2022 Scientific Consensus Statement

Question 2.4 How do water quality and climate change interact to influence the health and resilience of Great Barrier Reef ecosystems?

Question 2.4.1 How are the combined impacts of multiple stressors (including water quality) affecting the health and resilience of Great Barrier Reef coastal and inshore ecosystems?

Question 2.4.2 Would improved water quality help ecosystems cope with multiple stressors including climate change impacts, and if so, in what way?

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Citation

Uthicke S, Fabricius K, Brown A, Molinari B, Robson B (2024) Question 2.4 How do water quality and climate change interact to influence the health and resilience of Great Barrier Reef ecosystems? In Waterhouse J, Pineda M-C, Sambrook K (Eds) 2022 Scientific Consensus Statement on land-based impacts on Great Barrier Reef water quality and ecosystem condition. Commonwealth of Australia and Queensland Government.

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

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

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

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

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

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

Guidance for using the synthesis of evidence

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

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

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

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

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

Peer Review and Quality Assurance

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

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Acknowledgements

We are grateful to Rob Richards (Evidentiary), Jane Waterhouse (C_2O Consulting) and Mari-Carmen Pineda (C_2O Consulting) for comments and suggestions on earlier versions of this document. Thanks to Elisa Westmore (CANEGROWERS) for submitting literature for consideration in this synthesis.

Executive Summary

Questions

Primary Question 2.4 How do water quality and climate change interact to influence the health and resilience of Great Barrier Reef ecosystems?

Secondary Question 2.4.1 How are the combined impacts of multiple stressors (including water quality) affecting the health and resilience of Great Barrier Reef coastal and inshore ecosystems?

Secondary Question 2.4.2 Would improved water quality help ecosystems cope with multiple stressors including climate change impacts, and if so, in what way?

Background

While climate change can only be addressed through concerted international efforts, local and regional policy measures can address other causes of ecosystem stress. To assist in prioritising policy measures and interventions, it is important to understand not only the individual impact of each source of stress on Great Barrier Reef (GBR) ecosystems, but also to understand how multiple stressors interact. This synthesis of evidence summarises results from experimental, modelling and synthesis studies, mainly restricting the geographic focus to the GBR.

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 included Scopus, Web of Science, and the National Environmental Science Program (NESP) Tropical Water Quality Hub website.
- Main source of evidence: Publications directly relevant to the GBR and Queensland waters, also drawing in relevant reviews covering larger geographic areas.
- The literature searches for Q2.4 and Q2.4.1 (plus additional wetland and mangrove searches and manual additions) resulted in 3,187 evidence items for initial screening, of which 117 met the eligibility criteria for inclusion in the synthesis.

Method limitations and caveats to using this Evidence Summary

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

- Only studies written in English were included (although no reports in other languages were detected in the searches).
- With a few exceptions, only GBR and Queensland studies were included.
- Only studies published after 1990 were included.

Key Findings

Summary of evidence to 2022

The literature was searched for evidence items (peer reviewed publications and reports) that assessed interactions between the effects of climate change and water quality (WQ), and between climate

[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

change related stressors (mainly temperature and ocean acidification) within coastal ecosystems (coral reefs, seagrass meadows, coastal wetlands), and on organisms found within these ecosystems. From the searches, 117 eligible evidence items were identified, all of which were published since 2002. Most studies (61%) used an experimental approach, manipulating combinations of the stressors.

This Evidence Summary found that many studies have investigated interacting effects on several groups of coral reef organisms (mainly coral, algae and foraminifera). Coastal wetlands were less well studied, with the exception of seagrass meadows.

The majority of evidence items showed aggravating impacts (i.e., effects of combined stressors were greater than individual stressors) on at least some of the relevant response parameters (e.g., growth, mortality and photosynthesis) for most stressor combinations.

Although nutrients influence coral bleaching in some circumstances and have other aggravating effects on corals and other organisms, the full mechanism of the combined effects of climate change and water quality on bleaching is not understood. However, given this Evidence Summary and other international reviews demonstrate additional stress under elevated nutrients, it remains important to manage nutrient runoff and invest further in understanding these mechanisms.

Several other key messages were identified:

Q 2.4, 2.4.1:

- 68% (63% if only experimental studies were considered) of the 117 evidence items included, found additive/aggravating interactive effects between water quality and climate change stressors. Hence, removing one of the stressors will improve species and ecosystem outcomes.
- Of the many stressor combinations, of particular note are strong cumulative effects between **climate change** (either temperature increase alone, or temperature combined with ocean acidification) and **herbicides.** These effects are reasonably well studied (9 studies) with aggravating interactive effects in several phyla. Data on this interaction (and also the interaction of copper contamination and temperature) are sufficient to model species sensitivity distributions and suggest climate adjusted thresholds for individual herbicides. Of the nine evidence items on climate change and herbicide interactions, 89% (88% removing one modelling study) showed aggravating effects (Table 9), whereas the remaining studies showed no effect or mitigating effects.
- The effects of **climate change** and **nutrient** input have also been well studied across a broad spectrum of organisms, with 77% (72% without modelling studies) of the 26 studies indicating that nutrients impose an additional stress when combined with climate change (mainly temperature increase).
- Despite caveats on insufficient understanding of the mechanisms and the importance of nutrient influences on bleaching in coral, there is consistent evidence that nutrients constitute important pressures on the GBR.
- Although only tested on corals and seagrasses, the effects of **climate change** and **light reduction** (encompassing turbidity increases and higher sediment/sedimentation load) are also relatively strong and consistent, with 70% of the 10 studies indicating a worse outcome if climate change and light reduction are present. However, during bleaching events, light reduction can also help to mitigate coral bleaching.
- Two out of six studies indicated cumulative effects of **ocean acidification** and **light reduction**.
- A large number of studies (34) tested the interactive effects of **temperature** increase and **ocean acidification** (Table 9). 56% (55% without modelling studies) of these studies identified aggravating effects, with effects found across many taxa.
- Some stressor combinations have not been or were rarely studied on the GBR. These included **salinity** on the water quality side, and **heatwaves** and **runoff event frequency** on the climate side.
- For **seagrasses and algae**, no aggravating effects were identified between ocean acidification and water quality (specifically **nutrients** and **light reduction**), likely due to possible positive

responses of these groups to ocean acidification (because of carbon limitation for photosynthesis).
- Several studies and conclusions to other SCS questions showed **indirect effects** of water quality on coral reefs and seagrass meadows. Removing water quality stress will bolster resilience to climate change (and other) stressors and thus likely improve recovery after acute disturbance.

Q 2.4.2:

- Given the synthesis of evidence to address Q2.4 and 2.4.1 revealed many instances of climate change effects being aggravated under additional water quality stress, management actions to improve water quality can provide some reprieve from climate change impacts.
- The strength and length of this reprieve currently cannot be quantified.
- Given that there are also many studies showing the deleterious effects of climate change alone, it remains imperative to address climate change.
- Improving water quality also has an indirect effect on coral reefs and seagrass meadows. Under better water quality conditions, these ecosystems are more resilient and can recover faster after acute disturbances (e.g., bleaching, crown-of-thorns starfish outbreaks, cyclones).

Recent findings 2016-2022

Because this question was not considered explicitly in the 2017 SCS, and research on interactive effects is new, data after 2016 were not analysed separately. This Evidence Summary includes 59 studies published before 2016 and 58 studies published during the period 2016-2022. There was high consistency in the findings of studies between these two periods.

Significance for policy, practice, and research

Given the number of studies that identified poorer outcomes for a range of species and ecosystems when water quality stressors were present in addition to climate change stressors, it is highly likely that reducing water quality stressors (specifically pesticides, nutrients and light reduction/sedimentation) would improve the outcome and resilience of GBR ecosystems in response to climate change. However, data are currently insufficient to quantify the strength and duration of this possible relief. Hence, it is prudent to assume that the period is short, and that additional action to ameliorate climate change is required.

Key uncertainties and/or limitations

Some stressors have not been (or have rarely been) studied in combination with other stressors on the GBR. These include salinity on the water quality side, and heatwaves and runoff event frequency on the climate side. Several stressor combinations have some temporal or spatial limitations because they were only studied in one season, in a short-term experiment or with specimens from a single location.

Evidence appraisal

The relevance of the overall body of evidence was High (Score: 7). Of the 117 articles included in the review of question (including the additional wetlands search), 68 were given a High score for overall relevance to the question, while 40 had a Moderate overall relevance score.

Given that most studies illustrated aggravating effects, the Consistency and Quantity of the evidence was considered High. Diversity of study approaches was High and Diversity of study organisms Moderate.

The overall measure of confidence for the evidence was High.

1. Background

Climate change is widely considered to be the single greatest threat to the Great Barrier Reef (GBR) (e.g., Bohensky et al., 2011; GBRMPA, 2019; Pörtner, 2022; Walpole, 2022). The global average surface temperature increased by about 1.1°C between the periods 1850-1900 and 2011-2019 (IPCC, 2021). Under the intermediate greenhouse gas emissions scenario (SSP2-4.5), the 2081-2100 global average surface temperature is extremely likely to reach temperatures of 2.1-3.5°C warmer than the 1850-1900 period, or 3.3-5.7°C warmer under the very high emissions scenarios (SSP5-8.5) (IPCC, 2021).

While climate change can only be addressed through concerted international efforts, local and regional policy measures can address other causes of ecosystem stress. To assist in prioritising policy measures and interventions, it is important to understand not only the individual impact of each source of stress on GBR ecosystems (addressed in other Scientific Consensus Statement (SCS) questions), but also to understand how multiple stressors interact.

'Climate change' affects ecosystems through several stressors (Figure 1). Those considered in this synthesis include: increasing mean ocean temperature; increasing frequency, duration and severity of marine heatwaves; ocean acidification; and changes in the frequency and magnitude of runoff events. The impact of climate change on GBR ecosystems is addressed in Question 2.2 '*What are the current and predicted impacts of climate change on Great Barrier Reef ecosystems (including spatial and temporal distribution of impacts)?' and 'How is climate change currently influencing water quality in coastal and marine areas of the Great Barrier Reef, and how is this predicted to change over time?*, and is therefore not addressed in detail here. In summary, the key findings from Question 2.2 (Fabricius et al., this SCS) show that:

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

'Water quality' also encompasses several stress factors (Figure 1). Those considered here include: enhanced nutrient loads and/or nutrient concentrations; reduced light due to increased suspended sediment concentrations; salinity (e.g., exposure of marine species to low salinity); and toxicants such as herbicides and pesticides. These impacts are also addressed in other SCS questions, including:

- *Question 3.2 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?* (Collier et al., this SCS)

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

- *Question 4.2 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?* (Diaz-Pulido et al., this SCS)

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

- *Question 5.1 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? What evidence is there for pesticide risk?* (Negri et al., this SCS)

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

- *Question 6.1 What is the spatial and temporal distribution and risk of other pollutants in GBR ecosystems, and what are the primary sources?* (Chariton and Hejl, this SCS)

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

When a species or ecosystem is exposed to more than one stressor (either simultaneously or in succession), the cumulative impact may take one of three forms (Uthicke et al., 2016):

- *Additive* effects: There is no interaction between the stressors. Each has a separate impact on the affected organism or ecosystem.
- *Synergistic* effects: The combined effects are greater than the sum of the individual effects.

- *Antagonistic* (mitigating) effects: The combined effects are less than the sum of the individual effects. This may be because both stressors affect the organism through the same physiological mechanism or because one stressor, despite having a negative effect on its own, can have a protective effect versus a second stressor.

When the cumulative effects are aggravating (additive or synergistic), effectively managing one stressor can be disproportionately effective in maintaining the health and resilience of a GBR ecosystem. In the context of climate change, improving water quality through local and regional action is sometimes spoken of as a way to 'buy time' for climate change interventions to take effect and for organisms and ecosystems to adapt (e.g., Wooldridge, 2009). Part of the aim of this synthesis was to assess the strength of evidence supporting this view (Q2.4.2). In addition to direct effects on species and communities of water quality and climate change combined, it is also likely that poor water quality will reduce recovery rates after thermal stress events. No research on this has been conducted on the GBR, but several modelling studies and analysis by the Marine Monitoring Program (MMP)[6] support this.

The indirect role of nutrients for resilience and recovery of coral reefs and seagrass meadows is also supported by the key findings of the following SCS questions:

Question 4.2 '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?'- "The most severe impacts of increased nutrients on corals may be indirect. For instance, elevated nutrient availability on inshore reefs is generally (but not always) positively correlated with increased fleshy macroalgal abundance. High fleshy macroalgae abundance and biomass can reduce coral settlement and recruitment, outcompete corals, reduce coral cover and negatively affect coral calcification. Another indirect effect is the relationship between excess nutrients and increasing phytoplankton food supplies for crown-of-thorns starfish larval stages which can potentially contribute to outbreaks."

Question 3.2 '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?'

- "Sediments and particulate nutrients are also suppressing reef recovery from disturbances due to their strong negative effects on coral recruitment including many of the early life stages."

- "Seagrass meadows are dynamic and will often recover with the rate depending on the extent of decline and the local and regional conditions that follow."

1.1 Questions

Primary question	**Q2.4** How do water quality and climate change interact to influence the health and resilience of Great Barrier Reef ecosystems?
Secondary questions	**Q2.4.1** How are the combined impacts of multiple stressors (including water quality) affecting the health and resilience of Great Barrier Reef coastal and inshore ecosystems?
	Q2.4.2 Would improved water quality help ecosystems cope with multiple stressors including climate change impacts, and if so, in what way?

Question 2.4 Do water quality parameters (nutrients, sediments, pesticides) interact with climate change parameters (including temperature, ocean acidification, and possibly other climate change impacts such as storms) to affect the health of key ecosystem builders (including coral, seagrass) and if yes in what way (additive, synergistic, antagonistic)?

The term 'how' is interpreted as asking for the direction of the interaction (i.e., are they additive, synergistic, or antagonistic), and not the actual mechanism of action on the organism. The question is

[6] https://www2.gbrmpa.gov.au/our-work/programs-and-projects/marine-monitoring-program

interpreted as "do water quality parameters interact with climate change parameters (e.g., temperature, ocean acidification) to alter reef health and resilience compared to when either stressor was present individually". As described in the Background, this question does not review the individual water quality impacts on GBR ecosystems as these are addressed in other SCS questions (Q3.2 Collier et al., Q4.2 Diaz-Pulido et al., Q4.3 Caballes et al., Q5.1 Negri et al., Q6.1 Chariton & Hejl).

Literature searches were focused on experimental and field evidence of impacts on key groups of organisms, focusing on main ecosystem builders (coral, seagrasses), but also other important organisms. Most studies were expected to focus on health (e.g., bleaching, mortality) or health indicators for organisms, and it is likely that the consequences for resilience will also be assessed based on health outcomes for most studies.

Question 2.4.1 What is the evidence for multiple stressors affecting indicators of Great Barrier Reef ecosystem health and resilience?

In this secondary question, climate-climate and water quality–water quality interactions were also considered (but not climate interactions with stressors other than water quality).

Question 2.4.2 Would improved water quality help ecosystems cope with multiple stressors including climate change impacts, and if so, in what way?

This question was interpreted as 'does improving water quality *buy time*' for addressing climate change impacts, and if yes, how? It is not yet possible to quantify the time that can be gained through water quality improvement. However, Question 2.2 (Fabricius et al., this SCS) has a secondary question, 2.2.1, which addresses the question '*How is climate change currently influencing water quality in coastal and marine areas of the GBR, and how is this predicted to change over time?'*. Evidence of these predicted changes are critical for answering Q2.2.1, and are considered in the response to this secondary question.

1.2 Conceptual diagram

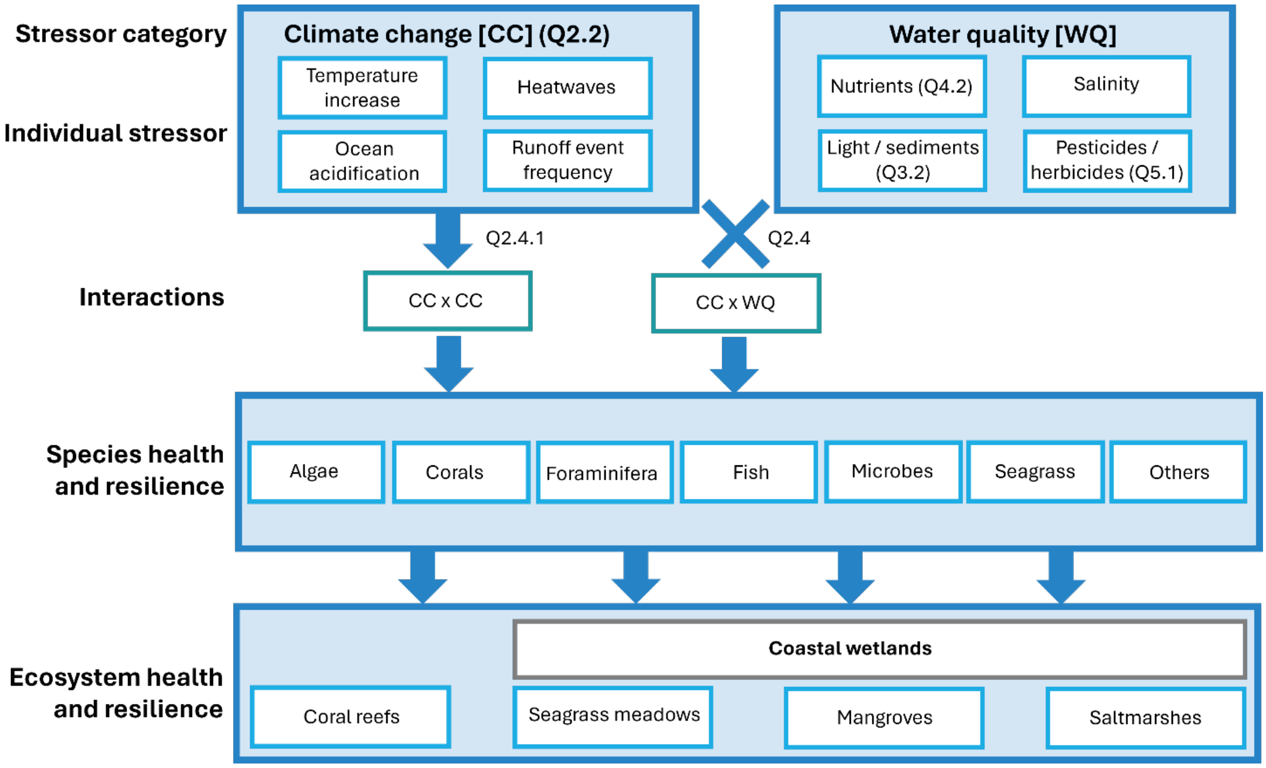


Figure 1. Conceptual model used to evaluate how water quality and climate change interact to influence the health and resilience of GBR ecosystems. Black numbers refer to questions addressed in this Evidence Summary, yellow or red numbers refer to other questions where individual stressors are discussed.

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 covering ecological processes, delivery and source, management options, human dimensions of water quality management, and future directions and emerging science. 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	**Q2.2** What are the current and predicted impacts of climate change on Great Barrier Reef ecosystems (including spatial and temporal distribution of impacts)? **(2.2.1)** How is climate change currently influencing water quality in coastal and marine areas of the Great Barrier Reef, and how is this predicted to change over time? **Q3.1** What are the spatial and temporal distributions of sediments and associated indicators within the Great Barrier Reef? **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? **Q4.1** What is the spatial and temporal distribution of nutrients and associated indicators within the Great Barrier Reef? **Q4.2** What are the measured impacts of nutrients on Great Barrier Reef ecosystems, what are the mechanism(s) for those impacts and where is there evidence of this occurring in the Great Barrier Reef? **Q5.1** What is the spatial and temporal distribution of pesticides across Great Barrier Reef ecosystems, what evidence is there for pesticide risk and what are the (potential or observed) ecological impacts in these ecosystems?

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

2.1 Primary question elements and description

The primary question is: ***How do water quality and climate change interact to influence the health and resilience of GBR ecosystems?***

The secondary questions are:

- ***2.4.1 How are the combined impacts of multiple stressors (including water quality) affecting the health and resilience of GBR coastal and inshore ecosystems?***
- ***2.4.2 Would improved water quality help ecosystems cope with multiple stressors including climate change impacts, and if so, in what way?***

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

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

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

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

Table 1. Description of primary question elements for Question 2.4.

Question S/PICO elements	Question term	Description
Subject/Population	GBR ecosystems	As per definitions. The main focus was coral and seagrass ecosystems, as well as coastal mangroves. The health and performance of the main ecosystem components (e.g., coral, algae, seagrass, invertebrates, microbes) can serve as proxy for ecosystem health.
Intervention, exposure & qualifiers	Climate change and water quality	Climate change (increased temperature, increased acidity, higher frequencies of heatwaves) and poor water quality (increased particulate and dissolved nutrients, salinity, reduced light, pesticides) and the combination of multiple stressors.
Comparator	(not relevant)	(not relevant)
Outcome & outcome qualifiers	Health and resilience of GBR ecosystems	Flourishing, productive and diverse ecosystems. High coral and seagrass cover in the respective ecosystems. In a healthy ecosystem, dynamic attributes are expressed within normal ranges of activity relative to its ecological stage of development.

Table 2. Definitions for terms used in Question 2.4.

Definitions	
Water quality	Components may include volumes, variability in river discharges of nutrients and sediments; concentrations in flood plumes; regionally resolved annual mean water clarity, nutrient concentrations. Excluded: carbonate chemistry/ocean acidification (covered by Question 2.2, Fabricius et al., this SCS).
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 (UN). Climate change-related potential threats in the context of this question include increasing temperature, intensity and frequency of heatwaves, and ocean acidification.
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 et al., 1992)[9].
Resilience	The capacity of ecosystems (or species or individuals) to resist from and recover after a disturbance
GBR ecosystems	In the context of the SCS, 'GBR ecosystems' include marine (coral, seagrass, pelagic, benthic and plankton communities), estuarine (estuaries, mangroves, saltmarsh), and freshwater (freshwater wetlands, floodplain wetlands) ecosystems.

[9] 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.

Definitions	
	In the context of this question, the focus was on coral reef ecosystems, seagrass meadows, and coastal mangrove forests, although other components were also included if the evidence was available (e.g., planktonic communities).
Coastal and inshore ecosystems	Marine areas from river mouth to the ~20 m depth line. This synthesis focused on coral reefs, seagrass meadows and coastal mangrove forests, with the coastline being the cut-off.
Combined impact	Negative effects of several stressors on an organism or ecosystem, independent of these being additive or synergistic.
Climate change impacts	Reduced capacity of individual species or ecosystems to thrive (and recover after disturbance: =resilience) as an acute or long-term consequence of increased CO_2 in the atmosphere.

2.2 Search and eligibility

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

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

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

a) Search locations

Searches were performed on:

- Web of Science, searching 'TS' fields (TS = Topic: Title, Abstract, Author Keywords and Keywords Plus®)
- Scopus, searching 'Title, Abstract, Keywords' fields
- NESP Tropical Water Quality reports (https://nesptropical.edu.au/)

b) Search terms

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

Table 3. Search terms for S/PICO elements of Question 2.4.

Question element	Search terms
"Great Barrier Reef" AND GBR	**Search 1 and 2:** ("Great Barrier Reef" OR "GBR") **Search 3:** ("Great Barrier Reef" OR "GBR" OR Queensland) (wetland* OR palustrine OR riverine OR lacustrine OR marsh* OR melaleuca OR floodplain) **Search 4:** ("Great Barrier Reef" OR "GBR" OR Queensland) (mangrove)
Exposure or Intervention	**Search 1:** ("Climate change" OR temperature OR thermal OR acidification OR sst OR pco* OR co2) ("water quality" OR nutrients OR light OR irradiance OR turbidity OR pesticide OR herbicide OR pollut* OR salinity OR sediment* OR thermal)

Question element	Search terms
	Search 2: (Acidification OR pCO* OR CO2) (“Climate change” OR Temperature OR Thermal OR SST) **Search 3 and 4:** (“Water Quality” OR Nutrient* OR Nitr* OR Phosph* OR light OR Irradiance OR Turbidity OR Pesticide OR Herbicide OR Pollut* OR Salinity OR Sediment*) (“Climate change” OR Temperature OR flood OR runoff OR “Sea-level rise” OR rainfall OR precipitation OR “extreme events”)
Comparator	(Not relevant)
Outcome	(Not relevant)

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 2.4.

Search strings All searches were in the date range 01/01/1990 to 31/10/2022
Search 1 - Primary search query (Q 2.4) **1,530 results** Web of Science: “TS=(("Great Barrier Reef" OR GBR) AND ("Climate change" OR temperature OR thermal OR acidification OR sst OR pco* OR co2) AND ("water quality" OR nutrients OR light OR irradiance OR turbidity OR pesticide OR herbicide OR pollut* OR salinity OR sediment* OR thermal))”
Search 1 - Primary search query (Q 2.4) **635 results** Scopus: “Abs-TI-Key(("Great Barrier Reef" OR GBR) AND ("Climate change" OR temperature OR thermal OR acidification OR sst OR pco* OR co2) AND ("water quality" OR nutrients OR light OR irradiance OR turbidity OR pesticide OR herbicide OR pollut* OR salinity OR sediment* OR thermal))”
Search 2 - Secondary search query (to target ocean acidification/temperature interactions, Q 2.4.1) **357 results** Web of Science: “TS=((“Great Barrier Reef” OR “GBR”) AND (Acidification OR pCO* OR CO2) AND (“Climate change” OR Temperature OR Thermal OR SST))”
Search 2 - Secondary search query (to target ocean acidification/temperature interactions, Q 2.4.1) **110 results** Scopus: “Abs-TI-Key((“Great Barrier Reef” OR “GBR”) AND (Acidification OR pCO* OR CO2) AND (“Climate change” OR Temperature OR Thermal OR SST))”
Search 3 - Secondary search query (to target wetlands) **241 results** Web of Science: “TS=((“Great Barrier Reef” OR “GBR” OR Queensland) AND (wetland* OR palustrine OR riverine OR lacustrine OR marsh* OR melaleuca OR floodplain)

Search strings All searches were in the date range 01/01/1990 to 31/10/2022
AND ("Water Quality" OR Nutrient* OR Nitr* OR Phosph* OR light OR Irradiance OR Turbidity OR Pesticide OR Herbicide OR Pollut* OR Salinity OR Sediment*) AND ("Climate change" OR Temperature OR flood OR runoff OR "Sea-level rise" OR rainfall OR precipitation OR "extreme events"))"
Search 3 - Secondary search query (to target wetlands) **156 results** Scopus: "Abs-TI-Key (("Great Barrier Reef" OR "GBR" OR Queensland) AND (wetland* OR palustrine OR riverine OR lacustrine OR marsh* OR melaleuca) AND ("Water Quality" OR Nutrients OR light OR Irradiance OR Turbidity OR Pesticide OR Herbicide OR Pollut* OR Salinity OR Sediment*) AND ("Climate change" OR Temperature OR flood OR runoff OR "Sea-level rise" OR rainfall OR precipitation OR "extreme events"))"
Search 4 - Secondary search query (to target mangroves) **99 results** Web of Science: "TS=(("Great Barrier Reef" OR "GBR" OR Queensland) AND (mangrove) AND ("Water Quality" OR Nutrient* OR Nitr* OR Phosph* OR light OR Irradiance OR Turbidity OR Pesticide OR Herbicide OR Pollut* OR Salinity OR Sediment*) AND ("Climate change" OR Temperature OR flood OR runoff OR "Sea-level rise" OR rainfall OR precipitation OR "extreme events"))"
Search 4 - Secondary search query (to target mangroves) **55 results** Scopus: "Abs-TI-Key (("Great Barrier Reef" OR "GBR" OR Queensland) AND (mangrove) AND ("Water Quality" OR Nutrient* OR Nitr* OR Phosph* OR light OR Irradiance OR Turbidity OR Pesticide OR Herbicide OR Pollut* OR Salinity OR Sediment*) AND ("Climate change" OR Temperature OR flood OR runoff OR "Sea-level rise" OR rainfall OR precipitation OR "extreme events"))"

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 2.4 applied to the search returns.

Question element	Inclusion	Exclusion
Subject/Population	Great Barrier Reef, Queensland (if relevant).	Studies outside of the GBR (unless deemed relevant and important).
Exposure or Intervention	Experiments and analyses considering the combined impacts of one or more climate change stressor (temperature, heatwaves, ocean acidification, sea level rise) with one or more water quality stressor (nutrients, sediments, pesticides, or irradiance).	Experiments and analyses considering the impacts of only one of these at a time. Impacts of changes in storm intensity or storm frequency.
Comparator (if relevant)	Experiments considering the impacts of only one of these at a time.	

Question element	Inclusion	Exclusion
Outcome	Parameters relating to the health of any GBR coastal ecosystem or key organisms in these ecosystems (as listed in the conceptual diagram), e.g., growth, photosynthesis, mortality or reproduction.	Parameters relating to organisms not included in the conceptual diagram.
Language	English	Any other language
Study type	Field studies, monitoring reports, modelling studies, laboratory studies, review articles.	Studies conducted before 1990, unreviewed comments or reports.

3. Search Results

Searches for this question were conducted in Web of Science and Scopus, separately for the primary question and the secondary question 2.4.1, with no specific additional searches conducted for the secondary question 2.4.2 as this is so closely related to 2.4 and 2.4.1. Overall, this resulted in 2,610 evidence items, in addition to 24 manual items, giving a total of 2,634 items (Figure 2a). The initial screening, based on scanning titles and abstracts of publications and removing duplicates between databases reduced this number to 220. Reading the publications (second screening) reduced this number to 115 evidence items, of which 62 were relevant for the primary question, 45 for the secondary question 2.4.1 and eight for both.

Initial screening indicated that there were no evidence items related to **mangrove ecosystems** or **coastal wetlands**. Because of concern that mangroves and wetlands were not picked up because the first search term does restrict results to the "GBR", "OR Queensland" was added in that line in an auxiliary search. In addition, 'AND Mangroves' (or 'AND wetland') was explicitly added as a separate term. This search resulted in 99 unique (after de-duplication) results for the first search mangroves, none of which passed the first screening. For the 'wetland' search, 241 unique evidence items were identified, 16 of which passed the initial screening. However, upon closer inspection (second screening) none of these was eligible, mainly because they did not address the question of cumulative impacts or were outside the geographic area considered. Only two eligible items, from the authors personal collection, were included (Figure 2b).

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

Date (d/m/y)	Search strings	Sources	
A) Academic databases		Web of Science	Scopus
12/10/2022	*Search string 1:* *("Great Barrier Reef" OR GBR)* *AND ("Climate change" OR temperature OR thermal OR acidification OR sst OR pco* OR co2)* *AND ("water quality" OR nutrients OR light OR irradiance OR turbidity OR pesticide OR herbicide OR pollut* OR salinity OR sediment* OR thermal)*	*131 of 1,531*	*94 of 615*
12/10/2022	*Search string 2:* *("Great Barrier Reef" OR "GBR")* *AND (Acidification OR pCO* OR CO2)* *AND ("Climate change" OR Temperature OR Thermal OR SST)*	*51 of 358*	*28 of 108*
22/01/2023	*Search string 3 (WoS):* *("Great Barrier Reef" OR "GBR" OR Queensland)* *AND (wetland* OR palustrine OR riverine OR lacustrine OR marsh* OR melaleuca OR floodplain)* *AND ("Water Quality" OR Nutrient* OR Nitr* OR Phosph* OR light OR Irradiance OR Turbidity OR Pesticide OR Herbicide OR Pollut* OR Salinity OR Sediment*)*	*14 of 241*	

Date (d/m/y)	Search strings	Sources	
	AND ("Climate change" OR Temperature OR flood OR runoff OR "Sea-level rise" OR rainfall OR precipitation OR "extreme events")		
14/01/2023	*Search string 3 (Scopus):* *("Great Barrier Reef" OR "GBR" OR Queensland)* *AND (wetland* OR palustrine OR riverine OR lacustrine OR marsh* OR melaleuca)* *AND ("Water Quality" OR Nutrients OR light OR Irradiance OR Turbidity OR Pesticide OR Herbicide OR Pollut* OR Salinity OR Sediment*)* *AND ("Climate change" OR Temperature OR flood OR runoff OR "Sea-level rise" OR rainfall OR precipitation OR "extreme events"))"*		*6 of 156*
12/01/2023	*Search string 4: ("Great Barrier Reef" OR "GBR" OR Queensland)* *AND (mangrove)* *AND ("Water Quality" OR Nutrient* OR Nitr* OR Phosph* OR light OR Irradiance OR Turbidity OR Pesticide OR Herbicide OR Pollut* OR Salinity OR Sediment*)* *AND ("Climate change" OR Temperature OR flood OR runoff OR "Sea-level rise" OR rainfall OR precipitation OR "extreme events"))"*	*0 of 99*	*0 of 55*
B) Search engines (e.g., Google Scholar)			
	(NA)		
Total items online searches (following duplicate removal)		***196 (89 %)***	
C) Manual search			
Date/time	Source	Number of items added	
27/10/2022	*Author personal collection*	*24*	
Total items manual searches		***24 (11 %)***	

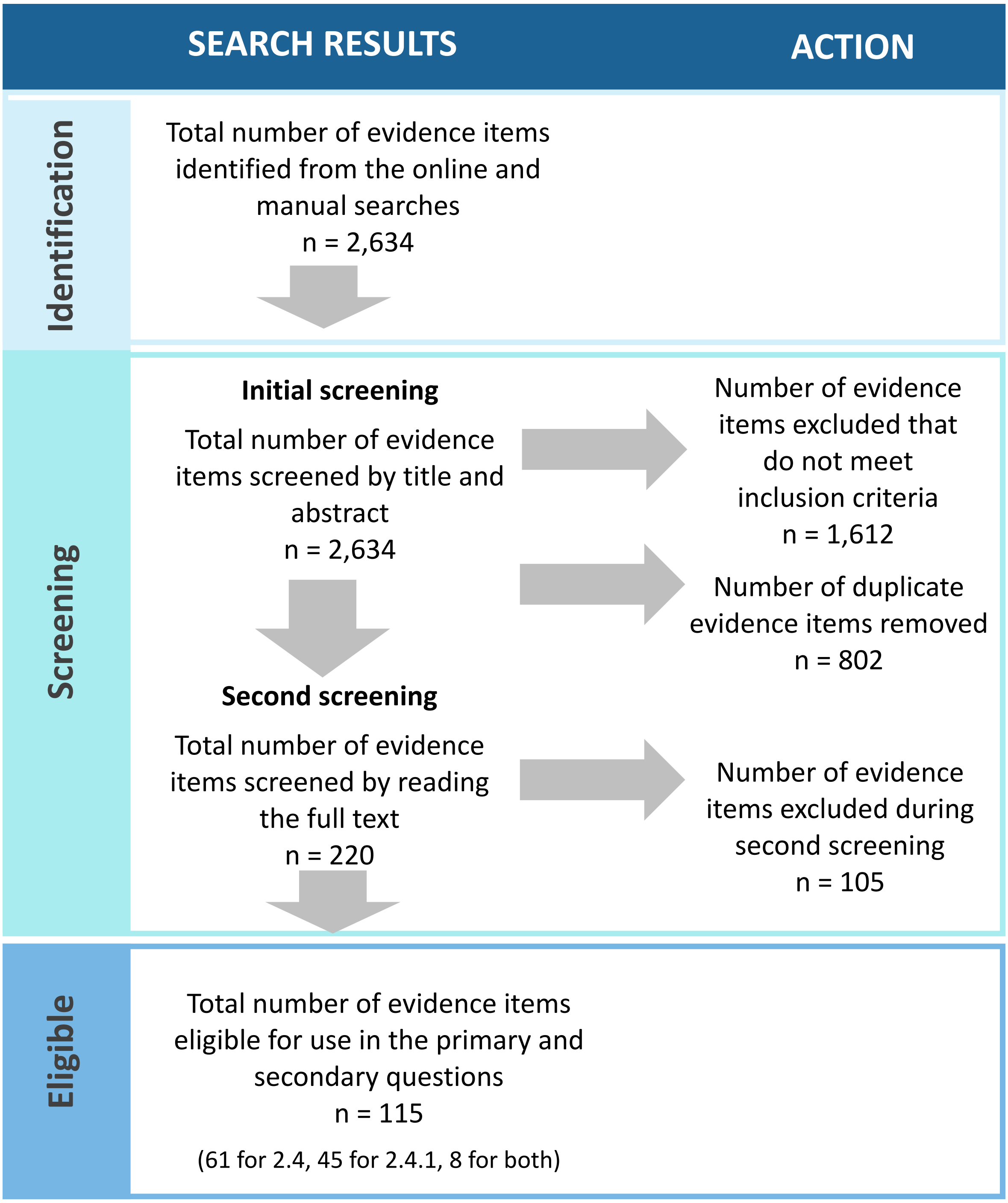


Figure 2a. Flow chart of results of screening and assessing all search results from Search 1 and Search 2 for Question 2.4.

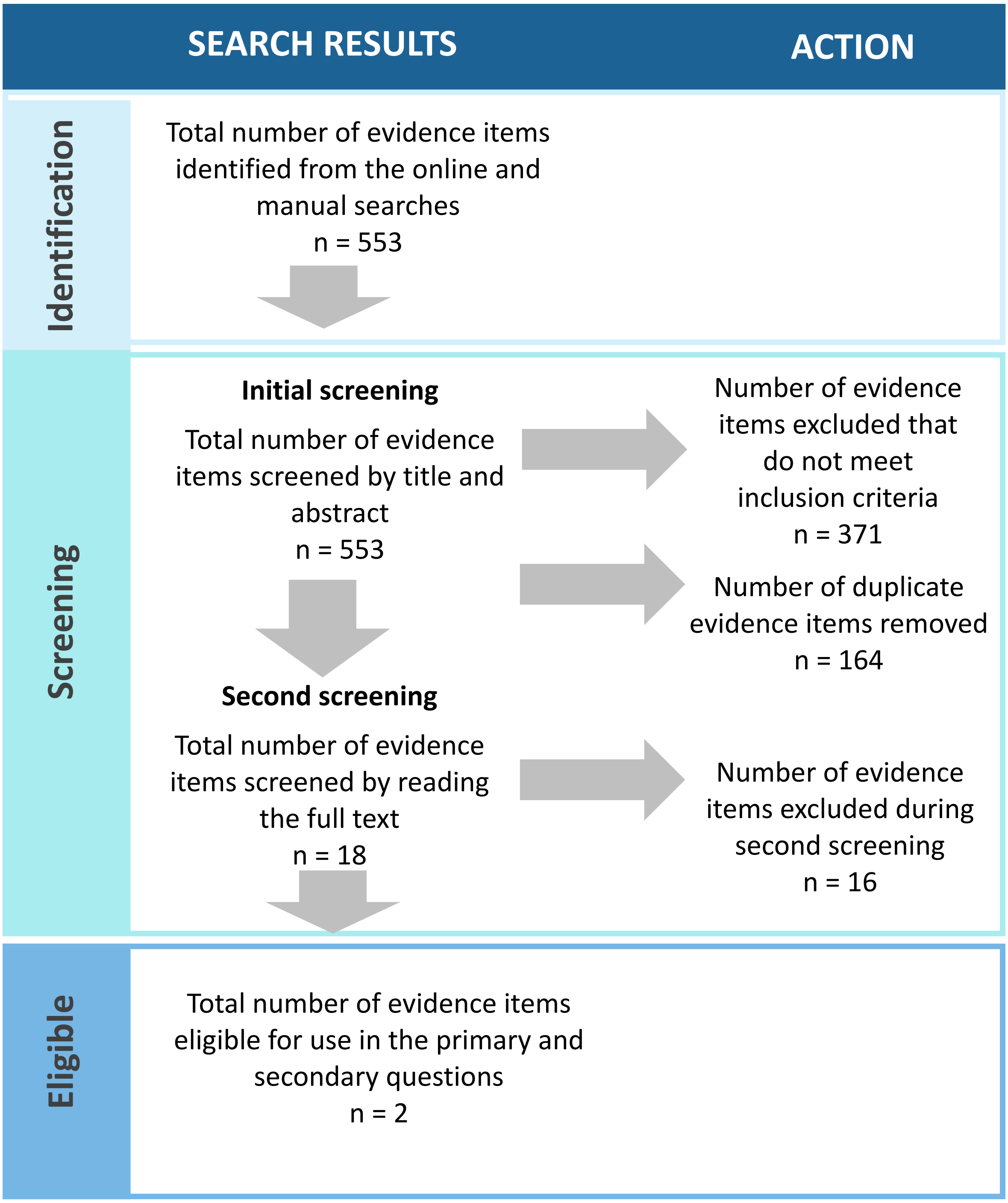


Figure 2b. Flow chart of results of screening and assessing all search results from Search 3 (wetlands) and Search 4 (mangroves) for Question 2.4.

4. Key Findings

4.1 Narrative synthesis

4.1.0 Summary of study characteristics

The conceptual diagram (Section 1.2, Figure 1) outlined the approach to analyse the interactive effects of climate change and water quality, and between climate change-related stressors (mainly temperature and ocean acidification) within the main coastal ecosystems (coral reefs, seagrass meadows, coastal wetlands), and within organism groups in these ecosystems. The narrative synthesis follows the structure outlined in Figure 1.

The first evidence items detected were published in 2002, although literature searches included publications from 1990 (Figure 3). Research outputs relevant to climate effects in coral reef ecosystems increased after the first major coral bleaching event in 1998. The analysis also illustrates that scientific and management interest in combined (or cumulative) effects of climate and other pressures began at the start of the current millennium (2000). A total of 45 studies (39%) have been published since the last SCS in 2017. Although the topic *"Cumulative effect and the challenge to managers"* had a short, dedicated section in the last SCS[10], this was not based on a systematic literature review. Thus, it was considered unnecessary to analyse the post 2016 evidence items separately and instead a full review of the relevant literature from 1990-2022 is presented. However, it appears that since 2017 more evidence has accumulated and there have been no major shifts in patterns or paradigms.

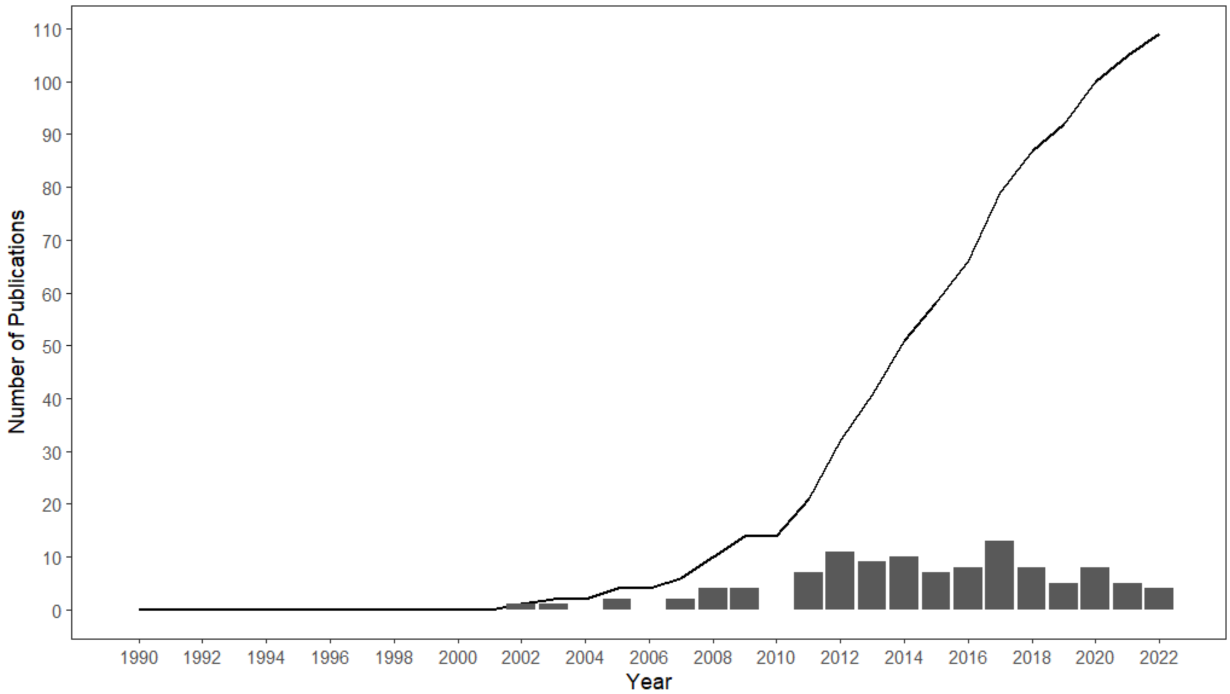


Figure 3. The annual (bars) and cumulative (line) evidence items (publications) eligible for the Evidence Summary for Question 2.4.

Most of the studies considered here (71/117 = 61%) that investigated cumulative or interactive effects between stressors used an experimental approach to manipulate combinations of the stressors (Table 7). Given the technical complexities involved in manipulating parameters e.g., ocean acidification, temperature, sediment, nutrient or pesticide levels, most of these experiments were conducted in research aquarium facilities. Modelling approaches formed the second largest group of studies

[10] Schaffelke, B., C. Collier, F. Kroon, J. Lough, L. McKenzie, M. Ronan, S. Uthicke and J. Brodie (2017). "Scientific Consensus Statement 2017." Scientific Consensus Statement 2017: 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, 2017.

identified (15/117, in addition to several other studies using modelling in addition to other tools). Many of these studies assemble large (often multi-year) datasets on environmental variables (e.g., chlorophyll levels, temperatures) and model which of these explain part of the variance in response variables (e.g., coral cover, performance, species composition, COTS densities), in combination or cumulatively (e.g., Castro-Sanguino et al., 2021; Matthews et al., 2020; Mellin et al., 2019). Fifteen review papers were also included in this synthesis. These include global analyses on coastal pollution which also increasingly acknowledge the importance of cumulative effects between climate change and water quality for marine and terrestrial management (Malone & Newton, 2020). Although the main search terms restricted publications to the GBR, global reviews were also included, especially when they focused on cumulative effects on coral reefs or mentioned the GBR explicitly (Ban et al., 2014a; Brodie & Waterhouse, 2012; Fabricius et al., 2013; Harvey et al., 2018). Most remaining papers combine two of these research approaches (Table 7).

Table 7. Types of studies used to infer interactions between climate and water quality stressors or between climate stressors.

Primary study type	Number of studies
Experimental	71
Experimental, Modelling	1
Field collection, Modelling	1
Field gradient, Experimental	1
Field measurements, Modelling	3
Field measurements, Observational	1
Modelling	15
Modelling, Review	1
Observational	5
Observational, Experimental	1
Review	15
Review, Experimental	1
Review, Expert elicitation	1

4.1.1 Summary of evidence to 2022

Question 2.4 How do water quality and climate change interact to influence the health and resilience of Great Barrier Reef ecosystems? And Question 2.4.1 How are the combined impacts of multiple stressors (including water quality) affecting the health and resilience of Great Barrier Reef coastal and inshore ecosystems?

Most of the evidence reviewed refers to Q2.4 (Figure 1, water quality x climate change interactions) and 2.4.1 (Figure 1, adding climate change x climate change interactions). Because the secondary question 2.4.2 is a minor topical extension to the primary question, an interpretation for that question is provided in a separate section. For testing cumulative, or combined effects, technical definitions of the type of interactions such as ‘synergistic’, ‘antagonistic’ or ‘additive’ were avoided (see Figure 4 legend), and instead focused on whether effects on individual response parameters or species documented in each evidence item were ‘aggravating’ or ‘mitigating’ (see Figure 4).

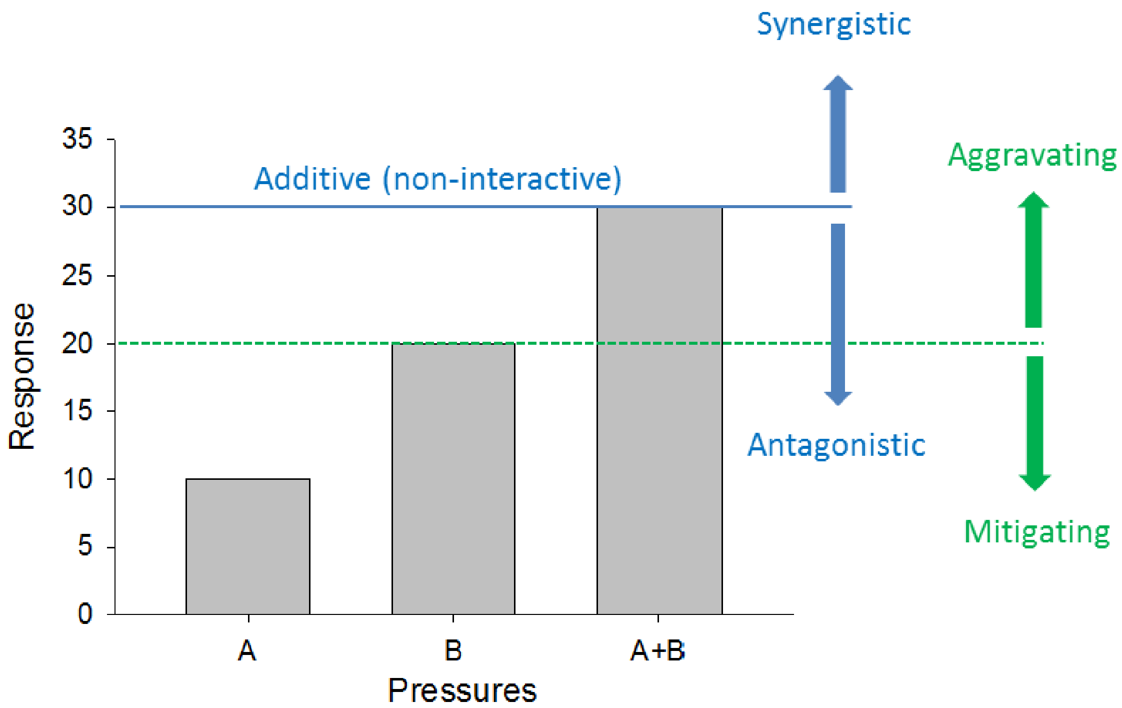


*Figure 4. Model explaining the classification of studies on multiple pressures as **aggravating** or **mitigating**. More detailed definitions define 'Synergistic' as the outcome of two pressures being larger than expected when both effect sizes are combined ("Additive"). If the effect is smaller under two pressures than under one individual the term 'Antagonistic" is used, by some authors also applied when the sum is smaller than additive (also sometimes referred to as sub-additive). Details in Uthicke et al. (2016).*

Across ecosystems, this synthesis found considerable evidence that shows cumulative effects, or simultaneous exposure to two or more stressors, result in worse outcomes for the ecosystem or organism, than when subjected to individual pressures. In total, 80 (68%) of the evidence items contained at least one species or response parameter, where combined effects were aggravating (Table 8). However, six examples of mitigation were also detected. The proportion of studies demonstrating aggravating effects for each organism is shown in Table 9.

Table 8. Summary table of all publications considered in the Evidence Summary, sorted by ecosystem, organism and climate change and water quality stressors. Response: the number of publications measuring aggravation or mitigation in at least one parameter or species investigated. Aggravation and mitigation can act in both directions, e.g., if a temperature x nutrient effect is aggravating, reducing the stress of either reduces the overall stress. Some review papers were not considered in the response category.

Climate change stressors	Water quality stressors	Response	Reference
General Marine Ecosystems (1)			
Multiple organisms (1)			
Temperature	Nutrients	Review	Malone & Newton, 2020
Coral Reefs (107)			
Algae (13)			
Temperature x OA (6*)		Mitigating: 1 Aggravating: 3	Bender et al., 2014b; 2015; Diaz-Pulido et al., 2012; Ho et al., 2021; Sinutok et al., 2011; Vogel et al., 2016
Temperature x OA (1)	Nutrients	Mitigating: 0 Aggravating: 0	Bender et al., 2014a
OA (1**)	Reduced light	Mitigating: 0 Aggravating: 0	Vogel et al., 2015
Temperature x OA (1)	Herbicides	Mitigating: 0	Marques et al., 2020

Climate change stressors	Water quality stressors	Response	Reference
		Aggravating: 1	
Temperature (1)	Herbicides	Mitigating: 0 Aggravating: 1	Chakravarti et al., 2019
OA (1)	Organic Carbon	Mitigating: 0 Aggravating: 1	Meyer et al., 2015
OA (1)	Sediments	Mitigating: 0 Aggravating: 1	Smith et al., 2020
Temperature x increased light (1)		Mitigating: 0 Aggravating: 1	Fine et al., 2005
Coral (54)			
OA (1)	Organic Carbon	Mitigating: 0 Aggravating: 1	Meyer et al., 2016
OA (1**)	Reduced light	Mitigating: 0 Aggravating:1	Vogel et al., 2015
OA (1)	Turbidity	Mitigating: 0 Aggravating: 0	Noonan et al., 2022
Temperature x increased light (1)	General water quality	Mitigating: 0 Aggravating: 1	Ban et al., 2014b
Temperature x increased light (1)	Sediments	Mitigating: 1 Aggravating: 0	Anthony et al., 2007
Temperature x increased light (2)		Mitigating: 0 Aggravating: 2	Abrego et al., 2008; Boyett et al., 2007
Temperature x OA (1)	Sediments	Mitigating: 0 Aggravating: 1	Brunner et al., 2021
Temperature x OA (1)	Reduced light	Mitigating: 0 Aggravating: 1	Brunner et al., 2022
Temperature x OA (11)		Mitigating: 0 Aggravating: 4	Albright & Mason, 2013; Anthony et al., 2008; Chua et al., 2013; Cooper et al., 2008; De'ath et al., 2009; D'Olivo et al., 2019; Hoegh-Guldberg, 2005; Hoegh-Guldberg et al., 2017; Noonan & Fabricius, 2016; Rocker et al., 2015; Wooldridge, 2012
Temperature (3)	Herbicides	Mitigating: 0 Aggravating: 2	Brodie & Waterhouse, 2012; Jones & Kerswell, 2003; Negri et al., 2011
Temperature (10)	Nutrients	Mitigating: 0 Aggravating: 9	Baird et al., 2021; Fabricius et al., 2013; Humanes et al., 2016; Morris et al., 2019; Wiedenmann et al., 2013; Wooldridge, 2009, 2020; Wooldridge et al., 2012, 2017; Wooldridge & Done, 2009
Temperature (1)	Sediments	Mitigating: 0 Aggravating: 1	Bessell-Browne et al., 2017
Temperature (1)	Turbidity	Mitigating: 0 Aggravating: 0	Abrego et al., 2012
Temperature, Cyclones (2)	Water quality, COTS	Mitigating: 0 Aggravating: 2	Castro-Sanguino et al., 2021; Mellin et al., 2019
Temperature, Cyclones (1)	Nutrients, COTS	Mitigating: 0 Aggravating: 1	Wolff et al., 2018
Temperature x increased light (6)		Mitigating: 0 Aggravating: 5	Chen et al., 2017; Fischer & Jones, 2012; Hill et al., 2012; Jackson et al., 2020; Sato et al., 2011; Smith et al., 2022
Temperature, OA (1)	Herbicides	Mitigating: 0 Aggravating: 1	Flores et al., 2021
Temperature (1)	Copper	Mitigating: 0	Negri & Hoogenboom, 2011

Climate change stressors	Water quality stressors	Response	Reference
		Aggravating: 1	
Temperature (2)	Nutrients, sediments	Mitigating: 0 Aggravating: 2	D'Olivo et al., 2013; Humanes et al., 2017
Temperature (1)	Nutrients, turbidity	Mitigating: 0 Aggravating: 0	Hughes et al., 2018
Temperature (1)	Reduced light	Mitigating: 0 Aggravating: 1	Rosic et al., 2020
Temperature (1)	Turbidity, reduced light	Mitigating: 1 Aggravating: 0	Morgan et al., 2017
Temperature (2)	Water quality	Mitigating: 1 Aggravating: 2	Cantin et al., 2021; MacNeil et al., 2019
Temperature, OA, storms, sea level rise (1)	Nutrients, sedimentation reduced light, salinity, disease, COTS	Mitigating: 0 Aggravating: 1	Ban et al., 2014a
Isolated dinoflagellate symbionts (1)			
Temperature (1)	Herbicide	Mitigating: 0 Aggravating: 1	van Dam et al., 2015
Echinoderms (6)			
Temperature x OA (4)		Mitigating: 0 Aggravating: 3	Kamya et al., 2014; 2018; Sparks et al., 2017; Uthicke et al., 2014
Temperature (2)	Nutrients (chlorophyll *a* as proxy)	Mitigating: 0 Aggravating: 2	Matthews et al., 2020; Uthicke et al., 2015
Fish (2)			
Temperature x OA (2)		Mitigating: 0 Aggravating: 1	Clark et al., 2017; Munday et al., 2009
Foraminifera (9)			
Temperature x OA (4*)		Mitigating: 1 Aggravating: 2	Doo et al., 2014; Schmidt et al., 2014; Sinutok et al., 2011; 2014
Temperature (1)	Herbicides	Mitigating: 0 Aggravating: 1	van Dam et al., 2012
Temperature (4)	Nutrients	Mitigating: 0 Aggravating: 4	Prazeres et al., 2017; Reymond et al., 2011; 2013; Uthicke et al., 2012
Molluscs (3)			
Temperature x OA (1)		Mitigating: 0 Aggravating: 0	Lefevre et al., 2015
Temperature x increased light (1)		Mitigating: 0 Aggravating: 1	Buck et al., 2002
OA (1)	Turbidity	Mitigating: 0 Aggravating: 1	Watson, 2015
Porifera (sponges) (7)			
Temperature x OA (5)		Mitigating: 1 Aggravating: 4	Bennett et al., 2017; Fang et al., 2013; 2014; 2018; Wisshak et al., 2013
Temperature x OA (1)	Nutrients	Mitigating: 0 Aggravating: 1	Achlatis et al., 2017
Temperature (1)	Nutrients	Mitigating: 0 Aggravating: 0	Simister et al., 2012
Microbial and Sediment community (4)			
Temperature x OA (2)		Mitigating: 1	Trnovsky et al., 2016; Webster et al., 2016

Climate change stressors	Water quality stressors	Response	Reference
		Aggravating: 1	
OA (1)	Nutrients, reduced light	Mitigating: 0 Aggravating: 1	Witt et al., 2012
Temperature (1)	Nutrients	Mitigating: 0 Aggravating: 0	Lantz et al., 2017
Multiple organisms (10)			
Temperature x OA (2)		Mitigating: 0 Aggravating: 2	Dove et al., 2013; 2020
Temperature, cyclones (1)		Mitigating: 0 Aggravating: 1	Puotinen et al., 2020
Temperature, increased Light (1)	Nutrients, sediments	Mitigating: 0 Aggravating: 1	Maina et al., 2011
Multiple (1)	Nutrients, sediments	Mitigating: 0 Aggravating: 1	Harvey et al., 2018
Multiple (3)	Multiple	Reviews	Brodie & Waterhouse, 2018; Przeslawski et al., 2008; Uthicke et al., 2016
Temperature, cyclones (1)	Water quality, COTS	Mitigating: 0 Aggravating: 1	Ortiz et al., 2018
Temperature (1***)	Herbicides	Mitigating: 0 Aggravating: 1	Negri et al., 2020
Temperature (1***)	Copper	Mitigating: 0 Aggravating: 1	Negri et al., 2020
Seagrass meadows (7)			
Temperature (2)	Reduced light	Mitigating: 0 Aggravating: 1	Chartrand et al., 2018; Collier et al., 2011
Temperature x OA (1)	Reduced light	Mitigating: 0 Aggravating: 1	Collier et al., 2018
Temperature (1)	Herbicides	Mitigating: 0 Aggravating: 1	Wilkinson et al., 2017
Temperature, others (1)	Nutrients, turbidity, sediments, others	Mitigating: 0 Aggravating: 1	McMahon et al., 2022
OA (1)	Nutrients	Mitigating: 0 Aggravating: 0	Ow et al., 2016b
OA (1)	Reduced light	Mitigating: 0 Aggravating: 0	Ow et al., 2016a
Coastal wetlands (2)			
Multiple (2)	Multiple	Reviews	Ostrowski et al., 2021; Sippo et al., 2020
Mangroves (0)			
Saltmarshes (0)			

* Sinutok et al., 2011 listed twice as it considers both algae and foraminifera
** Vogel et al., 2015 listed twice as it considers both coral and algae
*** Negri et al., 2020 listed twice as it considers temperature x copper and temperature x herbicides

Coral Reefs

The vast majority (107/117 = 91%) of evidence items in our search were related to **coral reef** ecosystems. Among those were several recent review papers that addressed cumulative impacts on coral reefs in general (Ban et al., 2014a; 2014b; Brodie & Waterhouse, 2012; Harvey et al., 2018) or focused on interactive effects of nutrients and temperature on coral bleaching (Morris et al., 2019).

i) Algae

Thirteen studies in coral reef environments were on **algae**, including turf algae and brown algae (e.g., Bender 2014a; 2014b), green algae (e.g., Marques et al., 2020; Meyer et al., 2015) or other macroalgae or microalgae (Chakravarti et al., 2019). Many of these studies focused on the interaction between temperature and ocean acidification, or ocean acidification and a water quality parameter like nutrients or herbicides. Responses in primary producers such as algae and seagrasses (see below) often vary from those in heterotrophic (e.g., fishes, echinoderms) or mixotrophic (e.g., corals, foraminifera, giant clams) organisms. In primary producers, dissolved inorganic carbon (DIC) under ocean acidification or inorganic nutrients may not act as stressors because they are typically limiting photosynthesis. Hence, additional DIC or nutrients can stimulate production (e.g., Ow et al., 2016a; 2016b). However, in calcifying algae (crustose coralline algae and *Halimeda* spp.) ocean acidification can have negative impacts, similar to other calcifying organisms (Vogel et al., 2015). Overall, light reduction, effects of sediments, or herbicides are the most frequently investigated water quality stressors for algae, and several aggravating interactions with climate stressors have been reported.

ii) Coral

Half of the studies (54/107 = 50%) on coral reefs investigate **hard corals**, with 47% (25/54) focusing primarily on one genus (*Acropora*).

In hard corals, the interaction of temperature and high light conditions is the most studied interaction when studies outside the GBR not considered here (but reviewed in Ban et al., 2014a) are included. The reason for this is that coral bleaching, although mainly caused by increased temperatures, is modulated by light conditions, i.e., often a combination of heat and high light stress.

Since modelling studies by Wooldridge (2009; 2012a; 2012b; 2017; 2020) suggested that water quality improvements (specifically the reduction of nutrients) may ameliorate thermal bleaching events, several studies have investigated this experimentally, or using field data and modelling. A review by Fabricius et al. (2013) suggested a variety of outcomes under simultaneous nutrient and temperature stress, ranging from synergistic to antagonistic. An experiment conducted by the latter authors showed no additional aggravating effect of inorganic nutrients (nitrate), but coral exposed to organic enrichment and heat stress showed higher mortality and reduced photosynthesis compared to those only exposed to heat stress. In addition, the former treatment group took longer to recover once the heat stress was removed. Key experiments conducted by Wiedenmann et al. (2013) outside the GBR suggested that it was not nutrient *concentration* but an *imbalance* between inorganic phosphate and nitrogen that causes higher bleaching susceptibility of corals.

One of the most recent studies on the GBR (Cantin et al., 2021) suggested the 2017 bleaching event was mainly driven by the degree heating weeks. The study suggested that during strong heatwave events the role of nutrients in exaggerating bleaching may be limited. However, nutrients (e.g., expressed as chlorophyll content) and turbidity explained a significant amount of the variation in their model. These field and modelling studies were supported by experimental work (Chapters 5 and 6 in Cantin et al., 2021). That work confirmed that inshore corals at that time were less vulnerable to heat stress, but also showed that coral symbionts under elevated phosphate and nitrate levels had high levels of photoinhibition, making them vulnerable to further stress.

Although the models by Wooldridge (see above) assumed that bleaching is promoted by symbiont growth and densities being increased through excess nutrients, Wiedenmann's study and a recent review by Morris et al. (2019) challenge this view. In both papers, the symbiotic algal communities are presumed to change in response to specific nutrient species or the ratio between nutrients. In addition, the latter study predicts that it is not algal growth, but algal carbon metabolism that is primarily influenced by nutrients.

Results of modelling and observational studies on bleaching and water quality interactions exhibit inconsistent results. A simulation study by Baird et al. (2021, in part contained in Cantin et al., 2021) suggested removal of anthropogenic fractions of the runoff load during the 2017 bleaching event would not have improved the bleaching outcome for corals. This conclusion is similar to that made by Hughes et al. (2018) based on observational data and measured water quality parameters. The main reason for this and some other ambiguous results from modelling studies may be that *acute* nutrient stress (runoff events or flood plumes) will be quite rare during heatwave conditions (Cantin et al., 2021). In addition, in some instances flood plumes may have positive effects on coral bleaching, e.g., due to shading and thus preventing high light stress. However, due to the proximity of the mainland and runoff sources, it can be assumed that inshore reefs are subjected to *chronic* nutrient stress (see Question 4.1, Robson et al., and Question 4.2, Diaz-Pulido et al., this SCS). One modelling study (MacNeil et al., 2019) suggested that adverse water quality might even ameliorate bleaching. Water quality in that study was expressed as an index based on the frequency of riverine plume waters. On the other hand, the same study suggested that poor water quality would slow coral reef recovery time and make them more susceptible to COTS (see Question 4.3, Caballes et al., this SCS). These findings illustrate that the role of water quality in acute bleaching can be different to that in later recovery. Higher COTS densities under elevated chlorophyll concentrations were also suggested in modelling by Matthews et al. (2020). Overall, the relationship between temperature and nutrients in coral bleaching is less clear than initial modelling studies suggested; and surprisingly few experimental studies on the topic have been conducted.

Apart from possible influences on bleaching, water quality (alone, or in conjunction with climate change) may have other impacts on coral. Coral growth rate and resilience were suggested to be higher in offshore reefs of the GBR, where they are less influenced by flood plumes and poor water quality (Mellin et al., 2019). At early life stages, corals exhibited negative effects to enhanced nutrients and/or to interactions of nutrients with other stressors, including effects on fertilisation and gamete abnormality, photosynthetic yield and survivorship (Humanes et al., 2016). The latter study found aggravating effects on fertilisation and abnormal development but ameliorating effects on juvenile survival. Coral settlement success has also been found to be reduced by the individual effects of temperature, sediment and nutrients (Humanes et al., 2017).

For corals, the other main water quality factors investigated in conjunction with climate change are sediment-related variables such as increased turbidity, reduced light and sedimentation (e.g., Abrego et al., 2012; Brunner et al., 2021; 2022) (see Question 3.2, Collier et al., this SCS, for a comprehensive review of sediment impacts). Most likely due to a clear effect pathway (light reduction results in decreased photosynthesis, sedimentation can physically affect the corals), sediment-climate aggravating interactions are common. Other aggravations were found for temperature and herbicide or copper interactions (e.g., Flores et al., 2021; Negri & Hoogenboom, 2011) (see Question 5.1, Negri et al., this SCS, for a comprehensive review of pesticide impacts). Effects of temperature thresholds and the LD_{50} for copper and herbicides on coral and other organisms were reviewed and summarised in Negri et al. (2020). Their analysis suggested that increased vulnerability to these (and possibly other) contaminants would in future require reduced guideline values (*'Climate adjusted thresholds'*). The mechanisms for many of these interactions are unknown, but Negri et al. (2020) argued that climate stressors and chemical stressors are additive and can be combined in an 'independent action' model to derive the amount of cumulative stress.

Many coral studies (11) on the GBR assessed the interaction of temperature increase and ocean acidification on corals. Although detrimental effects of both climate stressors individually are well documented (refer to Question 2.2, Fabricius et al., this SCS), only four studies provided evidence for aggravation (Table 8).

iii) Isolated dinoflagellate symbionts

One study investigated two coral symbiont clades in isolation and investigated their response to temperature and herbicide stress (van Dam et al., 2015). The study found that stressors were clearly additive. Hence, elevated concentrations of herbicide lower the temperature thresholds of those symbionts, or, viewed from the other direction, climate change will lower herbicide tolerance (see above).

iv) Echinoderms

Most (4/6) studies on echinoderms reviewed here studied the interaction between temperature and ocean acidification and found several aggravating effects affecting individuals of this phylum. Most of these studies (5) were on COTS. Given the importance of COTS outbreaks in coral cover loss on the GBR, these interactions can have important cascading effects on GBR health. A detailed analysis of the effects of nutrients on COTS outbreaks is given in Question 4.3 (Caballes et al., this SCS). A modelling study (Matthews et al., 2020) suggested that exposure to higher temperatures and flood plumes were the best predictors for high COTS densities, which was interpreted as a possible aggravating effect. An experimental study on COTS (Uthicke et al., 2015) suggested that sufficient algal food was the main driver for survivorship of COTS larvae, but that increased temperature can further modulate the outcome and result in fast development and higher larval survival, which might provide a mechanism for explaining Matthew et al.'s (2020) results.

v) Fish

Only two evidence items studying fish were identified (Clark et al., 2017; Munday et al. 2009), both investigating interactive effects of temperature and ocean acidification. The first study found no effect of ocean acidification on damselfish, hence no aggravation with temperature. The second found aggravating effects of temperature and ocean acidification on metabolic scope and resting metabolism of two cardinal fish species.

vi) Foraminifera

Three experimental studies (Schmidt et al., 2014; Sinutok et al., 2011; 2014) on the GBR and one global analysis and review (Doo et al., 2014) investigated temperature and ocean acidification interactions in large benthic foraminifera. Similar to coral, these symbiont-bearing, calcifying protists are vulnerable to individual climate change pressures, and aggravating effects have been detected for all species investigated on the GBR, as well as for nearly all species in a pan-tropical review (Doo et al., 2014).

Foraminifera can also bleach (i.e., shed symbiotic algae or chloroplasts) under temperature stress. The interactions between temperature and nutrients were tested in four experimental studies, with each of these showing clear aggravating effects when these stressors are combined, e.g., on growth and mortality (Prazeres et al., 2017; Reymond et al., 2011; Uthicke et al., 2012) or maximum productivity (Reymond et al., 2013). Van Dam et al. (2012) investigated the effects of temperature and herbicides on a variety of foraminifera and found strong aggravating effects of the two stressors.

vii) Molluscs

Only three studies investigated interactive effects in marine molluscs of the GBR. One study on a gastropod species found no temperature or ocean acidification effect (Lefevre et al., 2015). A study on giant clams demonstrated that bleaching under high temperatures is exacerbated by high light conditions (Buck et al., 2002). By contrast, giant clams stressed by ocean acidification demonstrated stronger negative effects when kept under low light conditions (Watson et al., 2015).

viii) Porifera (sponges)

For sponges, the majority of studies (5/7) focused on temperature x ocean acidification interactions (see Table 8). Bennet et al. (2017) found that heterotrophic species exhibited aggravating effects for mortality, necrosis and bleaching, whereas autotrophic sponges exhibited mitigating effects for the same parameters. Similar to autotrophs (e.g., algae, seagrasses), the different outcomes may be because DIC can be a limiting factor for photosynthesis. Thus, ocean acidification may increase productivity. A series of publications on temperature and ocean acidification effects on *Cliona orientalis* showed aggravating effects on bleaching, respiration, photosynthesis and mortality (Fang et al., 2013; 2014; 2018), while another study found no cumulative effects of temperature and ocean acidification in *Cliona orientalis* (Wisshak et al., 2013).

A study on the same species also manipulated nutrients and found aggravating effects on bioerosion rates of temperature and ocean acidification, but no additional nutrient effect (Achlatis et al., 2017).

Sinister et al. (2012) found no effect of temperature or nutrient increase on microbial communities in another sponge species.

ix) Microbial and sediment communities

Two studies specifically focused on temperature x ocean acidification interactions in this group (e.g., Trnovsky et al., 2016; Webster et al., 2016). The first study demonstrated mitigating effects of both stressors on calcareous sediment dissolution. The second study investigated microbial communities in a variety of invertebrate hosts and described that when both stressors were combined, distinct communities developed. Furthermore, an experimental study by Dove et al. (2013) on patch reefs found that sediment-associated microbial communities had significantly greater microbial biomass under business-as-usual conditions compared to lower emission conditions. A microbial biofilm community study testing the effect of nutrients under different ocean acidification scenarios showed aggravating effects on community metabolism, but community composition was mainly affected by temperature (Witt et al., 2012). A study on temperature and nutrient interactions on sediment microbial communities showed no cumulative effect (Lantz et al., 2017).

x) Studies on multiple organisms or communities

Several (11) evidence items in this review considered the entire community, including coral reefs in general. In two of those papers, experiments on a calcifying community within patch reefs found the combination of temperature and ocean acidification had aggravating effects on community calcification rates (Dove et al., 2013; 2020).

Several other studies in this category are modelling-based. The effects of temperature and cyclones on coral communities (a climate-climate interaction not specifically highlighted in Figure 1) were assumed additive (Puotinen et al., 2020), similar to the effect of several other stressors (e.g., water quality, COTS, temperature, cyclones) in Ortiz et al. (2018). Also, several review papers generally assume the effects of multiple stressors on coral reefs as additive/aggravating (e.g., Brodie & Waterhouse, 2018; Harvey et al., 2018; Maina et al., 2011). Although additivity is an assumption and not evidence in these papers, the overwhelming evidence from the experimental studies (see Table 8) and logic clearly support this assumption. A study on several groups of organisms used a species sensitivity distribution approach (Negri et al., 2020, see above) to model interactive effects of temperature and copper or herbicides. That study illustrated that the number of species affected is larger under combined water quality and temperature stress than under individual stress.

Seagrass meadows

Seven evidence items investigated seagrasses, six of these using an experimental approach. Source populations for these experiments are often from inshore islands (e.g., Magnetic Island) or midshelf reefs (Green Island). In two of three experimental studies (Chartrand et al., 2018; Collier et al., 2011; 2018) on temperature and reduced light or the combination of temperature and ocean acidification with reduced light, light reduction aggravated the negative effects of temperature stress. Similar to corals, free symbionts and foraminifera, herbicides rendered seagrasses more vulnerable to temperature increase (Wilkinson et al., 2017). Evidence items testing for interactive effects of ocean acidification and nutrients (Ow et al., 2016a) or ocean acidification and reduced light (Ow et al., 2016b) identified no interactive effects. The main reason for this is that for most parameters tested, ocean acidification has no effect or a positive effect on seagrass growth or photosynthesis.

One modelling paper on stressors of (Australia-wide) seagrasses (McMahon et al., 2022) uses a risk map approach to identify the most important combination of stressors. In general, risk map approaches assume additivity, hence most stressors in the review are aggravating. However, for tropical seagrasses future climate related pressures (temperature increase, increased rainfall, sea level rise) are mainly highlighted as 'cumulative'. As with other species groups, modelling studies assuming additivity need to be regarded with caution when interpreting if the overall effects are aggravating. Given the few studies on seagrass for each factor combination and variable results the interaction of climate change and water quality on this group cannot be generalised. However, it appears that temperature increase and water quality (mainly light reduction and herbicides) have aggravating effects on seagrass.

Coastal Wetlands

Neither the original searches or additional more specific searches identified any papers on cumulative effects of water quality and climate change on mangroves or coastal saltmarshes in the GBR region. Given very little is known on the individual effects of water quality (see Questions 3.2, 4.2 and 5.1, this SCS) or climate change (see Question 2.2, Fabricius et al., this SCS) on mangroves or coastal saltmarshes alone, there has been no research effort on interactive effects on these ecosystems in Queensland. Outside the GBR area, a large mangrove dieback in the Northern Territory was mainly related to climate induced sea level fluctuations, but additional stress through high iron levels was suggested (Sippo et al., 2020). In a review by Ostrowski et al. (2021), the most common (climate change-water quality or climate change-climate change) stressor combination investigated for **saltmarshes** was CO_2 increase and salinity, and for **mangroves** sea level rise and salinity. However, these studies did not quantify the responses to combined pressures.

Question 2.4.2 Would improved water quality help ecosystems cope with multiple stressors including climate change impacts, and if so, in what way?

No study addresses this question directly, but answers on this can be gleaned from the overall evidence of experimental and modelling studies. Given the high percentage of studies (68% of total, and 63% excluding modelling) across species groups and ecosystems that identified that the outcome was worse when an additional water quality stressor was present, it is implicit that a reduction in those stressors through water quality management (specifically pesticides, nutrient and light reduction/sedimentation) will improve the outcome and resilience of the ecosystem. Examples (gleaned from experimental studies) of how water quality improvement would improve the outcome (from all papers listed in Table 8) include:

- Removing copper or pesticide stress on the ecosystem would make a number of species more resilient to temperature increase (Negri et al., 2011).
- Removing inorganic nutrients ameliorated the effects of high temperatures on foraminifera (Uthicke et al., 2012).
- Removing organic nutrients reduced negative effects of temperature stress in two coral species (Fabricius et al., 2013).
- Coral fertilisation was more successful under heat stress without additional nutrient stress (Humanes et al., 2016).
- Removing the stress caused by copper contamination could protect corals from negative effects of 2-3℃ increase (Negri & Hoogenboom, 2011).
- Since climate change doubles the sensitivity of coral recruits to sedimentation (Brunner et al., 2021), it can also be inferred that reduced sedimentation improves the resilience of coral recruits to climate change.
- Removing herbicide stress made coral less susceptible to elevated temperatures (Negri et al., 2011).

Data are insufficient to quantify the strength and period of time this would ‘buy’ for addressing climate stressors. Hence, it is prudent to assume that the period of time ‘gained’ is short, and that interventions would need to be long-term commitments. The example of recent bleaching events which, likely due to the strength of the climate pressure, were influenced little by water quality (Cantin et al., 2021; Hughes et al., 2018) illustrates the necessity of simultaneous action on climate change and water quality.

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

Because this question was not considered explicitly in the previous SCS and the field of research on interactive effects is relatively new data after 2016 was not analysed separately. This Evidence Summary includes 59 studies published before 2016 and 58 studies published during the period 2016-2022. There was high consistency in the findings of studies between these two periods.

Table 9. Summary of the main interactions detected in the synthesis of evidence, only for studies on individual species or where results for individual species could be extracted (i.e., studies listed as "Multiple" in the coral reef section or "Multiple" ecosystems in Table 8 are omitted). "Light reduction" in the summary includes turbidity and sedimentation/sediments. "Climate" mainly consists of studies using increased temperature, but also includes some studies where "Temperature and ocean acidification" were combined into future climate scenarios. Results of the single study on dinoflagellates (coral symbionts) are included into the coral category. "Nutrients" includes studies mentioning only water quality but mainly focusing on nutrients. The numbers of studies demonstrating some aggravating effects are given over the total number of studies in that group (e.g., 2/3 means 2 studies with aggravation out of 3 total). "Total" is the percentage of studies demonstrating aggravations across all groups of organisms. Overall, 68% of all studies included in this synthesis reported aggravating effects, this number changes to 63% if modelling studies are excluded.

	Algae	Coral	Echinoderms	Fish	Foraminifera	Molluscs	Microbes, Sediments	Sponges	Seagrass	Total	Total (excluding modelling studies)
Climate x Herbicide	2/2	4/5			1/1				1/1	89%	88%
Climate x Nutrients	0/1	13/16	2/2		4/4		0/1	1/2		77%	72%
Climate x Light Reduction		5/7							2/3	70%	70%
OA x Light Reduction	0/2	1/2				1/1			0/1	33%	33%
Temperature x OA	3/6	4/11	3/4	1/2	2/4	0/1	2/1	4/5		56%	55%

4.1.3 Key conclusions

The Evidence Summary demonstrated that many studies have investigated the interactive effects of water quality and climate change stressors on several groups of organisms. The outcome for species and ecosystems under both stressors is not always worse, but our analyses showed that at least some of the relevant response parameters (e.g., growth, mortality, photosynthesis) are negatively impacted by a large majority of the stressors. Although a more detailed analysis of whether effects are antagonistic, sub-additive, additive or synergistic was not possible, the simplified approach to evaluate whether effects were aggravating or not proved useful.

With regards to coral bleaching, although nutrients aggravate coral bleaching under certain circumstances and nutrients have other aggravating effects on corals and other organisms (e.g., foraminifera), the full mechanism is not understood. In addition, in some cases shading by sediment plumes may protect coral from bleaching. Given this Evidence Summary and other international reviews demonstrate additional stress under elevated nutrients, it remains important to manage nutrient runoff and invest further in understanding these mechanisms. As Morris et al. (2019) summarised: “Renewed investigations into the coral nutrient metabolism will be required to truly elucidate the cellular mechanisms leading to coral bleaching”.

The key conclusions of studies on the interactions between water quality and climate change stressors identified in this Evidence Summary include:

Q 2.4, 2.4.1:

- 68% (63% if only experimental studies were considered) of all (117) evidence items included, found additive/aggravating interactive effects between water quality and climate change stressors. Hence, removing one of the stressors will improve species and/or ecosystem outcomes.
- Of the many stressor combinations, of particular note are strong cumulative effects between **climate change** (either temperature increase alone, or temperature combined with ocean acidification) and **herbicides.** These effects are reasonably well studied (9 studies) with aggravating interactive effects in several taxa. Data on this interaction (and also the interaction of copper and temperature) are sufficient to model species sensitivity distributions and suggest climate adjusted thresholds for individual herbicides. Of the nine evidence items on climate change and herbicide interactions, 89% (88% without modelling studies) showed aggravating effects (Table 9), whereas the remaining studies showed no effect or mitigating effects.
- The effects of **climate change** and **nutrient** input have also been well studied across a broad spectrum of organisms, with 77% (72% without modelling studies) of the 26 studies indicating that nutrients impose an additional stress when combined with climate change.
- Despite caveats on insufficient understanding of the mechanisms and the importance of nutrient influences on bleaching in coral, it is apparent and consistent that nutrients constitute important pressures on the GBR.
- Although only tested on corals and seagrasses, the effects of **climate change** and **light reduction** (encompassing turbidity increases and higher sediment/sedimentation loads) are also relatively strong and consistent, with 70% of the 10 studies indicating a worse outcome if climate change and light reduction are present.
- Two out of six studies indicated cumulative effects of **ocean acidification** and **light reduction**.
- A large number of studies (34) tested the interactive effects of **temperature** increase and **ocean acidification** (Table 9). 56% (55% without modelling studies) of these studies identified aggravating effects, with effects found across many taxa, indicating the importance of this interaction.
- Some stressor combinations have not been or were rarely studied on the GBR. These include **salinity** on the water quality side, and **heatwaves** and **runoff event frequency** on the climate side.

- For **seagrasses and algae**, no aggravating effects were identified between ocean acidification and water quality (specifically **nutrients** and **light reduction**), likely due to the possible positive responses of these groups to ocean acidification.
- Several studies and conclusions to other SCS questions showed **indirect effects** of water quality on coral reefs and seagrass meadows. Removing water quality stress will bolster resilience to climate change (and other) stressors and thus likely improve recovery after acute disturbance.

Q 2.4.2:

No study specifically addresses this question. However, given the number of studies across different species groups and ecosystems that identified that the outcome was worse when the additional water quality stressor was present, removal of these water quality stressors (specifically pesticides, nutrient and light reduction/sedimentation) would improve the outcome and resilience of ecosystems.

Data are insufficient to quantify the strength and period (in the sense of 'buying time') of this possible relief. Hence, it is prudent to assume that the period of time 'gained' is short, and that interventions would need to be long-term. Thus, the imperative to address climate change remains. The example of recent bleaching events which, likely due to the strength of the climate pressure, were influenced little by water quality (Cantin et al., 2021; Hughes et al., 2018) illustrates the necessity of simultaneous action on climate change and water quality.

In addition to direct effects on species and communities of water quality and climate change combined, it is also likely that water quality will reduce recovery rates after thermal stress events. However, no research on this has been conducted on the GBR. The latest report of the Marine Monitoring Program (Thompson et al., 2023) concluded: "that environmental conditions associated with the increased loads of sediments and nutrients delivered by these floods were sufficiently stressful to limit the recovery of coral cover, and/or induce disease in susceptible species"; indicating that improvement of water quality would improve coral recovery rates. Similarly, in a GBR-wide modelling study, Mellin et al. (2019) suggested lower nutrient concentrations promote coral reef health on outer reefs, and that the frequency of flood plumes influences reef resilience. Similarly, Castro-Sanguino et al. (2021) modelled that water quality influences coral performance (i.e., recovery and resilience after disturbance).

- Given that the synthesis under 2.4 and 2.4.1 revealed many instances of aggravation of climate change effects under additional water quality stress, there is no doubt that water quality management can provide some reprieve from climate change impacts.
- The strength and length of this reprieve cannot currently be quantified.
- Given that there are many studies showing deleterious effect of climate change alone, it remains imperative to address climate change.
- Improving water quality also has an indirect effect on coral reefs and seagrass meadows. Under better water quality conditions these ecosystems are more resilient and can recover faster after acute disturbances.

4.1.4 Significance of findings for policy, management and practice

These results confirm that improving water quality can be expected to improve the health and resilience of coral and seagrass ecosystems in the GBR and "buy time" for climate change interventions. This Evidence Summary confirms the importance of meeting GBR water quality targets within the next decade, before climate impacts exceed the capacity for reef ecosystems to recover. GBR water quality improvement may help the GBR dealing with climate change through for example:

- Improving the survival and reproduction of a variety of species during heatwave events.
- Improving resilience of a number of key species groups to climate change, thus ensuring a smaller fraction of the species is affected.
- Thus protecting ongoing species richness and productivity on coral reefs.
- Giving coral more resilience and ameliorating bleaching events.
- Protecting seagrass habitats.

4.1.5 Uncertainties and/or limitations of the evidence

- Some combinations of climate change and water quality stressors highlighted in the conceptual diagram (Figure 1) have not been studied, or only studied in some species groups.
- Interpretation can be hampered because effects of stressors can depend on species group and trophic status (e.g., autotroph vs heterotroph).
- Even for better studied organisms (e.g., corals), the number of species investigated is small compared to the overall number, and often only studied in one location.
- Many species groups are barely represented, even important groups such as fish or molluscs are represented only in a few studies.

Q2.4.2 No study specifically investigated this question. Therefore, it was not possible to assess the magnitude of the combined impacts or the likely duration of the relief that water quality improvements might provide from climate change impacts.

4.2 Contextual variables influencing outcomes

Table 10 describes the contextual variables for Question 2.4.

Table 10. Summary of contextual variables for Question 2.4.

Contextual variables	Influence on question outcome or relationships
Climate change (or climate variability)	Climate change is one of the pressures considered to address the question in cumulative impacts, hence it has not been considered as a separate 'Contextual Variable'.
Climatic event intensity/frequency	Flood variability and intensity (and therefore nutrients, herbicides/pesticides and sediments delivered) between years. Occurrence of cyclones. See Question 2.2, Fabricius et al., this SCS.
El Niño-Southern Oscillation (ENSO)	ENSO variability can impact climate and connectivity patterns throughout the GBR and Queensland.
Hydrodynamics	Flushing, etc. influences the intensity and duration of exposure to poor water quality.
Regional variation	Water quality and inputs/runoff varies between GBR regions and with distance from shore, as addressed in Question 4.1, Robson et al., this SCS.
Land use	With the expansion of agricultural land use throughout Queensland, the amount of nutrients, herbicides/pesticides and sediments delivered into the GBR has also increased.

4.3 Evidence appraisal

Relevance

The relevance of the overall body of evidence used in this Evidence Summary was High (Score: 7; Table 11). The relevance of each individual indicator was Moderate to High (2.5) for overall relevance to the question, Moderate to High (2.3) for spatial relevance, and Moderate to High (2.3) for temporal relevance. Of the 117 articles included, 68 were given a High score for overall relevance to the question, while 40 had a Moderate overall relevance score. Only 35 studies had a High spatial relevance, due to many experimental studies only including source organisms from a single location. 36 evidence items had a High temporal relevance score, while most studies (57) had a Moderate temporal relevance score. Similar to the caveats for spatial relevance, these temporal scores reflect that many experimental studies were only conducted at a single point in time or reflected only summer or winter (or average) conditions.

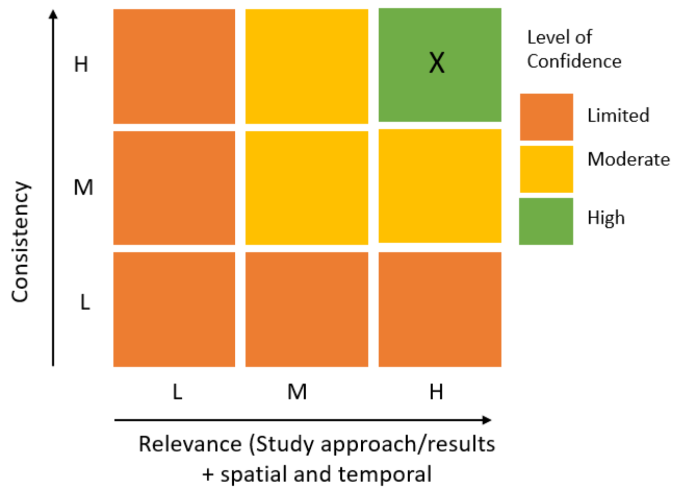
Consistency, Quantity and Diversity

Given most studies illustrated aggravating effects, Consistency was considered High. Although difficult to compare, the Quantity (117 studies) of evidence items was categorised as High, and the Diversity of study approaches also as High. Given most studies were on coral and a few other invertebrates, the Diversity of study organisms was Moderate.

Confidence

Overall, the confidence in the body of evidence used to answer the primary and secondary questions was High (Table 11). This is a result of High overall relevance of papers and High consistency in the findings between papers, with most studies reporting that the interaction between water quality and climate change stressors are aggravating, causing negative impacts to GBR ecosystems and organisms.

Table 11. Summary of results for the evidence appraisal of the whole body of evidence in addressing Question 2.4. 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 2.4, 2.4.1, 2.4.2	High	
-Spatial	Moderate-High	
-Temporal	Moderate-High	
Consistency	High	
Quantity	High (117)	
Diversity	Moderate-High (61% experimental, 13% modelling, 13% reviews, 9% mixed methods, and 4% observational)	

4.4 Indigenous engagement/participation within the body of evidence

There was no Indigenous engagement or participation noted or identified in any of the evidence items.

4.5 Knowledge gaps

The key knowledge gaps for Question 2.4 are presented in Table 12.

Table 12. Summary of knowledge gaps for Question 2.4.

Gap in knowledge (based on what is presented in Section 4.1)	Possible research or Monitoring & Evaluation (M&E) question to be addressed	Potential outcome or Impact for management if addressed
Interactive effects of low salinity.	Does low salinity in runoff events exaggerate climate effects?	Understanding and quantification of effects.

Gap in knowledge (based on what is presented in Section 4.1)	Possible research or Monitoring & Evaluation (M&E) question to be addressed	Potential outcome or Impact for management if addressed
Mechanistic understanding of nutrients and bleaching.	Long-term experiments and field data, manipulating temperature, individual nutrients. More detailed measurements than bleaching scores, symbiont density, fluorometry.	Understanding if phosphorus, nitrogen, or light (turbidity) more important to manage.
Effects on organisms after multi-generational acclimation.	Long-term multi-generational experiments.	Understanding if potential exists for acclimation/adaptation over relevant time scales. Understanding urgency of problem.
Understanding effects of heatwaves (vs. chronic temperature increase).	Field and aquarium experiments.	Detailed understanding of climate impacts.
Cumulative impacts in mangrove and saltmarsh ecosystems.	Modelling, experiments.	Fill major knowledge gap identified here, to establish if management of water quality can help mitigating climate impacts.

5. Evidence Statement

The synthesis of the evidence for **Question 2.4** was based on 117 studies undertaken mostly in the Great Barrier Reef and published between 1990 and 2022, including a *High* diversity of study types (61% experimental, 13% modelling, 13% reviews, 9% mixed methods, and 4% observational) and with a *High* confidence rating (based on *High* consistency and *High* overall relevance of studies).

Summary of findings relevant to policy or management action

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

Supporting points

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

- There has been limited research on some combinations of water quality and climate change stressors in the Great Barrier Reef including salinity, and heatwaves and the frequency and intensity of runoff events.
- To reduce the cumulative pressures and the associated detrimental outcomes on coral reef ecosystems and organisms, improved water quality throughout the Great Barrier Reef is essential, together with national and global reductions in carbon emissions to reduce the rate of warming and ocean acidification.

6. References

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

Body of Evidence

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Appendix 1: 2022 Scientific Consensus Statement author contributions to Question 2.4

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

Primary Question 2.4 How do water quality and climate change interact to influence the health and resilience of Great Barrier Reef ecosystems?

Secondary Question 2.4.1 How are the combined impacts of multiple stressors (including water quality) affecting the health and resilience of Great Barrier Reef coastal and inshore ecosystems?

Secondary Question 2.4.2 Would improved water quality help ecosystems cope with multiple stressors including climate change impacts, and if so, in what way?

Author Team

Name	Organisation	Expertise	Role in addressing the Question	Sections/Topics involved
1. Sven Uthicke	AIMS	Tropical marine ecologist	Lead author	All Sections, searches, data extraction, writing
2. Katharina Fabricius	AIMS	Tropical marine ecologist	Contributor	Writing
3. Aimee Brown	Private Consultant	Marine scientist	Contributor	Searches, data extraction, writing
4. Bianca Molinari	C_2O Consulting	Aquatic ecology, trophic ecology, environmental science	Contributor (wetlands component)	Wetlands conceptual model, searches and data extraction
5. Barbara Robson	AIMS	Oceanographer	Contributor	Writing