change. Explicit protection of non-marine waters.	Improved freshwater and estuarine management, including water resource infrastructure, through education, regulation, incentives and penalties, based on ecosystem specific evidence base.

5. Evidence Statement

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[13]) 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[14]. Wetlands are considered stable but in Moderate condition[15] 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 km^2 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[15] 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 mass coral bleaching and/or crown-of-thorns starfish between 2016 and 2019[16].
- 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.

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[13] Reef Water Quality Report Card 2020
[14] Great Barrier Reef Outlook Report 2019
[15] Reef Water Quality Report Card 2020
[16] AIMS Long Term Monitoring Program

- Seagrass meadows are dynamic, changing seasonally in extent and condition, and cover an estimated 35,679 km^2. Inshore seagrass meadows across the Great Barrier Reef declined from Moderate abundance and resilience in 2017 to Poor in 2020[15], 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[17]. 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 km^2 of mangroves and 1,757 km^2 of salt flats and saltmarshes. Apart from minor localised losses, they are stable and in Good condition[17]. 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 km^2 of mapped wetlands (artificial/highly modified, lacustrine, palustrine, riverine and estuarine), estimated at around 85% of pre-development extent, in stable and Moderate condition[18]. 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).

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[17] Great Barrier Reef Outlook Report 2019
[18] Reef Water Quality Report Card 2020

6. References

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

Body of Evidence

Abessa, D. M. S., Albuquerque, H. C., Morais, L. G., Araújo, G. S., Fonseca, T. G., Cruz, A. C. F., Campos, B. G., Camargo, J. B. D. A., Gusso-Choueri, P. K., Perina, F. C., Choueri, R. B., & Buruaem, L. M. (2018). Pollution status of marine protected areas worldwide and the consequent toxic effects are unknown. *Environmental Pollution*, *243*, 1450–1459. https://doi.org/10.1016/j.envpol.2018.09.129

Adame, M. F., Arthington, A. H., Waltham, N. J., Hasan, S., Selles, A., & Ronan, M. (2019). Managing threats and restoring wetlands within catchments of the Great Barrier Reef, Australia. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *29*(5), 829–839. https://doi.org/10.1002/aqc.3096

Anderson, K. D., Cantin, N. E., Heron, S. F., Lough, J. M., & Pratchett, M. S. (2018). Temporal and taxonomic contrasts in coral growth at Davies Reef, central Great Barrier Reef, Australia. *Coral Reefs*, *37*(2), 409–421. https://doi.org/10.1007/s00338-018-1666-1

Australian Institute of Marine Science (AIMS) (2022). Annual Summary Report of Coral Reef Condition 2021/22. https://www.aims.gov.au/sites/default/files/2022-08/AIMS_LTMP_Report_on GBR_coral_status_2021_2022_040822F3.pdf

Babcock, R. C., Bustamante, R. H., Fulton, E. A., Fulton, D. J., Haywood, M. D. E., Hobday, A. J., Kenyon, R., Matear, R. J., Plagányi, É. E., Richardson, A. J., & Vanderklift, M. A. (2019). Corrigendum: Severe Continental-Scale Impacts of Climate Change Are Happening Now: Extreme Climate Events Impact Marine Habitat Forming Communities Along 45% of Australia's Coast (Frontiers in Marine Science, (2019), 6, 10.3389/fmars.2019.00411). *Frontiers in Marine Science*, *6*. https://doi.org/10.3389/fmars.2019.00558

Babcock, R. C., Plagányi, É. E., Condie, S. A., Westcott, D. A., Fletcher, C. S., Bonin, M. C., & Cameron, D. S. (2020). Suppressing the next crown-of-thorns outbreak on the Great Barrier Reef. *Coral Reefs*, *39*(5), 1233–1244. https://doi.org/10.1007/s00338-020-01978-8

Baird, A. H., Madin, J. S., Álvarez-Noriega, M., Fontoura, L., Kerry, J. T., Kuo, C., Precoda, K., Torres-Pulliza, D., Woods, R. M., Zawada, K. J. A., & Hughes, T. P. (2018). A decline in bleaching suggests that depth can provide a refuge from global warming in most coral taxa. *Marine Ecology Progress Series*, *603*, 257–264. https://doi.org/10.3354/meps12732

Baird, M. E., Mongin, M., Rizwi, F., Bay, L. K., Cantin, N. E., Morris, L. A., & Skerratt, J. H. (2021). The effect of natural and anthropogenic nutrient and sediment loads on coral oxidative stress on runoff-exposed reefs. *Marine Pollution Bulletin*, *168*, 112409. https://doi.org/10.1016/j.marpolbul.2021.112409

Bartley, R., Thompson, C., Croke, J. C., Pietsch, T. J., Baker, B., Hughes, K., & Kinsey-Henderson, A. E. (2018). Insights into the history and timing of post-European land use disturbance on sedimentation rates in catchments draining to the Great Barrier Reef. *Marine Pollution Bulletin*, *131*, 530–546. https://doi.org/10.1016/j.marpolbul.2018.04.070

Bell, P. R. F. (2021). Analysis of satellite imagery using a simple algorithm supports evidence that *Trichodesmium* supplies a significant new nitrogen load to the GBR lagoon. *Ambio*, *50*(6), 1200–1210. https://doi.org/10.1007/s13280-020-01460-3

Booth, D. T., Dunstan, A., Bell, I. P., Reina, R., & Tedeschi, J. (2020). Low male production at the world's largest green turtle rookery. *Marine Ecology Progress Series*, *653*, 181–190. https://doi.org/10.3354/meps13500

Bozec, Y.-M., Hock, K., Mason, R. A. B., Baird, M. E., Castro-Sanguino, C., Condie, S. A., Puotinen, M. L., Thompson, A. A., & Mumby, P. J. (2022). Cumulative impacts across Australia's Great Barrier Reef: a mechanistic evaluation. *Ecological Monographs*, *92*(1), 1. https://doi.org/10.1002/ecm.1494

Brodie, J. E., Devlin, M. J., & Lewis, S. E. (2017). Potential enhanced survivorship of Crown of Thorns Starfish larvae due to near-annual nutrient enrichment during secondary outbreaks on the Central Mid-Shelf of the Great Barrier Reef, Australia. *Diversity*, *9*(1), 17. https://doi.org/10.3390/d9010017

Brodie, J. E., & Landos, M. (2019). Pesticides in Queensland and Great Barrier Reef waterways - potential impacts on aquatic ecosystems and the failure of national management. *Estuarine, Coastal and Shelf Science*, *230*, 106447. https://doi.org/10.1016/j.ecss.2019.106447

Brodie, J. E., & Waterhouse, J. (2018). Great Barrier Reef (Australia): A multi-ecosystem wetland with a multiple use management regime. In G. R. Milton, R. C. Prentice, & N. C. Davidson (Eds.), *The Wetland Book* (Vol. 1, pp. 447–460). *Springer Netherlands*. https://doi.org/10.1007/978-94-007-4001-3_46

Burn, D., Pratchett, M. S., Heron, S. F., Thompson, C. A., Pratchett, D., & Hoey, A. S. (2018). Limited cross-shelf variation in the growth of three branching corals on Australia's Great Barrier Reef. *Diversity*, *10*(4), 122. https://doi.org/10.3390/d10040122

Cagnazzi, D., Parra, G. J., Harrison, P. L., Brooks, L., & Rankin, R. (2020). Vulnerability of threatened Australian humpback dolphins to flooding and port development within the southern Great Barrier Reef coastal region. *Global Ecology and Conservation*, *24*, e01203. https://doi.org/10.1016/j.gecco.2020.e01203

Camp, E. F., Edmondson, J., Doheny, A., Rumney, J., Grima, A. J., Huete, A., & Suggett, D. J. (2019). Mangrove lagoons of the Great Barrier Reef support coral populations persisting under extreme environmental conditions. *Marine Ecology Progress Series*, *625*, 1–14. https://doi.org/10.3354/meps13073

Carbery, M., Herb, F., Reynes, J., Pham, C. K., Fong, W.-K. K., & Lehner, R. (2022). How small is the big problem? Small microplastics <300 µm abundant in marine surface waters of the Great Barrier Reef Marine Park. *Marine Pollution Bulletin*, *184*, 114179. https://doi.org/10.1016/j.marpolbul.2022.114179

Castro-Sanguino, C., Ortiz, J.-C., Thompson, A. A., Wolff, N. H., Ferrari, R., Robson, B. J., Magno-Canto, M. M., Puotinen, M. L., Fabricius, K. E., & Uthicke, S. (2021). Reef state and performance as indicators of cumulative impacts on coral reefs. *Ecological Indicators*, *123*, 107335. https://doi.org/10.1016/j.ecolind.2020.107335

Ceccarelli, D. M., Evans, R. D., Logan, M., Mantel, P., Puotinen, M. L., Petus, C., Russ, G. R., & Williamson, D. H. (2020). Long-term dynamics and drivers of coral and macroalgal cover on inshore reefs of the Great Barrier Reef Marine Park. *Ecological Applications*, *30*(1). https://doi.org/10.1002/eap.2008

Chamberlain, D. A., Phinn, S. R., & Possingham, H. P. (2020). Remote sensing of mangroves and estuarine communities in Central Queensland, Australia. *Remote Sensing*, *12*(1), 197. https://doi.org/10.3390/rs12010197

Cheal, A. J., MacNeil, M. A., Emslie, M. J., & Sweatman, H. P. A. (2017). The threat to coral reefs from more intense cyclones under climate change. *Global Change Biology*, *23*(4), 1511–1524. https://doi.org/10.1111/gcb.13593

Cheung, M. W. M., Hock, K., Skirving, W. J., & Mumby, P. J. (2021). Cumulative bleaching undermines systemic resilience of the Great Barrier Reef. *Current Biology*, *31*(23), 5385-5392.e4. https://doi.org/10.1016/j.cub.2021.09.078

Coles, R. G., Rasheed, M. A., Grech, A., & McKenzie, L. J. (2018). Seagrass meadows of Northeastern Australia. In *The Wetland Book* (Vol. 3, pp. 1967–1975). *Springer Netherlands*. https://doi.org/10.1007/978-94-007-4001-3_266

Condie, S. A., Anthony, K. R. N., Babcock, R. C., Baird, M. E., Beeden, R. J., Fletcher, C. S., Gorton, R., Harrison, D. P., Hobday, A. J., Plagányi, É. E., & Westcott, D. A. (2021). Large-scale interventions may delay decline of the Great Barrier Reef. *Royal Society Open Science*, *8*(4), rsos.201296. https://doi.org/10.1098/rsos.201296

Condie, S. A., Plagányi, É. E., Morello, E. B., Hock, K., & Beeden, R. J. (2018). Great Barrier Reef recovery through multiple interventions. *Conservation Biology*, *32*(6), 1356–1367. https://doi.org/10.1111/cobi.13161

D'Olivo, J. P., & McCulloch, M. T. (2022). Impact of European settlement and land use changes on Great Barrier Reef river catchments reconstructed from long-term coral Ba/Ca records. *Science of The Total Environment*, *830*, 154461. https://doi.org/10.1016/j.scitotenv.2022.154461

Davis, A. M., Pearson, R. G., Brodie, J. E., & Butler, B. B. (2017). Review and conceptual models of agricultural impacts and water quality in waterways of the Great Barrier Reef catchment area. *Marine and Freshwater Research*, *68*(1), 1–19. https://doi.org/10.1071/MF15301

Davis, K. L., Colefax, A. P., Tucker, J. P., Kelaher, B. P., & Santos, I. R. (2021). Global coral reef ecosystems exhibit declining calcification and increasing primary productivity. *Communications Earth & Environment*, *2*(1), 105. https://doi.org/10.1038/s43247-021-00168-w

Deaker, D. J., & Byrne, M. (2022). Crown of thorns starfish life-history traits contribute to outbreaks, a continuing concern for coral reefs. *Emerging Topics in Life Sciences*, *6*(1), 67–79. https://doi.org/10.1042/ETLS20210239

DeCarlo, T. M., Harrison, H. B., Gajdzik, L., Alaguarda, D., Rodolfo-Metalpa, R., D'Olivo, J., Liu, G., Patalwala, D., & McCulloch, M. T. (2019). Acclimatization of massive reef-building corals to consecutive heatwaves. *Proceedings of the Royal Society B: Biological Sciences*, *286*(1898), 20190235. https://doi.org/10.1098/rspb.2019.0235

Dietzel, A., Connolly, S. R., Hughes, T. P., & Bode, M. (2021). The spatial footprint and patchiness of large-scale disturbances on coral reefs. *Global Change Biology*, *27*(19), 4825–4838. https://doi.org/10.1111/gcb.15805

Emslie, M. J., Logan, M., & Cheal, A. J. (2019). The distribution of planktivorous damselfishes (Pomacentridae) on the Great Barrier Reef and the relative influences of habitat and predation. *Diversity*, *11*(3), 33. https://doi.org/10.3390/d11030033

Fabricius, K. E., Neill, C., Van Ooijen, E., Smith, J. N., & Tilbrook, B. (2020). Progressive seawater acidification on the Great Barrier Reef continental shelf. *Scientific Reports*, *10*(1), 18602. https://doi.org/10.1038/s41598-020-75293-1

Fine, M., Hoegh-Guldberg, O., Meroz-Fine, E., & Dove, S. G. (2019). Ecological changes over 90 years at Low Isles on the Great Barrier Reef. *Nature Communications*, *10*(1), 4409. https://doi.org/10.1038/s41467-019-12431-y

Fordyce, A. J., Ainsworth, T. D., Heron, S. F., & Leggat, W. (2019). Marine heatwave hotspots in coral reef environments: Physical drivers, ecophysiological outcomes, and impact upon structural complexity. *Frontiers in Marine Science*, *6*. https://doi.org/10.3389/fmars.2019.00498

Frade, P. R., Bongaerts, P., Englebert, N., Rogers, A., Gonzalez-Rivero, M., & Hoegh-Guldberg, O. (2018). Deep reefs of the Great Barrier Reef offer limited thermal refuge during mass coral bleaching. *Nature Communications*, *9*(1), 3447. https://doi.org/10.1038/s41467-018-05741-0

Frade, P. R., Glasl, B., Matthews, S. A., Mellin, C., Serrão, E. A., Wolfe, K., Mumby, P. J., Webster, N. S., & Bourne, D. G. (2020). Spatial patterns of microbial communities across surface waters of the Great Barrier Reef. *Communications Biology*, *3*(1), 442. https://doi.org/10.1038/s42003-020-01166-y

Gallen, C., Heffernan, A. L., Kaserzon, S. L., Dogruer, G., Samanipour, S., Gomez-Ramos, M. J., & Müller, J. F. (2019a). Integrated chemical exposure assessment of coastal green turtle foraging grounds on the Great Barrier Reef. *Science of The Total Environment*, *657*, 401–409. https://doi.org/10.1016/j.scitotenv.2018.11.322

Gaus, C., Villa, C. A., Dogruer, G., Heffernan, A. L., Vijayasarathy, S., Lin, C.-Y., Flint, M., Hof, C. A. M., & Bell, I. P. (2019). Evaluating internal exposure of sea turtles as model species for identifying regional chemical threats in nearshore habitats of the Great Barrier Reef. *Science of The Total Environment*, *658*, 732–743. https://doi.org/10.1016/j.scitotenv.2018.10.257

Glasl, B., Bourne, D. G., Frade, P. R., Thomas, T., Schaffelke, B., & Webster, N. S. (2019). Microbial indicators of environmental perturbations in coral reef ecosystems. *Microbiome*, *7*(1), 94. https://doi.org/10.1186/s40168-019-0705-7

Good, A. M., & Bahr, K. D. (2021). The coral conservation crisis: interacting local and global stressors reduce reef resiliency and create challenges for conservation solutions. *SN Applied Sciences*, *3*(3), 312. https://doi.org/10.1007/s42452-021-04319-8

Great Barrier Reef Marine Park Authority (GBRMPA). (2019). Great Barrier Reef Outlook Report 2019. *Great Barrier Reef Marine Park Authority*. https://elibrary.gbrmpa.gov.au/jspui/handle/11017/3474

Guo, W., Bokade, R., Cohen, A. L., Mollica, N. R., Leung, M., & Brainard, R. E. (2020). Ocean acidification has impacted coral growth on the Great Barrier Reef. *Geophysical Research Letters*, *47*(19). https://doi.org/10.1029/2019GL086761

Hairsine, P. B. (2017). Review: sediment-related controls on the health of the Great Barrier Reef. *Vadose Zone Journal*, *16*(12), 1–15. https://doi.org/10.2136/vzj2017.05.0115

Hock, K., Wolff, N. H., Ortiz, J.-C., Condie, S. A., Anthony, K. R. N., Blackwell, P. G., & Mumby, P. J. (2017). Connectivity and systemic resilience of the Great Barrier Reef. *PLOS Biology*, *15*(11), e2003355. https://doi.org/10.1371/journal.pbio.2003355

Hof, C. A. M., Smallwood, E., Meager, J. J., & Bell, I. P. (2017). First citizen-science population abundance and growth rate estimates for green sea turtles *Chelonia mydas* foraging in the northern Great Barrier Reef, Australia. *Marine Ecology Progress Series*, *574*, 181–191. https://doi.org/10.3354/meps12173

Hoogenboom, M. O., Frank, G. E., Chase, T. J., Jurriaans, S., Álvarez-Noriega, M., Peterson, K., Critchell, K., Berry, K. L. E., Nicolet, K. J., Ramsby, B. D., & Paley, A. S. (2017). Environmental drivers of variation in bleaching severity of *Acropora* Species during an extreme thermal anomaly. *Frontiers in Marine Science*, *4*. https://doi.org/10.3389/fmars.2017.00376

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

Hughes, T. P., Kerry, J. T., Álvarez-Noriega, M., Álvarez-Romero, J. G., Anderson, K. D., Baird, A. H., Babcock, R. C., Beger, M., Bellwood, D. R., Berkelmans, R., Bridge, T. C. L., Butler, I. R., Byrne, M., Cantin, N. E., Comeau, S., Connolly, S. R., Cumming, G. S., Dalton, S. J., Diaz-Pulido, G., … Wilson, S. K. (2017). Global warming and recurrent mass bleaching of corals. *Nature*, *543*(7645), 373–377. https://doi.org/10.1038/nature21707

Hughes, T. P., Kerry, J. T., Baird, A. H., Connolly, S. R., Chase, T. J., Dietzel, A., Hill, T., Hoey, A. S., Hoogenboom, M. O., Jacobson, M., Kerswell, A. P., Madin, J. S., Mieog, A., Paley, A. S., Pratchett, M. S., Torda, G., & Woods, R. M. (2019). Global warming impairs stock–recruitment dynamics of corals. *Nature*, *568*(7752), 387–390. https://doi.org/10.1038/s41586-019-1081-y

Hughes, T. P., Kerry, J. T., Baird, A. H., Connolly, S. R., Dietzel, A., Eakin, C. M., Heron, S. F., Hoey, A. S., Hoogenboom, M. O., Liu, G., McWilliam, M. J., Pears, R. J., Pratchett, M. S., Skirving, W. J., Stella, J.

S., & Torda, G. (2018b). Global warming transforms coral reef assemblages. *Nature*, *556*(7702), 492–496. https://doi.org/10.1038/s41586-018-0041-2

Hughes, T. P., Kerry, J. T., & Simpson, T. (2018c). Large-scale bleaching of corals on the Great Barrier Reef. *Ecology*, *99*(2), 501–501. https://doi.org/10.1002/ecy.2092

Jonker, M. J., Thompson, A. A., Menéndez, P., & Osborne, K. (2019). Cross-shelf variation among juvenile and adult coral assemblages on Australia's Great Barrier Reef. *Diversity*, *11*(6), 85. https://doi.org/10.3390/d11060085

King, O. C., Smith, R. A., Warne, M. S. J., van de Merwe, J. P., Connolly, R. M., & Brown, C. J. (2021). Combined impacts of photosystem II-inhibiting herbicides and light availability on seagrass and marine microalgae. *Marine Ecology Progress Series*, *668*, 215–230. https://doi.org/10.3354/meps13717

Kroon, F. J., Berry, K. L. E., Brinkman, D. L., Kookana, R. S., Leusch, F. D. L., Melvin, S. D., Neale, P. A., Negri, A. P., Puotinen, M. L., Tsang, J. J., van de Merwe, J. P., & Williams, M. (2020). Sources, presence and potential effects of contaminants of emerging concern in the marine environments of the Great Barrier Reef and Torres Strait, Australia. *Science of The Total Environment*, *719*, 135140. https://doi.org/10.1016/j.scitotenv.2019.135140

Lam, V. Y. Y., Chaloupka, M., Thompson, A. A., Doropoulos, C., & Mumby, P. J. (2018). Acute drivers influence recent inshore Great Barrier Reef dynamics. *Proceedings of the Royal Society B: Biological Sciences*, *285*(1890), 20182063. https://doi.org/10.1098/rspb.2018.2063

Lambert, V. M., Bainbridge, Z. T., Collier, C. J., Lewis, S. E., Adams, M. P., Carter, A. B., Saunders, M. I., Brodie, J. E., Turner, R. D. R., Rasheed, M. A., & O'Brien, K. R. (2021). Connecting targets for catchment sediment loads to ecological outcomes for seagrass using multiple lines of evidence. *Marine Pollution Bulletin*, *169*, 112494. https://doi.org/10.1016/j.marpolbul.2021.112494

Lewis, S. C., & Mallela, J. (2018). A multifactor risk analysis of the record 2016 Great Barrier Reef bleaching. *Bulletin of the American Meteorological Society*, *99*(1), S144–S149. https://doi.org/10.1175/BAMS-D-17-0074.1

MacNeil, M. A., Mellin, C., Matthews, S. A., Wolff, N. H., McClanahan, T. R., Devlin, M. J., Drovandi, C. C., Mengersen, K., & Graham, N. A. J. (2019). Water quality mediates resilience on the Great Barrier Reef. *Nature Ecology & Evolution*, *3*(4), 620–627. https://doi.org/10.1038/s41559-019-0832-3

Matthews, S. A., Mellin, C., & Pratchett, M. S. (2020). Larval connectivity and water quality explain spatial distribution of crown-of-thorns starfish outbreaks across the Great Barrier Reef. In B. M. Riegl (Ed.), *Advances in Marine Biology* (Vol. 87, Issue 1, pp. 223–258). *Academic Press*. https://doi.org/10.1016/bs.amb.2020.08.007

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

McClure, E., Richardson, L. E., Graba-Landry, A., Loffler, Z., Russ, G. R., & Hoey, A. S. (2019). Cross-shelf differences in the response of herbivorous fish assemblages to severe environmental disturbances. *Diversity*, *11*(2), 23. https://doi.org/10.3390/d11020023

McKenzie, L. J., Collier, C. J., Langlois, L. A., Yoshida, R. L., Uusitalo, J., & Waycott, M. (2022a). Marine Monitoring Program: Annual Report inshore seagrass monitoring 2020-21. *Great Barrier Reef Marine Park Authority*. https://elibrary.gbrmpa.gov.au/jspui/handle/11017/3930

McKenzie, L. J., Langlois, L. A., & Roelfsema, C. M. (2022b). Improving approaches to mapping seagrass within the Great Barrier Reef: From field to spaceborne earth observation. *Remote Sensing*, *14*(11), 2604. https://doi.org/10.3390/rs14112604

McWhorter, J. K., Halloran, P. R., Roff, G., Skirving, W. J., Perry, C. T., & Mumby, P. J. (2022). The importance of 1.5°C warming for the Great Barrier Reef. *Global Change Biology*, *28*(4), 1332–1341. https://doi.org/10.1111/gcb.15994

Mellin, C., Matthews, S. A., Anthony, K. R. N., Brown, S. C., Caley, M. J., Johns, K. A., Osborne, K., Puotinen, M. L., Thompson, A. A., Wolff, N. H., Fordham, D. A., & MacNeil, M. A. (2019a). Spatial resilience of the Great Barrier Reef under cumulative disturbance impacts. *Global Change Biology*, *25*(7), 2431–2445. https://doi.org/10.1111/gcb.14625

Mellin, C., Thompson, A. A., Jonker, M. J., & Emslie, M. J. (2019b). Cross-shelf variation in coral community response to disturbance on the Great Barrier Reef. *Diversity*, *11*(3), 38. https://doi.org/10.3390/d11030038

Moran, D., Robson, B. J., Gruber, R. K., Waterhouse, J., Logan, M., Petus, C., Howley, C., Lewis, S. E., Tracey, D., James, C., Mellors, J., Bove, U., Davidson, J., Glasson, K., Jaworski, S., Lefèvre, C. D., Macadam, A., Shanahan, M., Vasile, R., … Shellberg, J. G. (2022). Marine Monitoring Program: Annual Report for Inshore Water Quality Monitoring 2020-2021. Report for the Great Barrier Reef Marine Park Authority. *Great Barrier Reef Marine Park Authority*. https://hdl.handle.net/11017/3931

Morgan, K. M., Perry, C. T., Johnson, J. A., & Smithers, S. G. (2017). Nearshore turbid-zone corals exhibit high bleaching tolerance on the Great Barrier Reef following the 2016 ocean warming event. *Frontiers in Marine Science*, *4*(224). https://doi.org/10.3389/fmars.2017.00224

Ortiz, J.-C., Wolff, N. H., Anthony, K. R. N., Devlin, M. J., Lewis, S. E., & Mumby, P. J. (2018). Impaired recovery of the Great Barrier Reef under cumulative stress. *Science Advances*, *4*(7), 8. https://doi.org/10.1126/sciadv.aar6127

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

Pratchett, M. S., Bridge, T. C. L., Brodie, J. E., Cameron, D. S., Day, J. C., Emslie, M. J., Grech, A., Hamann, M., Heron, S. F., Hoey, A. S., Hoogenboom, M. O., Lough, J. M., Morrison, T. H., Osborne, K., Read, M. A., Schauble, C., Smithers, S. G., Sweatman, H. P. A., & Waterhouse, J. (2019a). Chapter 15 - Australia's Great Barrier Reef. In C. Sheppard (Ed.), *World Seas: an Environmental Evaluation (Second Edition)* (pp. 333–362). *Academic Press*.

Pratchett, M. S., Hoey, A. S., Tan, C.-H., Kuo, C.-Y., Bauman, A. G., Kumaraswamy, R., & Baird, A. H. (2019b). Spatial and temporal variation in fecundity of *Acropora spp.* in the Northern Great Barrier Reef. *Diversity*, *11*(4), 60. https://doi.org/10.3390/d11040060

Razak, T. B., Roff, G., Lough, J. M., & Mumby, P. J. (2020). Growth responses of branching versus massive corals to ocean warming on the Great Barrier Reef, Australia. *Science of The Total Environment*, *705*, 135908. https://doi.org/10.1016/j.scitotenv.2019.135908

Richards, Z. T., & Day, J. C. (2018). Biodiversity of the Great Barrier Reef—how adequately is it protected? *PeerJ*, *6*(5), e4747. https://doi.org/10.7717/peerj.4747

Richards, Z. T., Juszkiewicz, D. J., & Hoggett, A. K. (2021). Spatio-temporal persistence of scleractinian coral species at Lizard Island, Great Barrier Reef. *Coral Reefs*, *40*(4), 1369–1378. https://doi.org/10.1007/s00338-021-02144-4

Richardson, L. E., Graham, N. A. J., Pratchett, M. S., Eurich, J. G., & Hoey, A. S. (2018). Mass coral bleaching causes biotic homogenization of reef fish assemblages. *Global Change Biology*, *24*(7), 3117–3129. https://doi.org/10.1111/gcb.14119

Roelfsema, C. M., Kovacs, E. M., Vercelloni, J., Markey, K. L., Rodriguez-Ramirez, A., Lopez-Marcano, S., Gonzalez-Rivero, M., Hoegh-Guldberg, O., & Phinn, S. R. (2021a). Fine-scale time series surveys reveal new insights into spatio-temporal trends in coral cover (2002–2018), of a coral reef on the

Southern Great Barrier Reef. *Coral Reefs*, *40*(4), 1055–1067. https://doi.org/10.1007/s00338-021-02104-y

Roelfsema, C. M., Lyons, M. B., Castro-Sanguino, C., Kovacs, E. M., Callaghan, D. P., Wettle, M., Markey, K. L., Borrego-Acevedo, R., Tudman, P., Roe, M., Kennedy, E. V, Gonzalez-Rivero, M., Murray, N. J., & Phinn, S. R. (2021b). How much shallow coral habitat is there on the Great Barrier Reef? *Remote Sensing*, *13*(21), 4343. https://doi.org/10.3390/rs13214343

Safaie, A., Silbiger, N. J., McClanahan, T. R., Pawlak, G., Barshis, D. J., Hench, J. L., Rogers, J. S., Williams, G. J., & Davis, K. A. (2018). High frequency temperature variability reduces the risk of coral bleaching. *Nature Communications*, *9*(1), 1671. https://doi.org/10.1038/s41467-018-04074-2

Schaffelke, B., Collier, C. J., Kroon, F. J., Lough, J. M., McKenzie, L. J., Ronan, M., Uthicke, S., & Brodie, J. E. (2017). 2017 Scientific Consensus Statement: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef, Chapter 1: The condition of coastal and marine ecosystems of the Great Barrier Reef and their responses to water quality and disturbances. *State of Queensland*.

Sih, T. L., Cappo, M., & Kingsford, M. J. (2017). Deep-reef fish assemblages of the Great Barrier Reef shelf-break (Australia). *Scientific Reports*, *7*(1), 10886. https://doi.org/10.1038/s41598-017-11452-1

Skerratt, J. H., Mongin, M., Baird, M. E., Wild-Allen, K. A., Robson, B. J., Schaffelke, B., Davies, C. H., Richardson, A. J., Margvelashvili, N., Soja-Woźniak, M., & Steven, A. D. L. (2019). Simulated nutrient and plankton dynamics in the Great Barrier Reef (2011–2016). *Journal of Marine Systems*, *192*, 51–74. https://doi.org/10.1016/j.jmarsys.2018.12.006

Smith, J. N., Mongin, M., Thompson, A. A., Jonker, M. J., De'ath, G., & Fabricius, K. E. (2020). Shifts in coralline algae, macroalgae, and coral juveniles in the Great Barrier Reef associated with present-day ocean acidification. *Global Change Biology*, *26*(4), 2149–2160. https://doi.org/10.1111/gcb.14985

Spilsbury, F. D., Warne, M. S. J., & Backhaus, T. (2020). Risk assessment of pesticide mixtures in Australian rivers discharging to the Great Barrier Reef. *Environmental Science & Technology*, *54*(22), 14361–14371. https://doi.org/10.1021/acs.est.0c04066

Stuart-Smith, R. D., Brown, C. J., Ceccarelli, D. M., & Edgar, G. J. (2018). Ecosystem restructuring along the Great Barrier Reef following mass coral bleaching. *Nature*, *560*(7716), 92–96. https://doi.org/10.1038/s41586-018-0359-9

Taucare, G., Bignert, A., Kaserzon, S. L., Thai, P., Mann, R. M., Gallen, C., & Müller, J. F. (2022). Detecting long temporal trends of photosystem II herbicides (PSII) in the Great Barrier Reef lagoon. *Marine Pollution Bulletin*, *177*, 113490. https://doi.org/10.1016/j.marpolbul.2022.113490

Thai, P., Paxman, C., Prasad, P., Elisei, G., Reeks, T. A., Eaglesham, G. K., Yeh, R., Tracey, D., Grant, S., Müller, J. F., & Gallen, C. (2020). Marine Monitoring Program: Annual Report for inshore pesticide monitoring 2018-2019. *Great Barrier Reef Marine Park Authority*. https://elibrary.gbrmpa.gov.au/jspui/handle/11017/3666

Thompson, A. A., Davidson, J., Logan, M., & Coleman, G. R. Y. (2022). Marine Monitoring Program: Annual Report inshore coral reef monitoring 2020-21. *Great Barrier Reef Marine Park Authority. https://elibrary.gbrmpa.gov.au/jspui/handle/11017/3929?mode=full*

Thompson, A. A., Martin, K., & Logan, M. (2020). Development of the coral index, a summary of coral reef resilience as a guide for management. *Journal of Environmental Management*, *271*(11103), 111038. https://doi.org/10.1016/j.jenvman.2020.111038

Tibby, J., Barr, C., Marshall, J. C., Richards, J., Perna, C. N., Fluin, J., & Cadd, H. R. (2019). Assessing the relative impacts of land-use change and river regulation on Burdekin River (Australia) floodplain wetlands. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *29*(10), 1712–1725. https://doi.org/10.1002/aqc.3151

Vandergragt, M. L., Warne, M. S. J., Borschmann, G., & Johns, C. V. (2020). Pervasive pesticide contamination of wetlands in the Great Barrier Reef catchment area. *Integrated Environmental Assessment and Management*, *16*(6), 968–982. https://doi.org/10.1002/ieam.4298

Villa, C. A., Flint, M., Bell, I. P., Hof, C. A. M., Limpus, C. J., & Gaus, C. (2017). Trace element reference intervals in the blood of healthy green sea turtles to evaluate exposure of coastal populations. *Environmental Pollution*, *220*, 1465–1476. https://doi.org/10.1016/j.envpol.2016.10.085

Warne, M. S. J., Smith, R. A., & Turner, R. D. R. (2020). Analysis of pesticide mixtures discharged to the lagoon of the Great Barrier Reef, Australia. *Environmental Pollution*, *265*, 114088. https://doi.org/10.1016/j.envpol.2020.114088

Waterhouse, J., Schaffelke, B., Bartley, R., Eberhard, R., Brodie, J. E., Star, M., Thorburn, P. J., Rolfe, J., Ronan, M., Taylor, B. M., & Kroon, F. J. (2017). 2017 Scientific Consensus Statement. Land use impacts on Great Barrier Reef water quality and ecosystem condition – summary. *The State of Queensland*. https://www.reefplan.qld.gov.au/__data/assets/pdf_file/0029/45992/2017-scientific-consensus-statement-summary.pdf

Wilkinson, A. D., Ariel, E., van de Merwe, J. P., & Brodie, J. E. (2022). Trace element concentrations in forage seagrass species of Chelonia mydas along the Great Barrier Reef. *PLOS ONE*, *17*(6), e0269806. https://doi.org/10.1371/journal.pone.0269806

Wolff, N. H., da Silva, E. T., Devlin, M. J., Anthony, K. R. N., Lewis, S. E., Tonin, H., Brinkman, R., & Mumby, P. J. (2018). Contribution of individual rivers to Great Barrier Reef nitrogen exposure with implications for management prioritization. *Marine Pollution Bulletin*, *133*, 30–43. https://doi.org/10.1016/j.marpolbul.2018.04.069

Zhao, W., Huang, Y., Siems, S., & Manton, M. (2021). The Role of Clouds in Coral Bleaching Events Over the Great Barrier Reef. *Geophysical Research Letters*, *48*(14), 14. https://doi.org/10.1029/2021GL093936

Supporting References

Adams, M. P., Koh, E. J. Y., Vilas, M. P., Collier, C. J., Lambert, V. M., Sisson, S. A., Quiroz, M., McDonald-Madden, E., McKenzie, L. J., & O'Brien, K. R. (2020). Predicting seagrass decline due to cumulative stressors. *Environmental Modelling & Software*, *130*, 104717. https://doi.org/10.1016/j.envsoft.2020.104717

Alluvium (2019). Effective and efficient pathways for investment in improved water quality in the Great Barrier Reef: Final Report. A report for the Great Barrier Reef Foundation. *Great Barrier Reef Foundation*. https://doi.org/20.500.12592/132q3v

Australian & Queensland Government (2022). *Paddock to Reef Integrated Monitoring, Modelling and Reporting Program: Report card 2020*. https://reportcard.reefplan.qld.gov.au/

Beaman, R. J. (2010). Project 3DGBR: A high-resolution depth model for the Great Barrier Reef and Coral Sea. Marine and Tropical Sciences Research Facility (MTSRF) Project 2.5i.1a Final Report. Marine and Tropical Sciences Research Facility (MTSRF). https://eatlas.org.au/data/uuid/25685ba5-6583-494f-974d-cce2f3429b78

Bongaerts, P., Muir, P. R., Englebert, N., Bridge, T. C. L., & Hoegh-Guldberg, O. (2013). Cyclone damage at mesophotic depths on Myrmidon Reef (GBR). *Coral Reefs*, *32*(4), 935–935. https://doi.org/10.1007/s00338-013-1052-y

Campbell, S. J., McKenzie, L. J., & Kerville, S. P. (2006). Photosynthetic responses of seven tropical seagrasses to elevated seawater temperature. *Journal of Experimental Marine Biology and Ecology*, *330*(2), 455–468. https://doi.org/10.1016/j.jembe.2005.09.017

Campbell, S. J., McKenzie, L. J., Kerville, S. P., & Bité, J. S. (2007). Patterns in tropical seagrass photosynthesis in relation to light, depth and habitat. *Estuarine, Coastal and Shelf Science*, *73*(3–4), 551–562. https://doi.org/10.1016/j.ecss.2007.02.014

Carruthers, T. J. B., Dennison, W. C., Longstaff, B. J., Waycott, M., Abal, E. G., McKenzie, L. J., & Lee Long, W. J. (2002). Seagrass habitats of northeast Australia: Models of key processes and controls. *Bulletin of Marine Science*, *71*(3), 1153–1169.

Carter, A. B., McKenna, S. A., Rasheed, M. A., Collier, C. J., McKenzie, L. J., Pitcher, C. R., & Coles, R. G. (2021). Synthesizing 35 years of seagrass spatial data from the Great Barrier Reef World Heritage Area, Queensland, Australia. *Limnology and Oceanography Letters*, *6*(4), 216–226. https://doi.org/10.1002/lol2.10193

Coles, R. G., McKenzie, L. J., De'ath, G., Roelofs, A., & Long, W. L. (2009). Spatial distribution of deepwater seagrass in the inter-reef lagoon of the Great Barrier Reef World Heritage Area. *Marine Ecology Progress Series*, *392*, 57–68. https://doi.org/10.3354/meps08197

Coles, R. G., Rasheed, M. A., McKenzie, L. J., Grech, A., York, P. H., Sheaves, M. J., McKenna, S. A., & Bryant, C. V. (2015). The Great Barrier Reef World Heritage Area seagrasses: Managing this iconic Australian ecosystem resource for the future. *Estuarine, Coastal and Shelf Science*, *153*, A1–A12. https://doi.org/10.1016/j.ecss.2014.07.020

Collier, C. J., Adams, M. P., Langlois, L. A., Waycott, M., O'Brien, K. R., Maxwell, P. S., & McKenzie, L. J. (2016). Thresholds for morphological response to light reduction for four tropical seagrass species. *Ecological Indicators*, *67*, 358–366. https://doi.org/10.1016/j.ecolind.2016.02.050

Collier, C. J., Ow, Y. X., Langlois, L. A., Uthicke, S., Johansson, C. L., O'Brien, K. R., Hrebien, V., & Adams, M. P. (2017). Optimum temperatures for net primary productivity of three tropical seagrass species. *Frontiers in Plant Science*, *8*, 1446. https://doi.org/10.3389/fpls.2017.01446

Collier, C. J., & Waycott, M. (2014). Temperature extremes reduce seagrass growth and induce mortality. *Marine Pollution Bulletin*, *83*(2), 483–490. https://doi.org/10.1016/j.marpolbul.2014.03.050

Collier, C. J., Waycott, M., & McKenzie, L. J. (2012). Light thresholds derived from seagrass loss in the coastal zone of the northern Great Barrier Reef, Australia. *Ecological Indicators*, *23*, 211–219. https://doi.org/10.1016/j.ecolind.2012.04.005

Congdon, B. C., Erwin, C. A., Peck, D. R., Baker, G. B., Double, M. C., & O'Neill, P. (2007). Vulnerability of seabirds on the Great Barrier Reef to climate change. *Great Barrier Reef Marine Park Authority*.

Cowman, P. F., Quattrini, A. M., Bridge, T. C. L., Watkins-Colwell, G. J., Fadli, N., Grinblat, M., Roberts, T. E., McFadden, C. S., Miller, D. J., & Baird, A. H. (2020). An enhanced target-enrichment bait set for *Hexacorallia* provides phylogenomic resolution of the staghorn corals (Acroporidae) and close relatives. *Molecular Phylogenetics and Evolution*, *153*(10694), 106944. https://doi.org/10.1016/j.ympev.2020.106944

De'ath, G., & Fabricius, K. E. (2008). Water quality of the Great Barrier Reef: Distributions, effects on reef biota and trigger values for the protection of ecosystem health. http://hdl.handle.net/11017/416

Department of Environment and Heritage Protection (DEHP) (2009). Queensland Water Quality Guidelines 2009 (Version 3). *State of Queensland (Department of Environment and Resource Management*. https://environment.des.qld.gov.au/__data/assets/pdf_file/0020/95150/water-quality-guidelines.pdf

Department of Environment and Science (DES) (2019). *Wetland data – version 5 - wetland areas – Queensland*. https://www.data.qld.gov.au/dataset/wetland-data-version-5-queensland-series%3E

Department of Environment and Science (DES) (2021). *Great Barrier Reef contributing catchments — facts and maps, Wetland*. https://wetlandinfo.des.qld.gov.au/wetlands/facts-maps/study-area-great-barrier-reef/

Devantier, L. M., De'ath, G., Turak, E., Done, T. J., & Fabricius, K. E. (2006). Species richness and community structure of reef-building corals on the nearshore Great Barrier Reef. *Coral Reefs*, *25*(3), 329–340. https://doi.org/10.1007/s00338-006-0115-8

Dietzel, A., Bode, M., Connolly, S. R., & Hughes, T. P. (2020). Long-term shifts in the colony size structure of coral populations along the Great Barrier Reef. *Proceedings of the Royal Society B: Biological Sciences*, *287*(1936), 20201432. https://doi.org/10.1098/rspb.2020.1432

Duke, N. C., & Larkum, A. W. D. (2019). Mangroves and seagrasses. In P. Hutchings, M. Kingsford, & O. Hoegh-Guldberg (Eds.), *The Great Barrier Reef: biology, environment and management* (2nd Edition, pp. 219–228). *CSIRO publishing*.

Duke, N. C., Mackenzie, J. R., Canning, A. D., Hutley, L. B., Bourke, A. J., Kovacs, J. M., Cormier, R., Staben, G., Lymburner, L., & Ai, E. (2022). ENSO-driven extreme oscillations in mean sea level destabilise critical shoreline mangroves—An emerging threat. *PLOS Climate*, *1*(8), e0000037. https://doi.org/10.1371/journal.pclm.0000037

Ebner, B. C., Fulton, C. J., Donaldson, J. A., & Schaffer, J. R. (2016). Distinct habitat selection by freshwater morays in tropical rainforest streams. *Ecology of Freshwater Fish*, *25*(2), 329–335. https://doi.org/10.1111/eff.12213

Emslie, M. J., Bray, P., Cheal, A. J., Johns, K. A., Osborne, K., Sinclair-Taylor, T., & Thompson, C. A. (2020). Decades of monitoring have informed the stewardship and ecological understanding of Australia's Great Barrier Reef. *Biological Conservation*, *252*, 108854. https://doi.org/10.1016/j.biocon.2020.108854

Fabricius, K. E., Logan, M., Weeks, S. J., Lewis, S. E., & Brodie, J. E. (2016). Changes in water clarity in response to river discharges on the Great Barrier Reef continental shelf: 2002–2013. *Estuarine, Coastal and Shelf Science*, *173*, A1–A15. https://doi.org/10.1016/j.ecss.2016.03.001

Gallen, C., Thai, P., Paxman, C., Prasad, P., Elisei, G., Reeks, T. A., Eaglesham, G. K., Yeh, R., Tracey, D., Grant, S., & Müller, J. F. (2019b). Marine Monitoring Program: Annual Report for inshore pesticide monitoring 2017–18. Report for the Great Barrier Reef Marine Park Authority. *Great Barrier Reef Marine Park Authority*. https://elibrary.gbrmpa.gov.au/jspui/handle/11017/3489

Great Barrier Reef Marine Park Authority (GBRMPA) (2009). Great Barrier Reef Outlook Report 2009. *Great Barrier Reef Marine Park Authority*. http://hdl.handle.net/11017/3474

Grech, A., Chartrand-Miller, K., Erftemeijer, P., Fonseca, M., McKenzie, L. J., Rasheed, M. A., Taylor, H., & Coles, R. G. (2012). A comparison of threats, vulnerabilities and management approaches in global seagrass bioregions. *Environmental Research Letters*, *7*(2), 024006. https://doi.org/10.1088/1748-9326/7/2/024006

Grech, A., Coles, R. G., & Marsh, H. (2011). A broad-scale assessment of the risk to coastal seagrasses from cumulative threats. *Marine Policy*, *35*(5), 560–567. https://doi.org/10.1016/j.marpol.2011.03.003

Hamann, M., Limpus, C. J., & Read, M. A. (2007). Vulnerability of marine reptiles in the Great Barrier Reef to climate change - Chapter 15. In J. E. Johnson & P. A. Marshall (Eds.), *Climate Change and the Great Barrier Reef: A Vulnerability Assessment, Part II: Species and species groups* (pp. 465–496). *Great Barrier Reef Marine Park Authority*.

Heupel, M. R., & Simpfendorfer, C. A. (2014). Importance of environmental and biological drivers in the presence and space use of a reef-associated shark. *Marine Ecology Progress Series*, *496*, 47–57. https://doi.org/10.3354/meps10529

Hughes, B. B., Lummis, S. C., Anderson, S. C., & Kroeker, K. J. (2018a). Unexpected resilience of a seagrass system exposed to global stressors. *Global Change Biology*, *24*(1), 224–234. https://doi.org/10.1111/gcb.13854

Hutchings, P., Ahyong, S., Byrne, M., Przeslawski, R., & W"orheide, G. (2007). Vulnerability of benthic invertebrates of the Great Barrier Reef to climate change - Chapter 11. In J. E. Johnson & P. A. Marshall (Eds.), *Climate Change and the Great Barrier Reef: A Vulnerability Assessment, Part II: Species and species groups* (pp. 309–356). *Great Barrier Reef Marine Park Authority*.

Jensen, M. P., Allen, C. D., Eguchi, T., Bell, I. P., LaCasella, E. L., Hilton, W. A., Hof, C. A. M., & Dutton, P. H. (2018). Environmental warming and feminization of one of the largest sea turtle populations in the world. *Current Biology*, *28*(1), 154-159.e4. https://doi.org/10.1016/j.cub.2017.11.057

Johns, L. (2019). Field guide to common saltmarsh plants of Queensland. *Queensland Government*.

Johnson, J., & Marshall, P. A. (2007). Climate change and the Great Barrier Reef (1st Edition). *Great Barrier Reef Marine Park Authority and Australian Greenhouse Office*. https://doi.org/10.4324/9781003090304-7

Kilminster, K., McMahon, K. M., Waycott, M., Kendrick, G. A., Scanes, P., McKenzie, L. J., O'Brien, K. R., Lyons, M. B., Ferguson, A. J. P., Maxwell, P. S., Glasby, T., & Udy, J. W. (2015). Unravelling complexity in seagrass systems for management: Australia as a microcosm. *Science of The Total Environment*, *534*, 97–109. https://doi.org/10.1016/j.scitotenv.2015.04.061

Kitahara, M. V, Fukami, H., Benzoni, F., & Huang, D. (2016). The new systematics of Scleractinia: Integrating molecular and morphological evidence. In S. Goffredo & Z. Dubinsky (Eds.), *The Cnidaria, Past, Present and Future* (pp. 41–59). *Springer International Publishing*. https://doi.org/10.1007/978-3-319-31305-4_4

Kroon, F. J., Hook, S. E., Metcalfe, S., & Jones, D. (2015). Altered levels of endocrine biomarkers in juvenile barramundi (*Lates calcarifer*; Bloch) following exposure to commercial herbicide and surfactant formulations. *Environmental Toxicology and Chemistry*, *34*(8), 1881–1890. https://doi.org/10.1002/etc.3011

Lovelock, C. E., & Ellison, J. C. (2007). Vulnerability of mangroves and tidal wetlands of the Great Barrier Reef to climate change - Chapter 9: In J. E. Johnson & P. A. Marshall (Eds.), *Climate Change and the Great Barrier Reef: A Vulnerability Assessment, Part II: Species and species groups* (pp. 239–269). *Great Barrier Reef Marine Park Authority*.

Marsh, H., Heatwole, H., & Lukoschek, V. (2019). Marine mammals and reptiles. In M. Kingsford & O. Hoegh-Guldberg (Eds.), *The Great Barrier Reef: biology, environment and management* (Second Edition, pp. 407–418). *CSIRO*.

McNeil, M. A., Firn, J., Nothdurft, L. D., Pearse, A. R., Webster, J. M., & Roland Pitcher, C. (2021). Inter-reef *Halimeda* algal habitats within the Great Barrier Reef support a distinct biotic community and high biodiversity. *Nature Ecology & Evolution*, *5*(5), 647–655. https://doi.org/10.1038/s41559-021-01400-8

McNeil, M. A., Webster, J. M., Beaman, R. J., & Graham, T. L. (2016). New constraints on the spatial distribution and morphology of the *Halimeda* bioherms of the Great Barrier Reef, Australia. *Coral Reefs*, *35*(4), 1343–1355. https://doi.org/10.1007/s00338-016-1492-2

Meager, J.J. & Limpus, C.J. (2012a). Marine wildlife stranding and mortality database annual report 2011. I. Dugong. *Conservation Technical and Data Report,* 2011(1): 1-30.

Meager, J.J. & Limpus, C.J. (2012b). Marine wildlife stranding and mortality database annual report 2011. III. Marine Turtle. *Conservation Technical and Data Report,* 2012(3): 1-46.

Oesterwind, D., Rau, A., & Zaiko, A. (2016). Drivers and pressures – Untangling the terms commonly used in marine science and policy. *Journal of Environmental Management*, *181*, 8–15. https://doi.org/10.1016/j.jenvman.2016.05.058

Petus, C., Devlin, M. J., Thompson, A. A., McKenzie, L. J., Teixeira da Silva, E., Collier, C. J., Tracey, D., & Martin, K. (2016). Estimating the exposure of coral reefs and seagrass meadows to land-sourced contaminants in river flood plumes of the Great Barrier Reef: Validating a simple satellite risk framework with environmental data. *Remote Sensing*, *8*(3), 210. https://doi.org/10.3390/rs8030210

Pitcher, C. R., Doherty, P. J., Arnold, P., Gribble, N. A., Bartlett, C., Browne, M., Campbell, N., Cannard, T., Cappo, M., Carini, G., Chalmers, S., Cheers, S., Chetwynd, D., Colefax, A. P., Coles, R. G., Cook, S., Davie, P., De'ath, G., Devereux, D., … Yearsley, G. (2007). Seabed biodiversity on the continental shelf of the Great Barrier Reef World Heritage Area. AIMS/CSIRO/QM/QDPI CRC Reef Research Task Final Report. *CSIRO*. https://era.daf.qld.gov.au/id/eprint/1704/1/CRC_GBR_Seabed_Biodiversity_Final_Report__Fri20July07c-sec.pdf

Ramírez-Portilla, C., Baird, A. H., Cowman, P. F., Quattrini, A. M., Harii, S., Sinniger, F., & Flot, J.-F. (2021). Solving the coral species delimitation conundrum. *Systematic Biology*, *71*(2), 461–475. https://doi.org/10.1093/sysbio/syab077

Rasheed, M. A., McKenna, S. A., Carter, A. B., & Coles, R. G. (2014). Contrasting recovery of shallow and deep water seagrass communities following climate associated losses in tropical north Queensland, Australia. *Marine Pollution Bulletin*, *83*(2), 491–499. https://doi.org/10.1016/j.marpolbul.2014.02.013

Segner, H., Schmitt-Jansen, M., & Sabater, S. (2014). Assessing the impact of multiple stressors on aquatic biota: The receptor's side matters. *Environmental Science & Technology*, *48*(14), 7690–7696. https://doi.org/10.1021/es405082t

Udy, J. W., Waycott, M., Collier, C. J., Kilminster, K., McMahon, K. M., Rasheed, M. A., McKenzie, L. J., Carter, A. B., Lawrence, E., Maxwell, P. S., Dwane, G., Martin, K., & Honchin, C. (2018). Monitoring seagrass within the Reef 2050 Integrated Monitoring and Reporting Program. *Great Barrier Reef Marine Park Authority*.

Waterhouse, J., Gruber, R. K., Logan, M., Petus, C., Howley, C., Lewis, S. E., Tracey, D., James, C., Mellors, J., Tonin, H., Skuza, M., Costello, P., Davidson, J., Gunn, K., Lefèvre, C. D., Moran, D., Robson, B. J., Shanahan, M., Zagorskis, I., & Shellberg, J. G. (2021). Marine Monitoring Program: Annual report for inshore water quality monitoring 2019-20. *Great Barrier Reef Marine Park Authority*. https://hdl.handle.net/11017/3826

Wooldridge, S. A. (2017). Preventable fine sediment export from the Burdekin River catchment reduces coastal seagrass abundance and increases dugong mortality within the Townsville region of the Great Barrier Reef, Australia. *Marine Pollution Bulletin*, *114*(2), 671–678. https://doi.org/10.1016/j.marpolbul.2016.10.053

York, P. H., Carter, A. B., Chartrand, K. M., Sankey, T., Wells, L., & Rasheed, M. A. (2015). Dynamics of a deep-water seagrass population on the Great Barrier Reef: annual occurrence and response to a major dredging program. *Scientific Reports*, *5*(1), 13167. https://doi.org/10.1038/srep13167

Appendix 1: 2022 Scientific Consensus Statement author contributions to Question 1.2/1.3/2.1

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

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

Author team

Name	Organisation	Expertise	Role in addressing the Question	Sections/Topics involved
1. Len McKenzie	James Cook University	Seagrass, threats, ecosystem resilience	Lead Author	All Sections.
2. Mari-Carmen Pineda	C_2O Consulting	Coral, threats	Contributor	Question interpretation, conceptual diagram, search strategy, searches and screening, data extraction and evidence appraisal and assisted with narrative synthesis.
3. Alana Grech	James Cook University	Coral, megafauna, threats, ecosystem resilience	Contributor	Contributed to narrative synthesis and final revision of overall report.
4. Angus Thompson	Australian institute of Marine Science	Coral, threats, ecosystem resilience	Contributor	Contributed to narrative synthesis and final revision of overall report.