2022 Scientific Consensus Statement

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

Anthony Chariton[1], Natalie Hejl[1]
[1]Macquarie University

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Explanatory Notes for readers of the 2022 SCS Syntheses of Evidence

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

What is the Scientific Consensus Statement?

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

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

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

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

Method used to address the 2022 SCS Questions

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

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

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 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

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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

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 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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Executive Summary

Question

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

Background

In addition to well documented and routinely monitored pollutants such as nutrients, sediments, and pesticides, there are numerous other groups of pollutants which have the capacity to enter the waters and sediments of the Great Barrier Reef (GBR) (Kroon et al., 2020). Consequently, biota have the potential to be exposed and accumulate these pollutants which often co-occur with other environmental stressors (e.g., pesticides, nutrients, turbidity, pH and salinity). This diverse array of pollutants can be classified into the following groups: metals; persistent organic pollutants (POPs); pharmaceuticals and veterinary products (PVPs); plastics, including microplastics and fibres; Per- and polyfluoroalkyl substances (PFAS) and fire retardants; coal (including fly ash); and sunscreens. Given the geographic size of the GBR and diversity of its environments (including coastal freshwater bodies), this question aimed to synthesise the current knowledge on the spatial and temporal distributions of these pollutant groups, their sources, and where possible, identify potential risks within the context of guidelines and relevant ecotoxicological studies. Given the varied sources and complexities associated with categorising these pollutants, each group was individually examined.

Methods

- A formal Rapid Review approach was used for the 2022 Scientific Consensus Statement (SCS) synthesis of evidence. Rapid reviews are a systematic review with a simplification or omission of some steps to accommodate the time and resources available[5]. For the SCS, this applies to the search effort, quality appraisal of evidence and the amount of data extracted. The process has well-defined steps enabling fit-for-purpose evidence to be searched, retrieved, assessed and synthesised into final products to inform policy. For this question, an Evidence Summary method was used.
- Search locations were Scopus and Web of Science.
- Each pollutant group was searched independently. Five searches (using modified strings) were performed on each database for each pollutant group capturing: very broad (the Great Barrier Reef); measurements (concentrations); sediment and water; habitat; and biota.
- The searches for each pollutant group were aggregated and duplicates discarded.
- Data sources were constrained to the GBR region. The exception to this was sunscreen, as there were no relevant GBR sources of evidence and consequently additional material was sourced from overseas reviews. Perfluorooctane sulfonate (PFOS) data was provided by the Queensland Government and its use approved by the SCS Coordination Team.
- The initial searches returned 11,544 results which was reduced to 2,110 results after the first screening. Following the removal of duplicates and sources which did not meet the eligibility criteria, 532 studies were read in full. Of these, 92 studies met the eligibility criteria and contributed to the final 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.
- Only two academic databases were searched.

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[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

- Only GBR derived studies were included, the exception being the overview on sunscreen.
- Only peer reviewed studies published between 1990 and 2023 were included.

Key Findings

Summary of evidence to 2022

Ninety studies were considered in this Evidence Summary. The information was biased towards several groups of pollutants, most notably metals and plastics. Of particular note was the lack of long-term datasets and hence no temporal trends could be determined for any pollutant groups. Consequently, no direct comparisons are made between the current data and evidence from the 2017 Scientific Consensus Statement. The majority of datasets (including different pollutant groups) came from the same systems, including: Port Curtis, Townsville and Cairns, and collectively the data was very coastal focused. Furthermore, only relatively few offshore environments were sampled, and these varied greatly among the different types of pollutants. It is important to note that many of the results reported are from single studies.

The key conclusions from each pollutant group are summarised below.

Metals

- Forty-four studies were available on metal concentrations in waters, sediments and biota in the GBR. Metal concentrations in waters were only examined in a few studies, with these mostly associated with sources from Townsville, Port Curtis and acid sulfate soils from Trinity Bay. The monitoring results of metals in waters and sediments undertaken as part of the Regional Report Cards (e.g., Gladstone, Dry Tropics and Mackay Whitsunday) were not included in this review as the raw data is not published and publicly available. Summary statistics of the results are included in the Technical Reports and Report Cards.
- Metal concentrations in water and sediment are higher in more industrial and developed coastal environments compared to less developed catchments and offshore areas. There is also limited published temporal data for metals in water, sediments and biota in the GBR generally, and more particularly in less developed areas. Concentrations above national water quality guideline values have been recorded in some studies including for copper (associated with legacy mining in the Fitzroy basin), mercury (associated with sugarcane in the Tully catchment) and aluminium (from acid sulfate soils in Trinity Bay, Cairns). These metals may be more widespread than currently recognised due to the limited data collection.
- Elevated concentrations of metals in sediments have been recorded adjacent to heavily urbanised environments including: manganese and nickel in Port Curtis; copper, nickel and zinc in Townsville Harbour; and cadmium from acid sulfate soils in Trinity Bay. Additional sources in individual studies included a dump site within Townsville Harbour and road runoff.
- There is some evidence that biota found inshore (e.g., seagrass, algae, turtles, corals) have higher concentrations of metals in their tissues than those found offshore and that levels can increase following runoff events. For example, concentrations of metals in mud crabs showed clear differences between catchments, with metals generally being more elevated in crabs from catchments with operational and legacy mines (e.g., Normanby and Fitzroy). Whilst baseline zinc concentrations in biota are available prior to the Townsville zinc smelter, no follow up study has been performed. Only one study examined the interactions between metals and temperature. Importantly, the study showed that reducing copper concentrations by half roughly equates to protecting corals from a 2-3°C increase in sea surface temperature. From the available ecotoxicological studies, the ecological risk from metals in the Great Barrier Reef is relatively low and constrained to a few small areas. However, there is a lack of recent data to complete this assessment.

Persistent Organic Pollutants (POPS)

- Only nine studies were available on POP concentrations in sediments and waters in the GBR.

- POPs are associated with industry, oil spills, coal, and urbanisation. However, some sources remain uncertain as it is unknown whether some restricted products (e.g., PCBs which require importation approval from the Department of Home Affairs under Regulation 4AB) are still being used in the region or whether the sources are legacy.
- POPs are detectable in Great Barrier Reef sediments, and from the limited data available, decrease across an inshore to offshore gradient. POPs are generally below guideline values where they have been recorded but there are exceptions (e.g., following oil spills). For example, naphthalene and pyrene were present in two studies on dolphins, as were other polychlorinated biphenyl (PCB) congeners and hexachlorobenzene (HCB). Evidence suggests that concentrations may have increased in dolphins following the 2010 flood and/or expansion of Gladstone Harbour. In two studies spanning the GBR, concentrations of POPs in turtles, while limited in sample size, appeared to be low.
- Experimental studies have shown that POPs can affect fish physiology and behaviour, coral reproduction and trophic food webs at a range of concentrations. However, there are insufficient data to determine if POPs are at concentrations in the GBR to cause these adverse effects, or to establish guideline values for most POPs.

PFAS and fire retardants

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

Plastics

- Nineteen studies were available on plastics in GBR waters and biota.
- Plastics, including microplastics and fibres, are extensively distributed in coastal and marine environments.
- The sources and types of plastics varies with geographic location. Coastal sites are influenced by surrounding land use (e.g., urbanised area), river and stormwater inputs. Islands are often the repository of wind-borne plastics, as well as general waste associated with tourism activities (fishing, boating and presence on islands), commercial boating and fishing, and localised stormwater runoff. Offshore sites are influenced by recreational activities, tourism, commercial shipping and fishing.
- Plastics been recorded in zooplankton, crustaceans, fishes, birds and turtles from the Great Barrier Reef. The ecological risks may vary markedly depending on species, feeding behaviour and life stages. For example, biota (fish and birds) appear to non-randomly select plastics based on colour, shape and texture. Plastics were used in bird nests and also consumed by chicks during feeding. Plastic consumption may affect the survivorship of fish via changes in anti-predatory behaviour. Although based on a limited sample size, it appears that green turtles may be more susceptible to consuming plastics than other turtle species.
- There was a lack of information on the effects of plastics across a range of taxa and environments. The limited evidence suggest that plastics do not biomagnify but are found higher concentrations in some trophic levels than others (e.g., copepods). The review found that ecotoxicological data for plastics were very limited for GBR biota.

Pharmaceuticals, veterinary products and personal care products (PVPs)

- Only four studies were available on PVPs in GBR waters and biota, with only one survey that had limited replication, examining a suite of PVPs.
- There are insufficient data to provide insights about spatial or temporal patterns or ecological consequences of PVPs. A range of pharmaceuticals were detected, mostly derived from the wastewater treatment plant in Cleveland Bay, although there was evidence of a few PVPs in offshore islands in the southern GBR. Resistance to 12 antibiotics as well as multi-drug

resistance was found in green turtles. The sources of PVPs remain unclear, however, the limited evidence suggests that PVPs are more dominant near wastewater overflows and stormwaters. Numerous technical limitations are currently hindering the routine monitoring of PVPs. As a result, data were not quantifiable and assignment was often tentative.

Coal and fly ash

- Only five studies were available on coal in GBR waters and biota. There were no studies for fly ash.
- There are insufficient data to provide insights about spatial or temporal patterns of coal and fly ash in the GBR.
- Polycyclic aromatic hydrocarbons (PAHs), which are most likely derived from coal, exceeded guideline values in coastal sites near Hay Point (Mackay) and were detected up to 40 nautical miles from the coast.
- There is some evidence that elevated levels of suspended coal can affect coral reproduction, seagrass and fish.

Sunscreen

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

Recent findings 2016–2023

Chapters 1, 2 and 3 of the 2017 Scientific Consensus Statement (SCS) provided an overview of ‘other pollutants’, their distributions, sources and their risks. The notable difference between the 2017 SCS update and the present one is that antifoulants are not covered in the current review, as they are derived from offshore activities such as shipping and fishing. Furthermore, the current SCS review aimed to provide a more detailed focus on POPs, PVPs, PFAS and sunscreen. Many of the limitations emphasised in the 2017 SCS still remain. These include: a lack of data; the need to conduct targeted campaigns for pollutants; and a need to understand the ecological impacts of plastics and personal care products on the GBR’s organisms and ecosystems. Since the 2017 SCS, there have been a range of studies which has aided the information contained in the present review. This includes: a single but extensive PFAS sampling program; a number of studies looking at the distribution of plastics and their effects on selected biota; five studies on the effects of coal; and some significant advancements in the ecotoxicological tools for assessing the effects of pollutants on turtles. However, given the dearth of studies across all pollutant classes, the present review jointly assessed studies captured both in the 2017 SCS and those more recently published. Collectively, there are no substantial changes between the 2017 findings and the current review, with the gaps for the key pollutants still remaining, thereby hindering a comprehensive understanding of the spatial and temporal distributions of other pollutants, their sources and risks.

Significance for policy, practice, and research

Several points are highlighted for policy, practice and research from this review.

- Collectively, the review highlights that pollutant data is very patchy and lacks temporal replication. In contrast to programs for assessing nutrients, sediments and pesticides in the GBR, 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 is not publicly available.
- Fundamental data for most pollutant groups in the GBR are lacking, most notably for coal, PVPs, PFAS and sunscreen. This prevents any reliable assessment of spatial patterns, temporal trends or exposure risk for ecosystems and individual biota.
- Research for each group of pollutants is focused on a particular environment or region, and generally does not take into consideration co-occurring pollutants and other stressors.

- There is a dearth of studies which examine the relationships between exposure, dose and response for these pollutant groups. Fundamental data and establishment of water and sediment guidelines values is required for most of the ’other pollutant’ groups including coal, per- and poly-fluoroalkyl substances, pharmaceutical, veterinary, and personal health care products, sunscreens and pesticides and their degradation products. Sediment guideline values still need to be established for some metals (e.g., manganese, aluminium). This limits the ability to assess ecological risks, particularly for tropical ecosystems, as guidelines are predominantly derived from temperate taxa.
- Arguably, the sediment quality guidelines are outdated and lack a sufficient breadth of contaminants to assess risks within the GBR.
- There is an absence of studies examining the effects of pollutants on coastal fish communities, as well as a lack of studies on macrobenthos. Both are important biotic groups (ecologically, socially and environmentally) which are closely associated with coastal activities.
- Ecotoxicological studies that employ multiple lines of evidence are urgently required for all of the pollutant groups identified in the GBR to understand the risks that these pollutants pose to GBR biota and ecosystems.
- Only a single study examined the effects of a pollutant (copper) and temperature. While it is not possible to draw trends from a single study, the findings of this study suggested that lower pollutant levels increased the capacity for corals to deal with sea temperature rise.
- A more cohesive and co-ordinated approach to examine the interaction of multiple pollutants and stressors, including climate change, is required.

It is important to recognise that the above limitations are not a reflection of the research or science per se, but rather highlights the limitations of synthesising sources which are not collected in a co-ordinated manner, and the lack of regionally relevant tools and guidelines for confidently assigning risks.

Key uncertainties and/or limitations

- There are no sediment and/or water guideline values for many of the pollutants. Even in cases where they exist, they are often of suboptimal reliability. Furthermore, it is not known whether the sediment or water quality guidelines for the pollutants of interest in this question are relevant to the biota of the GBR, or tropical systems per se, as they are predominantly derived from temperate taxa.
- There are no baseline measurements for many of the pollutants, and this information is needed in a variety of matrices, including waters, sediments and tissues for taxa of interest.
- Data were often centred around known potential sources.
- No temporal data were available, with the exception of plastics.
- Approaches used to measure pollutants often varied, including metals and plastics.
- Sample size was often small due to the opportunistic nature of many studies (e.g., turtles and cetaceans). Sample size was also often small due to logistics and costs, e.g., measuring POPs and PVPS.
- For most pollutants there was not sufficient information to address the questions, most notably for PFOS, PVPs, coal and sunscreen.
- Data from non-primary literature (such as those associated with the Regional Report Cards) was rarely externally peer reviewed and publicly available and consequently excluded.

Evidence appraisal

Overall, the confidence rating in the collective evidence used in this review was Moderate. This was predominantly driven by the relevance of the studies to answering the question, which is unsurprising given the extensive and rigorous screening process. The confidence ratings varied among pollutant groups. Metals, POPs and plastics were overall rated as Moderate; while PFAS, PVPs, coal and sunscreen were rated *Low* due to the lack of sources. Both the spatial and temporal relevance of the data was *Low*, reflecting the patchiness of the sources and the general lack of temporal data. Spatial studies were rated: 1 (out of 3) - when only one study site was examined; 2 - if multiple sites were examined; and 3 -

if the study was performed over an area >500 kms, regardless of patchiness. Temporal studies were rated: 1 - if they sampled a single time point; 2 - if sampled on two occasions; and 3- if sampling was performed on three or more occasions. The majority of studies were from coastal systems, and although a number of studies did sample across a wide geographic range (>500 km), samples were generally patchy, for example, comparisons between sites near a major city and a few isolated islands in the far north. However, the spatial distribution of the data varied greatly between pollutants. Most sources were from *in situ* studies, although relevant experimental studies (using GBR biota) were included.

1. Background

In addition to well documented and routinely monitored pollutants such as nutrients, sediments and pesticides, there are numerous other groups of pollutants which have the capacity to enter the waters and sediments of the Great Barrier Reef (GBR) (Kroon et al., 2020) (Figure 1). Consequently, biota have the potential to be exposed or accumulate these pollutants which often co-occur with other environmental stressors (e.g., pesticides, nutrients, turbidity, pH and salinity) (Kroon et al., 2020). This diverse array of pollutants can be arbitrarily classified into the following groups: metals; persistent organic pollutants (POPs); pharmaceuticals and veterinary products (PVPs); plastics, including microplastics and fibres; per- and poly-fluoroalkyl substances (PFAS) and fire retardants; coal (including fly ash); and sunscreens.

Given the varied sources and complexities associated with categorising these pollutants, each group requires its own considerations with regards to its environmental distributions and concentrations, sources, effects, risks and knowledge gaps. In some cases, pollutants are naturally occurring (e.g., metals), however, their concentrations in the environment have increased due to anthropogenic activities (e.g., industrialisation and urbanisation). As such they can aggregate in specific parts of the environment, for example sediments. The aggregation of other pollutants (e.g., some POPs) may also occur in sediments due their hydrophobic properties, increasing their potential to accumulate in biota (Jones & De Voogt, 1999; Zhu et al., 2017).

The range of “contaminants of emerging concern” also provides a challenge for the environmental protection and management of the GBR. These include natural (e.g., oestrogens) and manmade or manufactured chemicals such as fire retardants (PFAS), pharmaceuticals (human and veterinary) (e.g., antibiotics and medicines), anti-bacterial agents (e.g., triclosan), and a suite of personal care products (e.g., DEET and sunscreen). In contrast to metals and POPs, many of these contaminants of emerging concern are challenging to measure in the environment and lack sufficient ecotoxicological data or guidelines for determining the risks associated with concentrations present within the environment. The co-occurrence of these chemicals from some sources, e.g., wastewaters, further hinders our capacity for determining which chemicals pose the most significant risks and at which concentrations. In addition, there are some significant unknowns with regards to how antibiotic deposition in the environment affects the antibiotic resistance of biota in the receiving waters (Suzuki et al., 2017). In recent years, there has also been a growing concern about the effects of UV filters (sunscreen) on corals, which is of high relevance given its potential close interaction with the water column (National Academies of Sciences, 2022; Watkins & Sallach, 2021).

Although the GBR covers an area of 348,000 km^2 (GBRMPA, 2014), it is logical to assume that the risks of many pollutants are greater in coastal regions with high urban, industrial or agricultural activity (Kroon et al., 2020). This is highlighted in Kroon et al. (2020) which presents potential sources of other pollutants in the GBR catchment area and marine ecosystems. However, the connectivity of the system, as well as its extensive recreational and commercial activities does not negate the influence of pollutants in more isolated offshore environments, nor the influence of activities from areas outside of the GBR (Saint-Amand et al., 2022). This is particularly evident with plastics, where their spread has been well documented along the shores and in the waters throughout the GBR, as well as its consumption by turtles and seabirds (Duncan et al., 2019; 2021; Wilcox et al., 2015; Wilson & Verlis, 2017). In addition, pollutants are stressors, be it chemical or physical, and consequently exposure can have negative implications to the health of biota. This is particularly pertinent given the increasing influence of climate change on the region’s biota and communities. As such, there are likely to be interactions between pollution exposure and the resistance of the region’s biota to climate change.

Question 6.1 considered the evidence for a diverse range of pollutants in the GBR, including current information on their spatial and temporal distributions in the environment (water, sediment and biota), the risk associated with these pollutants, and the primary sources of these pollutants.

1.1 Question

Primary question	**Q6.1** What is the spatial and temporal distribution and risk of other pollutants in Great Barrier Reef ecosystems, and what are the primary sources?

The primary question was considered as three components:

1) What is the spatial and temporal distribution of other pollutants in GBR ecosystems?
2) What is the risk of the other pollutants to the GBR ecosystem?
3) What are the primary sources of "other pollutants" and how do they enter into the GBR ecosystem?

Following discussions with stakeholders, the question was further interpreted as:

What is the distribution of 'other pollutants' derived from terrestrial sources across the freshwater, estuarine and marine components, including sediments, water and biota of the Great Barrier Reef over time.

'Other pollutants' here are defined as:

- **Metals (and metalloids):** consisting of arsenic (As), cadmium (Cd), cobalt (Co), copper (Cu), mercury (Hg), manganese (Mn), nickel (Ni), lead (Pb), selenium (Se), antimony (Sb) and zinc (Zn). Excludes tributyltin (TBT) as this is not considered to be terrestrially derived. Iron is also excluded as it is not considered to be a pollutant despite concentrations being intrinsically linked to land use.
- **Persistent Organic Pollutants (POPs):** includes oils, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), dioxins and hexachlorobenzene (HCB). Excludes organochlorines.
- Per- and poly-fluoroalkyl substances (PFAS/PFOS) and fire retardants.
- Coal and fly ash.
- **Plastics:** including microplastics and fibres.
- **Pharmaceuticals and personal health care products (PVPs)**: also includes antibiotics, veterinary products, hormones and endocrine disrupting contaminants.
- **Sunscreen**.

This component of the question was interpreted as being constrained to within the spatial boundaries of the Great Barrier Reef World Heritage Area (GBRWHA). However, in some cases, the boundary range was extended to include concentrations from land-based activities which are likely contributing to the enrichment of pollutants within the coastal freshwater and estuarine systems of the GBR, e.g., metals derived from road-runoff.

What is the risk of the other pollutants to the GBR ecosystem?

This component of the question was interpreted as, what evidence is there that the concentrations of "other pollutants" measured in the water, sediments or biota of the GBR ecosystem: 1) are potentially harmful as reflected as a change at any biological level from subcellular to ecosystem; and/or 2) concentrations exceed current or proposed national water or sediment quality guideline values.

This component also included laboratory studies which used endemic species sourced from the GBR, thereby providing some information about the links between dose and/or exposure and a biological or ecological response. It also included relevant bioaccumulation studies. In addition, based on preliminary searches and discussions with the SCS Coordination Team and government agencies, it was decided that information regarding the risks of sunscreen would be sourced from studies beyond the GBR, as no suitable literature from the GBR was found.

What are the primary sources of "other pollutants" and how do they enter into the GBR ecosystem?

This component of the question was interpreted as, what were the primary sources these pollutants were likely to have originated from? This question was restricted to terrestrial derived sources, and includes atmospheric deposition, however, sources directly associated with maritime and offshore practices (e.g., antifoulants, shipwrecks and oil spills) were excluded. As illustrated in the conceptual model (Figure 1), the types of pollutants which can enter the GBR are diverse, and their origins can be broadly classified into three primary sources: agricultural, urban and industrial. However, some pollutant groups, e.g., metals, and pharmaceuticals such as antibiotics can come from a range of sources. Furthermore, the sources can be diffuse and overlap, for example, stormwater and runoff can include pollutants from all three sources encapsulating all the activities within a catchment.

1.2 Conceptual diagram

Figure 1 illustrates the scope of Question 6.1, showing the different sources and types of other pollutants included in the review. The distribution of these pollutants and the potential impacts on downstream ecosystems were also considered.

1.3 Links to other questions

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

Links to other related questions	Excessive sediments and particulate nutrients, dissolved nutrients, and pesticides can be considered to be pollutants. These are covered in Questions 3.1, 3.2, 4.1, 4.2, and 5.1 and are not considered here. To aid future management strategies, the spatial boundaries and measured matrices (e.g., types of biota) used in this section are the same as those used in Question 5.1 (Negri et al.). **Q3.1** What are the spatial and temporal distributions of terrigenous 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 are the (potential or observed) ecological impacts in these ecosystems and what evidence is there for pesticide risk?

AGRICULTURE

Metals: As, Cd, Cu, Fe, Hg, Mn, Pb, Se and Zn
Fertiliser, pesticides, livestock manure and wastewater

Veterinary Products & Antibiotics
Given to livestock

Acid Sulfate Soils

URBAN

Personal Health Care Products
Wastewater discharge, recreational activities

Sunscreen
Recreational activities e.g., swimming

Antibiotics
Wastewater

Pharmaceuticals
Sewage and waste disposal

PCBs & PAHs
Improper dumping of industrial waste, consumer products, leaks from old electrical appliances, coal and petroleum

PFOS/PFAS group
Electronics, clothing, furniture, fire-fighting foam

Plastics, microplastics, microfibres
Personal care products, general litter, tyres, synthetic textiles, road markings, city dust, sewage, storm water and fishing equipment

INDUSTRIAL

Coal
Inland mining, transport via railways, shipping through ports internationally

Plastics, microplastics
Waste from plastic pellets, textiles and wrappings

Metals: As, Cd, Cu, Fe, Hg, Mn, Pb, Se and Zn
Mining and industrial production

Persistent Organic Pollutants (POPs)
Industrial chemicals, pesticide formulations and sewage sludge

Figure 1. Conceptual model illustrating the diverse range of pollutants which can potentially enter the Great Barrier Reef and their primary terrestrial sources considered with Question 6.1.

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

2.1 Primary question elements and description

The primary question is: ***What is the spatial and temporal distribution and risk of other pollutants in Great Barrier Reef ecosystems, and what are the primary sources?***

S/PICO frameworks (Subject/Population, Exposure/Intervention, Comparator, Outcome) can be used to break down the different elements of a question and help to define and refine the search process. The S/PICO structure is the most commonly used structure in formal evidence synthesis methods[7] but other variations are also available.

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

Table 1. Description of primary question elements for Question 6.1.

Question S/PICO elements	Question term	Description
Subject/ Population	Other pollutants	Metals/metalloids: As, Cd, Co, Cu, Hg, Mn, Ni, Pb, Sb, Se, Zn. Persistent Organic Pollutants (e.g., PAHS, PCBs, dioxins, HCBs and endocrine disrupting contaminants). PFAS group. Pharmaceuticals, veterinary products, personal health care products and endocrine disrupting contaminants. Plastics, microplastics and microfibres. Sunscreen. Coal and fly ash.
Intervention, exposure & qualifiers	GBR ecosystems	Including: seawater, freshwater, sediments, biota, marine, estuarine, freshwater, river, wetland, seagrass meadow, coral reef, and mangrove forest.
	Spatial and temporal distribution	What are the types, concentrations and combinations of other pollutants measured in water, sediments and biota

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

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

Question S/PICO elements	Question term	Description
		across the marine, estuarine, wetland and freshwater habitats of the GBR? Do concentrations differ across regions and habitats and how have they changed over time?
Comparator	Water quality and sediment quality guidelines. Ecotoxicity threshold values.	Threshold values are usually described for individual species, while guideline values refer to the Australian Water Quality Guideline Values and Revised Sediment Quality Guidelines.
Outcome & outcome qualifiers		Evidence that concentrations of individual or mixtures of pollutants measured in the environment, including shores (plastics), water, sediments or biota of the GBR reach concentrations which have the potential to be harmful to biota.

Table 2. Definitions for any relevant terms used in the question.

Definitions	
Pollutants	The term pollutants is used throughout to mean "any contaminant above natural background which may or may not cause an adverse effect." Pollutants are categorised into the following groups: **Metals (and metalloids):** consisting of As, Cd, Co, Cu, Hg, Mn, Ni, Pb, Sb, Se and Zn. **Persistent Organic Pollutants (POPS):** includes oils, PCBs, PAHs, dioxins and HCBs. Excludes organochlorines. PFAS/PFOS and fire retardants Coal and fly ash. **Plastics:** including microplastics and fibres. **Pharmaceuticals and personal health care products**: also includes antibiotics, veterinary products, hormones and endocrine disrupting contaminants. Sunscreen.
GBR ecosystems	Marine (coral, seagrass, pelagic, benthic + plankton communities), estuarine (estuaries, mangroves, saltmarsh), freshwater (rivers, natural or wetlands).
Spatial distribution	Includes GBR ecosystem. Comparisons among natural resource management (NRM) regions (possibly summary tables) and catchments consistent with the Marine Monitoring Program (MMP). Ecosystems include: reef, beaches (plastics only), seagrass meadows and algal turf, rivers, river mouths and wetlands. Spatial studies were rated: 1 - when only one study site was examined; 2 - if multiple sites were examined; and 3 - if the study was performed over an area > 500 kms, regardless of patchiness.
Temporal distribution	Temporal studies were rated: 1 - if they sampled a single time point; 2 - if sampled on two occasions; and 3 - if sampling was performed on at least three occasions. The majority of studies were from coastal systems, and whilst a number of studies did sample across a wide geographic range (>500 km), samples were generally patchy, for example, comparisons between sites near a major city and a few isolated islands in the far north.

Definitions	
Risk	Defined as Exposure x Consequences. There is a risk of harm to biota when measured concentrations of pollutants in aquatic systems exceed toxicity thresholds including water quality and sediment quality values.
Consequences	Negative effect on biota due to pollutant exposure.
SQG	Sediment Quality Guidelines, as described in the revised version (Simpson et al., 2013).
WQG	Water Quality Guideline(s). The WQG value applied in GBR waters is PC99. This is the guideline applied in waters of high ecological value. Concentrations of pesticides below the PC99 should not negatively affect 99% of species in an aquatic ecosystem. The nationally endorsed limits for pollutants in waterbodies in the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZG, 2018) are referred to as Default Guideline Values (DGVs).

Table 3. Acronyms used in Question 6.1.

Acronyms	
AD	Anthropogenic debris
ANZECC and ARMCANZ	Australian and New Zealand Environment and Conservation Council and the Agriculture and Resource Management Council of Australia and New Zealand
ANZG	Australian and New Zealand governments
APVMA	Australian Pesticides and Veterinary Medicines Authority
ASS	Acid sulfate soils
Cl8DD	2,3,7,8-Cl4DD
E1	Estrone
EC10	10% effect concentration
GBR	Great Barrier Reef
GVs	Guideline Values, a generic term that includes ecotoxicity threshold values, current and proposed default water quality and sediment quality guidelines
HCB	Hexachlorobenzene
LC10	10% lethal concentrations
MP	Microplastics
NOEC	No Observed Effect Concentration: the highest concentration that statistically has no effect on a species
NRM	Natural Resource Management region
PAHs	Polycyclic aromatic hydrocarbons
PBDEs	Polybrominated diphenyl ethers
PCBs	Polychlorinated biphenyls
PCDD	Polychlorinated-p-dioxins
PCDFS	Polychlorinated dibenzofurans
PET	Polyester
PFAS	Per- and poly-fluoroalkyl substances
(PFHxA)	Perfluorohexanoic acid
PFHxS	Perfluorohexane sulfonic acid
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctane sulfonate
POPs	Persistent Organic Pollutants
PP	Polypropylene

Acronyms	
PVPs	Pharmaceutical, Veterinary and Personal-Care Products
SQG	Sediment Quality Guidelines
UV	Ultraviolet
WQG	Water Quality Guideline(s)

2.2 Search and eligibility

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

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

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

a) Search locations

Searches were performed in:

- Scopus
- Web of Science

Searches were:

- Limited to Title-Abstract-Keywords.
- Limited to peer-reviewed publications between 1990 and 2023.

b) Search terms

Table 4 shows a list of the search terms used to conduct the online searches. Each 'class' of pollutant was searched independently. In total, seven classes of pollutants were searched. These were: metals (and metalloids); persistent organic pollutants (POPS); PFAS/PFOS and related contaminants; coal and fly ash; plastics; pharmaceuticals, veterinary and personal care products; and sunscreen.

Table 4. Search terms for S/PICO elements of Question 6.1.

Question element	Search terms
Subject/Population	Metals; persistent organic pollutant; pharmaceuticals, veterinary products and personal health care; plastics; coal; sunscreen
Exposure or Intervention	Great Barrier Reef, GBR, seawater, sediments, biota, inshore, offshore marine habitat, estuarine habitat, freshwater, river, seagrass, microalgae, crab, snail, turtle, dugong, environmental DNA, bacteria, wetlands, biota, coral, mangrove, distribution, accumulation, monitoring, concentration, bioaccumulation, biomagnification, spatial distribution, temporal distribution.
Comparator (if relevant)	guideline, ANZECC, water quality, WQGV, sediment quality, toxicity.
Outcome	ecological impacts, risk, harm

c) Search strings

Table 5. Search strings used for electronic searches for Question 6.1.

Search strings
(Metal* OR Metalloid* OR “heavy metal*” OR polymetallic OR copper OR lead OR cadmium OR manganese OR mercury OR zinc OR arsenic OR nickel OR selenium OR Aluminium) AND (“Great Barrier Reef” OR “GBR”)
(Metal* OR Metalloid* OR “heavy metal*” OR polymetallic OR Copper OR Lead OR Cadmium OR Manganese OR Mercury OR Zinc OR Arsenic OR Nickel OR Selenium OR Aluminium) AND (“Great Barrier Reef” OR “GBR”) AND (distribu* OR acum* OR monito* OR concentration* OR bioaccum* OR biomagni* OR level*)
(Metal* OR Metalloid* OR “heavy metal*” OR polymetallic OR Copper OR Lead OR Cadmium OR Manganese OR Mercury OR Zinc OR Arsenic OR Nickel OR Selenium OR Aluminium) AND (“Great Barrier Reef” OR “GBR”) AND (water OR sediment)
(Metal* OR Metalloid* OR “heavy metal*” OR polymetallic OR Copper OR Lead OR Cadmium OR Manganese OR Mercury OR Zinc OR Arsenic OR Nickel OR Selenium OR Aluminium) AND (“Great Barrier Reef” OR “GBR”) AND (marine OR estuar* OR wetland* OR river)
(Metal* OR Metalloid* OR “heavy metal*” OR polymetallic OR Copper OR Lead OR Cadmium OR Manganese OR Mercury OR Zinc OR Arsenic OR Nickel OR Selenium OR Aluminium) AND (“Great Barrier Reef” OR “GBR”) AND (coral OR seagrass OR mangrove OR alga* OR microalga* OR crab OR snail OR sponge OR urchin OR fish OR turtle OR dugong OR eDNA OR “environmental DNA” OR microb* OR bacteria OR prokaryot* OR biota)
(“persistent organic pollutant*” OR POPs* OR “polychlorinated biphenyl*” OR PCBS* OR “polycyclic aromatic hydrocarbon*” OR PAH*) AND (“Great Barrier Reef” OR “GBR” OR Queensland)
(“persistent organic pollutant*” OR POPs* OR “polychlorinated biphenyl*” OR PCBS* OR “polycyclic aromatic hydrocarbon*” OR PAH*) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (distribu* OR acum* OR monito* OR concentration* OR bioaccum* OR biomagni* OR level*)
(“persistent organic pollutant*” OR POPs* OR “polychlorinated biphenyl*” OR PCBS* OR “polycyclic aromatic hydrocarbon*” OR PAH*) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (water OR sediment)
(“persistent organic pollutant*” OR POPs* OR “polychlorinated biphenyl*” OR PCBS* OR “polycyclic aromatic hydrocarbon*” OR PAH*) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (marine OR estuar* OR wetland* OR river)
(“persistent organic pollutant*” OR POPs* OR “polychlorinated biphenyl*” OR PCBS* OR “polycyclic aromatic hydrocarbon*” OR PAH*) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (coral OR seagrass OR mangrove OR alga* OR microalga* OR crab OR snail OR sponge OR urchin OR fish OR turtle OR dugong OR eDNA OR “environmental DNA” OR microb* OR bacteria OR prokaryot* OR biota)
(“perfluorooctane sulfonic acid” OR “perfluorooctane sulfonate” OR “perfluorooctanesulfonic acid” OR “perfluorooctanoic acid” OR “perfluorohexane sulfonate” OR “perfluorohexanesulfonic acid” OR “per-fluoroalkyl” OR “poly-fluoroalkyl” OR “fire retardant*” OR PFOS* OR PFAS* OR PFC* OR PFOA OR PFHxS) AND (“Great Barrier Reef” OR “GBR” OR Queensland)
(“perfluorooctane sulfonic acid” OR “perfluorooctane sulfonate” OR “perfluorooctanesulfonic acid” OR “perfluorooctanoic acid” OR “perfluorohexane sulfonate” OR “perfluorohexanesulfonic acid” OR “per-fluoroalkyl” OR “poly-fluoroalkyl” OR “fire retardant*” OR PFOS* OR PFAS* OR PFC* OR PFOA OR PFHxS) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (distribu* OR acum* OR monito* OR concentration* OR bioaccum* OR biomagni* OR level*)
(“perfluorooctane sulfonic acid” OR “perfluorooctane sulfonate” OR “perfluorooctanesulfonic acid” OR “perfluorooctanoic acid” OR “perfluorohexane sulfonate” OR “perfluorohexanesulfonic acid” OR “per-fluoroalkyl” OR “poly-fluoroalkyl” OR “fire retardant*” OR PFOS* OR PFAS* OR PFC* OR PFOA OR PFHxS) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (water OR sediment)
(“perfluorooctane sulfonic acid” OR “perfluorooctane sulfonate” OR “perfluorooctanesulfonic acid” OR “perfluorooctanoic acid” OR “perfluorohexane sulfonate” OR “perfluorohexanesulfonic acid” OR “per-fluoroalkyl” OR “poly-fluoroalkyl” OR “fire retardant*” OR PFOS* OR PFAS* OR PFC* OR PFOA OR PFHxS) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (marine OR estuar* OR wetland* OR river)
(“perfluorooctane sulfonic acid” OR “perfluorooctane sulfonate” OR “perfluorooctanesulfonic acid” OR “perfluorooctanoic acid” OR “perfluorohexane sulfonate” OR “perfluorohexanesulfonic acid” OR “per-fluoroalkyl” OR “poly-fluoroalkyl” OR “fire retardant*” OR PFOS* OR PFAS* OR PFC* OR PFOA OR PFHxS) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (coral OR seagrass OR mangrove OR alga* OR microalga*

Search strings
OR crab OR snail OR sponge OR urchin OR fish OR turtle OR dugong OR eDNA OR “environmental DNA” OR microb* OR bacteria OR prokaryot* OR biota)
(plastic* OR microplastic* OR “micro-plastic*” OR “plastic fibre*” OR fibre* OR “plastic fiber*” OR fiber*) AND (“Great Barrier Reef” OR “GBR” OR Queensland)
(plastic* OR microplastic* OR “micro-plastic*” OR “plastic fibre*” OR fibre* OR “plastic fiber*” OR fiber*) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (distribu* OR acum* OR monito* OR concentration* OR bioaccum* OR biomagni* OR level*)
(plastic* OR microplastic* OR “micro-plastic*” OR “plastic fibre*” OR fibre* OR “plastic fiber*” OR fiber*) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (water OR sediment)
(plastic* OR microplastic* OR “micro-plastic*” OR “plastic fibre*” OR fibre* OR “plastic fiber*” OR fiber*) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (marine OR estuar* OR wetland* OR river)
(plastic* OR microplastic* OR “micro-plastic*” OR “plastic fibre*” OR fibre* OR “plastic fiber*” OR fiber*) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (coral OR seagrass OR mangrove OR alga* OR microalga* OR crab OR snail OR sponge OR urchin OR fish OR turtle OR dugong OR eDNA OR “environmental DNA” OR microb* OR bacteria OR prokaryot* OR biota)
(pharmaceutical* OR antibiotic* OR “personal health care product*” OR “personal care product*” OR PPCP* OR “health care product*” OR “veterinary product*” OR “hormone*” OR EDC* OR “endocrine disrupting contaminant*” OR “endocrine disrupting” OR “veterinary chemical*”) AND (“Great Barrier Reef” OR “GBR”) AND NOT ("guided bone regeneration" OR "germ* brown rice")
(pharmaceutical* OR antibiotic* OR “personal health care product*” OR “personal care product*” OR PPCP* OR “health care product*” OR “veterinary product*” OR “hormone*” OR EDC* OR “endocrine disrupting contaminant*” OR “endocrine disrupting” OR “veterinary chemical*”) AND (“Great Barrier Reef” OR “GBR”) AND (distribu* OR acum* OR monito* OR concentration* OR bioaccum* OR biomagni* OR level*)
(pharmaceutical* OR antibiotic* OR “personal health care product*” OR “personal care product*” OR PPCP* OR “health care product*” OR “veterinary product*” OR “hormone*” OR EDC* OR “endocrine disrupting contaminant*” OR “endocrine disrupting” OR “veterinary chemical*”) AND (“Great Barrier Reef” OR “GBR”) AND (water OR sediment)
(pharmaceutical* OR antibiotic* OR “personal health care product*” OR “personal care product*” OR PPCP* OR “health care product*” OR “veterinary product*” OR “hormone*” OR EDC* OR “endocrine disrupting contaminant*” OR “endocrine disrupting” OR “veterinary chemical*”) AND (“Great Barrier Reef” OR “GBR”) AND (marine OR estuar* OR wetland* OR river)
(pharmaceutical* OR antibiotic* OR “personal health care product*” OR “personal care product*” OR PPCP* OR “health care product*” OR “veterinary product*” OR “hormone*” OR EDC* OR “endocrine disrupting contaminant*” OR “endocrine disrupting” OR “veterinary chemical*”) AND (“Great Barrier Reef” OR “GBR”) AND (coral OR seagrass OR mangrove OR alga* OR microalga* OR crab OR snail OR sponge OR urchin OR fish OR turtle OR dugong OR eDNA OR “environmental DNA” OR microb* OR bacteria OR prokaryot* OR biota)
(Coal or “fly ash” or “fly-ash”) AND (“Great Barrier Reef” OR “GBR”)
(Coal or “fly ash” or “fly-ash”) AND (“Great Barrier Reef” OR “GBR”) AND (distribu* OR acum* OR monito* OR concentration* OR bioaccum* OR biomagni* OR level*)
(Coal or “fly ash” or “fly-ash”) AND (“Great Barrier Reef” OR “GBR”) AND (water OR sediment)
(Coal or “fly ash” or “fly-ash”) AND (“Great Barrier Reef” OR “GBR”) AND (marine OR estuar* OR wetland* OR river)
(Coal or “fly ash” or “fly-ash”) AND (“Great Barrier Reef” OR “GBR”) AND (coral OR seagrass OR mangrove OR alga* OR microalga* OR crab OR snail OR sponge OR urchin OR fish OR turtle OR dugong OR eDNA OR “environmental DNA” OR microb* OR bacteria OR prokaryot* OR biota)
(sunscreen* OR "sun screen" OR suncream* OR "sun cream" OR oxybenzone) AND (“Great Barrier Reef” OR “GBR” OR Queensland)
(sunscreen* OR "sun screen" OR suncream* OR "sun cream" OR oxybenzone) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (distribu* OR acum* OR monito* OR concentration* OR bioaccum* OR biomagni* OR level*)
(sunscreen* OR "sun screen" OR suncream* OR "sun cream" OR oxybenzone) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (water OR sediment)

Search strings
(sunscreen* OR "sun screen" OR suncream* OR "sun cream" OR oxybenzone) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (marine OR estuar* OR wetland* OR river)
(sunscreen* OR "sun screen" OR suncream* OR "sun cream" OR oxybenzone) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (coral OR seagrass OR mangrove OR alga* OR microalga* OR crab OR snail OR sponge OR urchin OR fish OR turtle OR dugong OR eDNA OR “environmental DNA” OR microb* OR bacteria OR prokaryot* OR biota)

d) Inclusion and exclusion criteria

Table 6 shows a list of the inclusion and exclusion criteria used for accepting or rejecting evidence items.

Table 6. Inclusion and exclusion criteria for Question 6.1 applied to the search returns.

Question element	Inclusion	Exclusion (numbers correspond to criteria in Data Extraction sheets)
Subject/Population	Metals/metalloids: As, Cd, Co, Cu, Hg, Mn, Ni, Pb, Sb, Se, Zn. Persistent Organic Pollutants (e.g., PAHS, PCBs, dioxins, HCBs and endocrine disrupting contaminants). PFAS group. Pharmaceuticals, veterinary products, personal health care products and endocrine disrupting contaminants. Plastics, microplastics and microfibres. Sunscreen. Coal and fly ash.	3: More relevant to pesticide or nutrient questions. 10: Not the pollutant of interest in this component or outside scope (e.g., antifoulants).
Exposure or Intervention	**GBR ecosystems** include: marine, estuarine and wetlands within the Great Barrier Reef Marine Park. **Spatial and temporal distribution Include:** Ecosystems include (reef, seagrass meadow, river mouth, and wetlands). Natural and near natural wetlands only, including estuarine, marshes and floodplain lakes. The detection of other pollutants in aquatic biota of the GBR provides evidence of exposure.	8: No direct information on pollutants or data could be extracted.
Comparator (if relevant)	Guideline, ANZECC, water quality, sediment quality, toxicity, threshold. **Water quality guideline values** guide aquatic ecosystem protection. Current and proposed (updated with improved data) Australian and New Zealand default guideline values (DGVs,	1: Not geographically in the GBR. 2: Relevant to artificial wetlands, channels, dams, farms, groundwater. 4: Tracer, biogeochemical, biomarkers or catchment processes: not relevant to *in situ* concentrations.

Question element	Inclusion	Exclusion (numbers correspond to criteria in Data Extraction sheets)
	including ANZECC & ARMCANZ 2000 and those developed for GBR waters) considered. **Threshold values:** Concentration of a pollutant above which there is a measurable or defined (i.e., 10%) effect on survival or sublethal responses.	12: Unclear where the samples were obtained (i.e., if from the GBR).
Outcome	**Ecological impact:** Ecologically relevant effects of pesticides on biota, including reduced survival, growth, reproductive success. Can be observed in controlled laboratory experiments or in the field following exposure. **Risk:** There is a risk of harm to biota when measured concentrations of pesticides in aquatic systems exceed toxicity thresholds including WQG values.	
Language	English	7. Non-English language
Study type	Journal articles and peer-reviewed reports.	6. Non peer reviewed studies including reports, reviews or position papers with little quantitative evidence. 5: Reviews or position pieces - little primary evidence. 11: Conference abstract only.
Study period	Studies published after 1990	9: No information on pollutant since 1990.

3. Search Results

A total of 11,544 studies were identified through online searches for peer reviewed and published literature. Two studies were identified manually through expert contact and personal collection. Following full text screening of 532 studies, 92 studies were eligible for inclusion in the synthesis of evidence (Table 7).

Tables 7a-g. Search results tables for each pollutant group, separated by A) Academic databases, and B) Manual searches. The search results for A are provided in the format X of Y, where: X (number of relevant evidence items retained for second screening); and Y (total number of search returns or hits).

Table 7a. Metals.

Date (d/m/y)	Search strings: **Metals**	Sources	
A) Academic databases		Web of Science	Scopus
05/02/2023	*(Metal* OR Metalloid* OR "heavy metal*" OR polymetallic OR copper OR lead OR cadmium OR manganese OR mercury OR zinc OR arsenic OR nickel OR selenium OR Aluminium) AND ("Great Barrier Reef" OR "GBR")* *AND NOT "guid* bone regeneration" OR "germinat* brown rice"*	*172/1247*	*65/492*
05/02/2023	*(Metal* OR Metalloid* OR "heavy metal*" OR polymetallic OR Copper OR Lead OR Cadmium OR Manganese OR Mercury OR Zinc OR Arsenic OR Nickel OR Selenium OR Aluminium) AND ("Great Barrier Reef" OR "GBR") AND (distribu* OR acum* OR monito* OR concentration* OR bioaccum* OR biomagni* OR level*)* *AND NOT "guid* bone regeneration" OR "germinat* brown rice"*	*170/773*	*58/268*
05/02/2023	*(Metal* OR Metalloid* OR "heavy metal*" OR polymetallic OR Copper OR Lead OR Cadmium OR Manganese OR Mercury OR Zinc OR Arsenic OR Nickel OR Selenium OR Aluminium) AND ("Great Barrier Reef" OR "GBR") AND (water OR sediment) AND NOT "guid* bone regeneration" OR "germinat* brown rice"*	*157/591*	*62/174*
05/02/2023	*(Metal* OR Metalloid* OR "heavy metal*" OR polymetallic OR Copper OR Lead OR Cadmium OR Manganese OR Mercury OR Zinc OR Arsenic OR Nickel OR Selenium OR Aluminium) AND ("Great Barrier Reef" OR "GBR") AND (marine OR estuar* OR wetland* OR river)* *AND NOT "guid* bone regeneration" OR "germinat* brown rice"*	*158/838*	*47/155*
05/02/2023	*(Metal* OR Metalloid* OR "heavy metal*" OR polymetallic OR Copper OR Lead OR Cadmium OR Manganese OR Mercury OR Zinc OR Arsenic OR Nickel OR Selenium OR Aluminium) AND ("Great Barrier Reef" OR "GBR") AND (coral OR seagrass OR mangrove OR alga* OR microalga* OR crab OR snail OR sponge OR urchin OR fish OR turtle OR dugong OR eDNA OR "environmental DNA" OR microb* OR bacteria OR prokaryot* OR biota)* *AND NOT "guid* bone regeneration" OR "germinat* brown rice"*	*138/879*	*55/200*

	Total items online searches	***363 of 4,731 (7.7%)***
B) Manual search		
Date	Source	Number of items added
		0
	Total items manual searches	***0 (0%)***

Table 7b. POPs.

Date (d/m/y)	Search strings: **POPs**	Sources	
A) Academic databases		Web of Science	Scopus
13/03/2023	*(“persistent organic pollutant*” OR POPs* OR “polychlorinated biphenyl*” OR PCBS* OR “polycyclic aromatic hydrocarbon*” OR PAH*) AND (“Great Barrier Reef” OR “GBR” OR Queensland)*	*38/183*	*32/94*
13/03/2023	*(“persistent organic pollutant*” OR POPs* OR “polychlorinated biphenyl*” OR PCBS* OR “polycyclic aromatic hydrocarbon*” OR PAH*) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (distribu* OR acum* OR monito* OR concentration* OR bioaccum* OR biomagni* OR level*)*	*37/145*	*30/70*
13/03/2023	*(“persistent organic pollutant*” OR POPs* OR “polychlorinated biphenyl*” OR PCBS* OR “polycyclic aromatic hydrocarbon*” OR PAH*) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (water OR sediment)*	*42/134*	*27/50*
13/03/2023	*(“persistent organic pollutant*” OR POPs* OR “polychlorinated biphenyl*” OR PCBS* OR “polycyclic aromatic hydrocarbon*” OR PAH*) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (marine OR estuar* OR wetland* OR river)*	*44/96*	*26/38*
13/03/2023	*(“persistent organic pollutant*” OR POPs* OR “polychlorinated biphenyl*” OR PCBS* OR “polycyclic aromatic hydrocarbon*” OR PAH*) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (coral OR seagrass OR mangrove OR alga* OR microalga* OR crab OR snail OR sponge OR urchin OR fish OR turtle OR dugong OR eDNA OR “environmental DNA” OR microb* OR bacteria OR prokaryot* OR biota)*	*40/77*	*28/32*
	Total items online searches	***66 of 919 (7%)***	
B) Manual search			
Date	Source	Number of items added	
		0	
	Total items manual searches	***0 (0%)***	

Table 7c. PFAS.

Date (d/m/y)	Search strings: **PFAS**	Sources	
A) Academic databases		Web of Science	Scopus
_06/02/2023_	_(“perfluorooctane sulfonic acid” OR “perfluorooctane sulfonate” OR “perfluorooctanesulfonic acid” OR “perfluorooctanoic acid” OR “perfluorohexane sulfonate” OR “perfluorohexanesulfonic acid” OR “per-fluoroalkyl” OR “poly-fluoroalkyl” OR “fire retardant*” OR PFOS* OR PFAS* OR PFC* OR PFOA OR PFHxS) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND NOT (“prefrontal cortex”)_	_8/30_	_7/22_
_06/02/2023_	_(“perfluorooctane sulfonic acid” OR “perfluorooctane sulfonate” OR “perfluorooctanesulfonic acid” OR “perfluorooctanoic acid” OR “perfluorohexane sulfonate” OR “perfluorohexanesulfonic acid” OR “per-fluoroalkyl” OR “poly-fluoroalkyl” OR “fire retardant*” OR PFOS* OR PFAS* OR PFC* OR PFOA OR PFHxS) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (distribu* OR acum* OR monito* OR concentration* OR bioaccum* OR biomagni* OR level*) AND NOT (“prefrontal cortex”)_	_11/23_	_8/15_
_06/02/2023_	_(“perfluorooctane sulfonic acid” OR “perfluorooctane sulfonate” OR “perfluorooctanesulfonic acid” OR “perfluorooctanoic acid” OR “perfluorohexane sulfonate” OR “perfluorohexanesulfonic acid” OR “per-fluoroalkyl” OR “poly-fluoroalkyl” OR “fire retardant*” OR PFOS* OR PFAS* OR PFC* OR PFOA OR PFHxS) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (water OR sediment)_	_10/16_	_8/10_
_06/02/2023_	_(“perfluorooctane sulfonic acid” OR “perfluorooctane sulfonate” OR “perfluorooctanesulfonic acid” OR “perfluorooctanoic acid” OR “perfluorohexane sulfonate” OR “perfluorohexanesulfonic acid” OR “per-fluoroalkyl” OR “poly-fluoroalkyl” OR “fire retardant*” OR PFOS* OR PFAS* OR PFC* OR PFOA OR PFHxS) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (marine OR estuar* OR wetland* OR river)_	_6/6_	_4/4_
_06/02/2023_	_(“perfluorooctane sulfonic acid” OR “perfluorooctane sulfonate” OR “perfluorooctanesulfonic acid” OR “perfluorooctanoic acid” OR “perfluorohexane sulfonate” OR “perfluorohexanesulfonic acid” OR “per-fluoroalkyl” OR “poly-fluoroalkyl” OR “fire retardant*” OR PFOS* OR PFAS* OR PFC* OR PFOA OR PFHxS) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (coral OR seagrass OR mangrove OR alga* OR microalga* OR crab OR snail OR sponge OR urchin OR fish OR turtle OR dugong OR eDNA OR “environmental DNA” OR microb* OR bacteria OR prokaryot* OR biota)_	_5/7_	_4/4_
	Total items online searches	**_14 relevant of 127 (11%)_**	
B) Manual search			
Date	Source	Number of items added	
	Personal collection	_1_	
	Total items manual searches	**_1 (<1%)_**	

Table 7d. Plastics.

Date (d/m/y)	Search strings: **Plastics**	Sources	
A) Academic databases		Web of Science	Scopus
_06/02/2023_	_(plastic* OR microplastic* OR “micro-plastic*” OR “plastic fibre*” OR fibre* OR “plastic fiber*” OR fiber*) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND NOT “guid* bone regeneration” OR “germinat* brown rice”_	_43/1200_	_28/612_
_06/02/2023_	_(plastic* OR microplastic* OR “micro-plastic*” OR “plastic fibre*” OR fibre* OR “plastic fiber*” OR fiber*) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (distribu* OR acum* OR monito* OR concentration* OR bioaccum* OR biomagni* OR level*) AND NOT “guid* bone regeneration” OR “germinat* brown rice”_	_32/607_	_24/259_
_06/02/2023_	_(plastic* OR microplastic* OR “micro-plastic*” OR “plastic fibre*” OR fibre* OR “plastic fiber*” OR fiber*) AND (“Great Barrier Reef” OR “GBR” OR Queensland) and AND (water OR sediment) AND NOT “guid* bone regeneration” OR “germinat* brown rice”_	_40/357_	_26/139_
_06/02/2023_	_(plastic* OR microplastic* OR “micro-plastic*” OR “plastic fibre*” OR fibre* OR “plastic fiber*” OR fiber*) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (marine OR estuar* OR wetland* OR river)_	_46/385_	_27/77_
_06/02/2023_	_(plastic* OR microplastic* OR “micro-plastic*” OR “plastic fibre*” OR fibre* OR “plastic fiber*” OR fiber*) AND (“Great Barrier Reef” OR “GBR” OR Queensland) AND (coral OR seagrass OR mangrove OR alga* OR microalga* OR crab OR snail OR sponge OR urchin OR fish OR turtle OR dugong OR eDNA OR “environmental DNA” OR microb* OR bacteria OR prokaryot* OR biota) AND NOT (“guid* bone regeneration” OR “germinat* brown rice”)_	_35/473_	_21/ 151_
	Total items online searches	**_53 relevant 4,260 (1.2%)_**	
B) Manual search			
Date	Source	Number of items added	
		0	
	Total items manual searches	**_0 (0%)_**	

Table 7e. Pharmaceutical and veterinary.

Date (d/m/y)	Search strings: **Pharmaceutical and veterinary**	Sources	
A) Academic databases		Web of Science	Scopus
_14/03/2023_	_(pharmaceutical* OR antibiotic* OR “personal health care product*” OR “personal care product*” OR PPCP* OR “health care product*” OR “veterinary product*” OR “hormone*” OR EDC* OR “endocrine disrupting contaminant*” OR “endocrine disrupting” OR “veterinary chemical*”) AND (“Great Barrier Reef” OR “GBR”) AND NOT ("guided bone regeneration" OR "germ* brown rice")_	_10/235_	_7/113_
_14/03/2023_	_(pharmaceutical* OR antibiotic* OR “personal health care product*” OR “personal care product*” OR PPCP* OR “health care product*” OR “veterinary product*” OR “hormone*” OR EDC* OR “endocrine disrupting contaminant*” OR “endocrine disrupting” OR “veterinary chemical*”) AND (“Great Barrier Reef” OR “GBR”) AND (distribu* OR acum* OR monito* OR concentration* OR bioaccum* OR biomagni* OR level*) AND NOT ("guided bone regeneration" OR "germ* brown rice")_	_10/120_	_7/69_
_14/03/2023_	_(pharmaceutical* OR antibiotic* OR “personal health care product*” OR “personal care product*” OR PPCP* OR “health care product*” OR “veterinary product*” OR “hormone*” OR EDC* OR “endocrine disrupting contaminant*” OR “endocrine disrupting” OR “veterinary chemical*”) AND (“Great Barrier Reef” OR “GBR”) AND (water OR sediment) AND NOT ("guided bone regeneration" OR "germ* brown rice")_	_11/38_	_6/13_
_14/03/2023_	_(pharmaceutical* OR antibiotic* OR “personal health care product*” OR “personal care product*” OR PPCP* OR “health care product*” OR “veterinary product*” OR “hormone*” OR EDC* OR “endocrine disrupting contaminant*” OR “endocrine disrupting” OR “veterinary chemical*”) AND (“Great Barrier Reef” OR “GBR”) AND (marine OR estuar* OR wetland* OR river) AND NOT ("guided bone regeneration" OR "germ* brown rice")_	_9/99_	_5/14_
_14/03/2023_	_(pharmaceutical* OR antibiotic* OR “personal health care product*” OR “personal care product*” OR PPCP* OR “health care product*” OR “veterinary product*” OR “hormone*” OR EDC* OR “endocrine disrupting contaminant*” OR “endocrine disrupting” OR “veterinary chemical*”) AND (“Great Barrier Reef” OR “GBR”) AND (coral OR seagrass OR mangrove OR alga* OR microalga* OR crab OR snail OR sponge OR urchin OR fish OR turtle OR dugong OR eDNA OR “environmental DNA” OR microb* OR bacteria OR prokaryot* OR biota) AND NOT ("guided bone regeneration" OR "germ* brown rice")_	_10/122_	_7/34_
	**Total items online searches**	_**15 eligible of 857 (1.8%)**_	

Date (d/m/y)	Search strings: **Pharmaceutical and veterinary**	Sources
B) Manual search		
Date	Source	Number of items added
		0
	Total items manual searches	***0 (0%)***

Table 7f. Coal.

Date (d/m/y)	Search strings: **Coal**	Sources	
A) Academic databases		Web of Science	Scopus
14/03/2023	*(Coal or "fly ash" or "fly-ash") AND ("Great Barrier Reef" OR "GBR")*	*11/39*	*13/34*
14/03/2023	*(Coal or "fly ash" or "fly-ash") AND ("Great Barrier Reef" OR "GBR") AND (distribu* OR acum* OR monito* OR concentration* OR bioaccum* OR biomagni* OR level*)*	*7/12*	*9/16*
14/03/2023	*(Coal or "fly ash" or "fly-ash") AND ("Great Barrier Reef" OR "GBR") AND (water OR sediment)*	*10/20*	*11/19*
14/03/2023	*(Coal or "fly ash" or "fly-ash") AND ("Great Barrier Reef" OR "GBR") AND (marine OR estuar* OR wetland* OR river)*	*5/10*	*9/16*
14/03/2023	*(Coal or "fly ash" or "fly-ash") AND ("Great Barrier Reef" OR "GBR") AND (coral OR seagrass OR mangrove OR alga* OR microalga* OR crab OR snail OR sponge OR urchin OR fish OR turtle OR dugong OR eDNA OR "environmental DNA" OR microb* OR bacteria OR prokaryot* OR biota)*	*6/13*	*9/18*
	Total items online searches	***13 retained from 197 (6.6%)***	
B) Manual search			
Date	Source	Number of items added	
		0	
	Total items manual searches	***0 (0%)***	

Table 7g. Sunscreen.

Date (d/m/y)	Search Strings: **Sunscreen**	Sources	
A) Academic databases		Web of Science	Scopus
06/02/2023	*(sunscreen* OR "sun screen" OR suncream* OR "sun cream" OR oxybenzone) AND ("Great Barrier Reef" OR "GBR" OR Queensland)*	*6/137*	*1/74*
06/02/2023	*(sunscreen* OR "sun screen" OR suncream* OR "sun cream" OR oxybenzone) AND ("Great Barrier Reef" OR "GBR" OR Queensland) AND (distribu* OR acum* OR monito* OR concentration* OR bioaccum* OR biomagni* OR level*)*	*6/60*	*1/25*
06/02/2023	*(sunscreen* OR "sun screen" OR suncream* OR "sun cream" OR oxybenzone) AND ("Great Barrier Reef" OR "GBR" OR Queensland) AND (water OR sediment)*	*4/10*	*1/6*
06/02/2023	*(sunscreen* OR "sun screen" OR suncream* OR "sun cream" OR oxybenzone) AND ("Great Barrier Reef" OR "GBR" OR Queensland) AND (marine OR estuar* OR wetland* OR river)*	*3/17*	*0/3*
06/02/2023	*(sunscreen* OR "sun screen" OR suncream* OR "sun cream" OR oxybenzone) AND ("Great Barrier Reef" OR "GBR" OR Queensland) AND (coral OR seagrass OR mangrove OR alga* OR microalga* OR crab OR snail OR sponge OR urchin OR fish OR turtle OR dugong OR eDNA OR "environmental DNA" OR microb* OR bacteria OR prokaryot* OR biota)*	*5/21*	*0/4*
	Total items online searches	***6 relevant of 357 (1.7%)***	
B) Manual search			
Date	Source	Number of items added	
	Author personal collection	*2*	
	Total items manual searches	***2 (<1%)***	

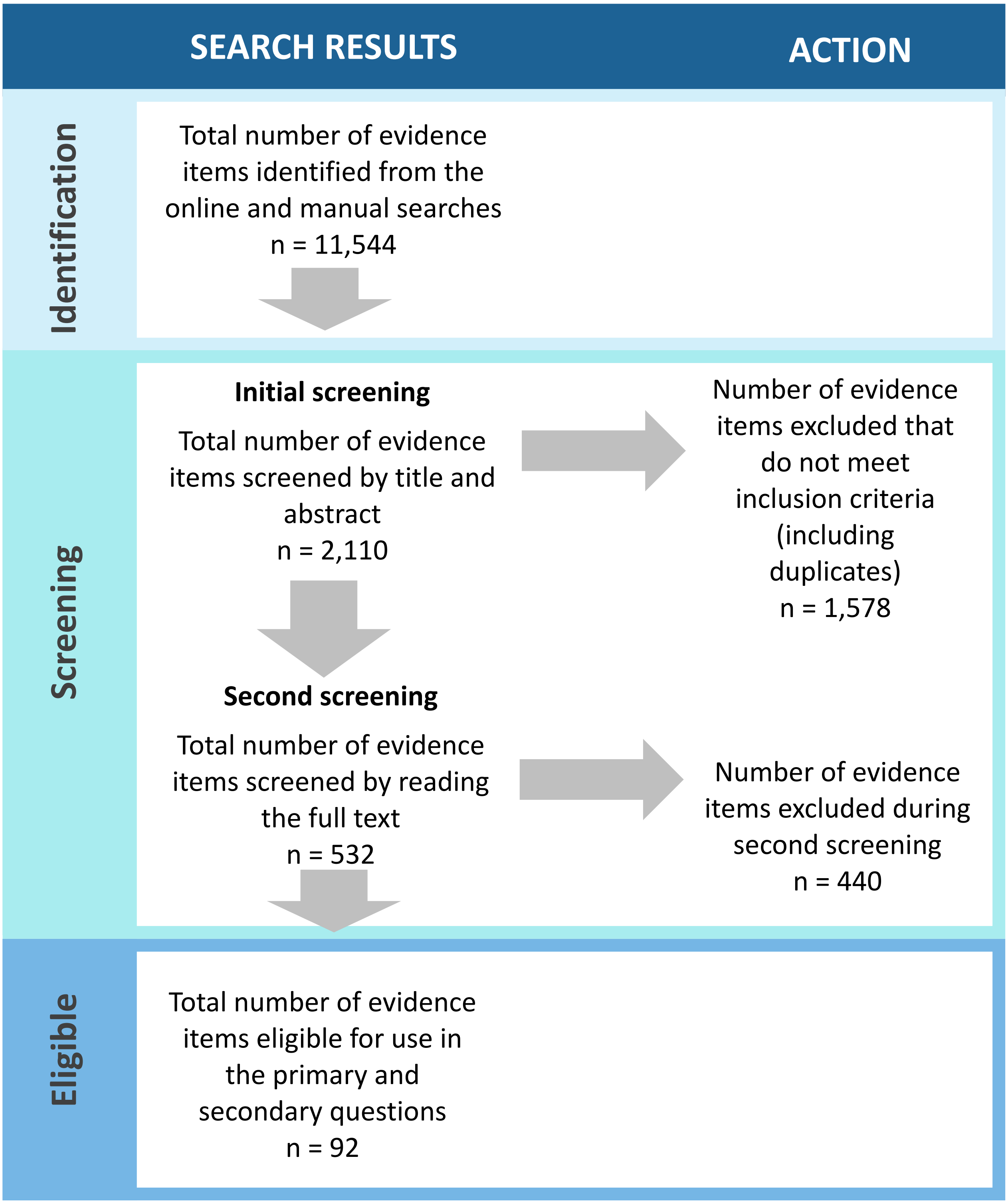

Figure 2. Flow chart of results of screening and assessing all search results for Question 6.1.

4. Key Findings

4.1 Narrative synthesis

4.1.1 Study characteristics and Summary of evidence to 2022

i. Metals

Study characteristics

In total, forty-four studies were deemed acceptable for extracting metal concentration and risk data used for this question, including the sub-questions. The monitoring results of metals in waters and sediments undertaken as part of the Regional Report Cards (e.g., Gladstone, Dry Tropics and Mackay Whitsunday) were not included in this review as the raw data is not published and publicly available. Summary statistics of the results are included in the Technical Reports and Report Cards.

For the primary question "What is the spatial and temporal distribution of **metals** in GBR ecosystems?", thirty-three observational studies were used. Figure 3 illustrates the number of studies in different locations where metal data was extracted. It should be noted that this includes: location specific studies (e.g., a particular island or catchment); gradient studies, which sampled from the coast (or estuary) to offshore reef environments; and large-scale studies which sampled over distances of more than 500 kms. In the case of the latter, these were generally opportunistic studies, e.g., the collection of tissues from deceased dugongs (Haynes et al., 2005) or samples from surveys of species with a wide distribution (e.g., turtles). In many cases, these studies did not comprehensively cover the entire range, with samples patchily collected across the range.

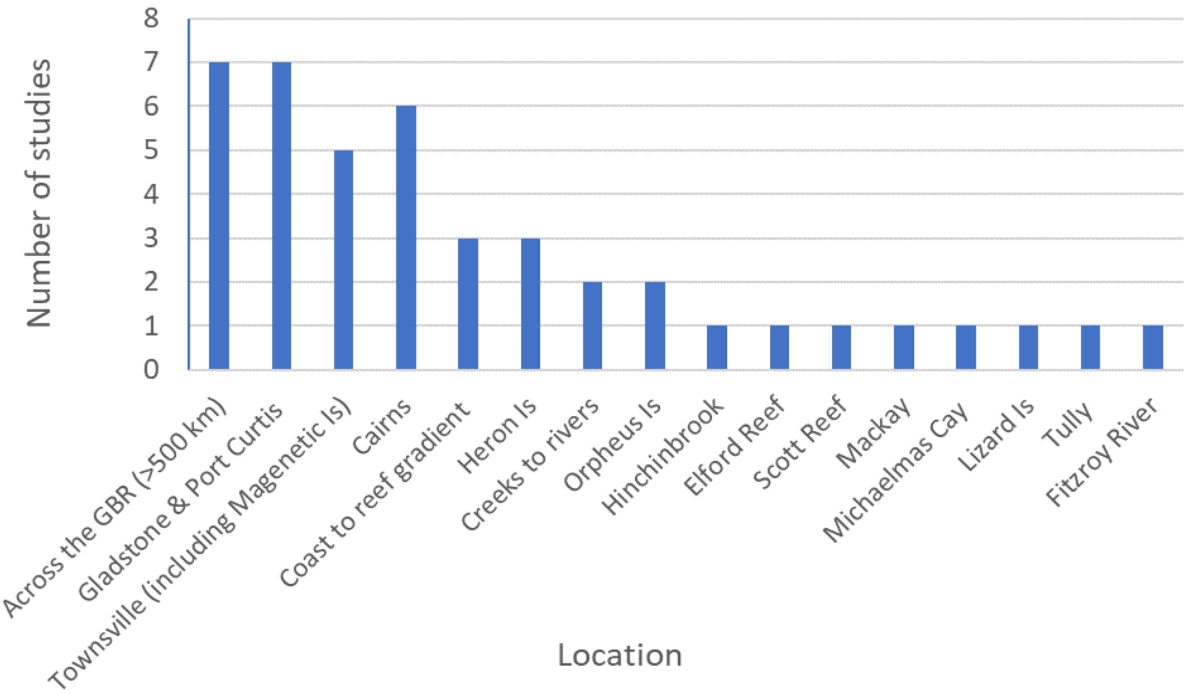

Figure 3. Number of studies from each location, region or system type where metal concentration data were extracted from suitable studies. Note some studies obtained data from one or more of these locations. Some locations associated with the 'Across the GBR (>500 km)', 'Coast to reef gradients' and 'Creeks to rivers' classes are not captured in specific location classes.

For each aspect discussed below:

- Seven studies were used to examine metal concentrations in waters.
- No selected studies for this question examined *in situ* concentrations of metals concurrently with biological or ecological endpoints.
- Fourteen studies were deemed suitable for extracting metal data on soils and sediments.
- Fourteen studies were used to obtain metal data from biota.

Summary of evidence to 2022

Metals in waters

A vast majority of the metal concentration data for waters were retained in non-peer reviewed material and were therefore excluded for this question (e.g., monitoring data reported in the Regional Report Cards). Only seven studies were used to examine metal concentrations in waters (Figure 4).

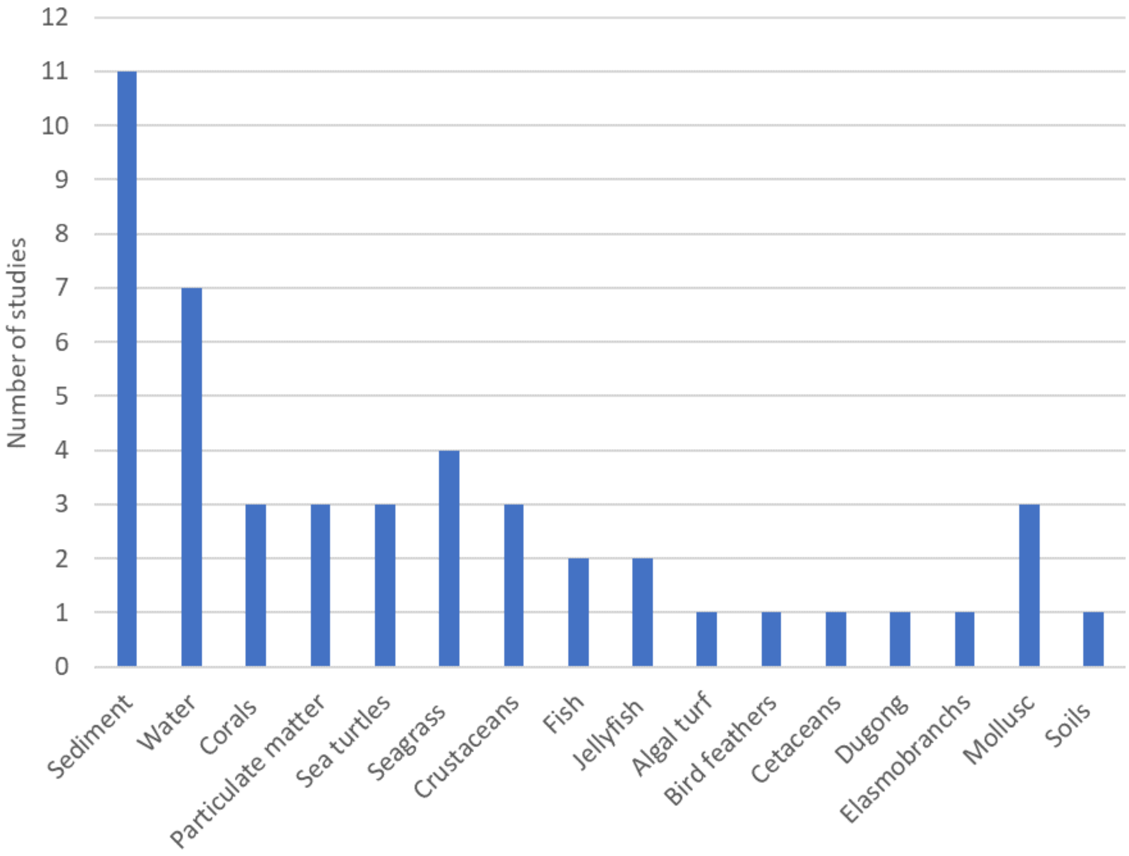

Figure 4. Environmental and biological matrices metal data were obtained from and the number of studies associated with each matrix. NB: some studies examined more than one matrix.

Spatial Patterns

Metal concentrations from waters were only examined in seven studies and were limited to only a few regions across the breadth of the GBR. Two studies were from Townsville (da Silva et al., 2004; Esslemont, 2000); two were from Port Curtis (Angel et al., 2010; Jones et al., 2005); one from an acid sulfate affected part of Trinity Bay, Cairns (Cook et al., 2000; one from Tully sugarcane fields (Turull et al., 2018); and one from a freshwater catchment of the Fitzroy Basin (Jones et al., 2019). Collectively, these studies all examined systems where catchment activities, e.g., urbanisation, mining and acid sulfate soils (ASS) were known to occur, and consequently, metal concentrations within the water bodies are likely to be enriched above background concentrations.

From this limited number of papers, the evidence suggests that metal concentrations are higher in more industrial and developed inshore environments. For example, in Port Curtis, dissolved concentrations of Manganese (Mn) were up to 19 µg L^{-1}L in the southern region of The Narrows (Targinne), almost three times higher than the maximum measured concentrations in other parts of The Narrows (Angel et al., 2010). However, all the values were below the current interim value of 80 µg L^{-1}. Similarly, dissolved concentrations of cadmium (Cd), copper (Cu), chromium (Cr), nickel (Ni), lead (Pb) and zinc (Zn) in the waters of Port Curtis generally declined in a downstream direction, and were consistently below guideline values for 95% protection (ANZG, 2018).

Esslemont (2000) found that dissolved concentrations of Cd, Cu and Pb were below guideline values in the waters from Townsville Harbour, Orpheus Island and Magnetic Island. However, it should be noted that the sample size was only two. In a study which measured Cd in the waters from Townsville Harbour and upstream into a creek (da Silva et al., 2004), concentrations were below (max 0.3 µg L^{-1}) the guideline value of 0.8 µg L^{-1} for 99% protection (ANZG, 2018).

The waters with the most enriched concentrations of metals were those associated with the acid sulfate soils from Trinity Bay (Cook et al., 2000). The freshwater discharge sites in this system had aluminium (Al) concentrations as high as 190,000 µg L^{-1}, with the guideline value being 0.8 µg L^{-1} in freshwaters with a pHh<6.5 (ANZG, 2018). Zn was also significantly enriched with a maximum concentration of 2,000 µg L^{-1}, where the guideline value for Zn is 8 µg L^{-1} (ANZG, 2018). Concentrations in the receiving marine waters of this system were markedly lower, with Al and Zn concentrations being 510 µg L^{-1} and 190 µg L^{-1}, respectively. While the guideline value for Zn is the same for both freshwater and marine waters (8 µg L^{-1}, 95% level of species protection), the water quality guideline value for Al in marine waters is 56 µg L^{-1} (95% protection of species) (van Dam et al., 2018), and consequently was still very much exceeded in the receiving marine waters.

In the southern GBR, upstream (freshwater) sites of the Fitzroy Basin, where there are active and legacy mines, had a median dissolved Cu concentration of 223 Cu µg L^{-1} (Jones et al., 2019), where the guideline value is 1.4 µg L^{-1} in freshwaters (ANZG, 2018). A similar but less pronounced trend was observed in the same study with Zn, where the median dissolved concentration in the upper reaches was 149 µg L^{-1} and the guideline value is 8 µg L^{-1} with 95% protection (ANZG, 2018).

One study in the Tully catchment examined mercury (Hg) concentrations in the freshwaters of sugarcane fields associated with the use of an organomercury fungicide (Turull et al., 2018). A number of sites had total Hg concentrations in water ranging from approximately 0.072 – 0.082 µg L^{-1}, exceeding the 99% level of protection guideline value of 0.06 µg L^{-1} (ANZG, 2018).

There were no identified studies that met the search criteria that had routine monitoring programs for metals in waters. Only one study had temporally replicated water measurements of metals (two occasions) (Angel et al., 2010). As a result, no temporal patterns could be extracted on the distribution of metals in the waters of the GBR. The monitoring results of metals in waters undertaken as part of the Regional Report Cards (e.g., Gladstone, Dry Tropics and Mackay Whitsunday) were not included in this review as the raw data is not published and publicly available. Summary statistics of the results are included in the Technical Reports and Report Cards.

Risks of metals in water

Metals speciation is an important factor for determining metal bioavailability and ecological risk, however, it is rarely considered in the assessment and reporting of ecological risk in the GBR. No selected studies for this question examined *in situ* concentrations of metals concurrently with biological or ecological endpoints. Consequently, risk is constrained to comparisons with national water quality guideline values. However, there are several important caveats associated with this: guidelines do not exist for all metals; some metals have guideline values which are of poor or unknown reliability; and the guidelines are generally derived from temperate and not tropical taxa, therefore, sensitivities may differ between temperate and tropical taxa (Peters et al., 1997).

The concentrations for a number of metals in the freshwater catchment of the Fitzroy Basin far exceeded national water quality guideline values (Jones et al., 2019), and consequently pose a significant risk to aquatic life. Similarly, the exceedingly high concentrations of dissolved Al and Zn derived from ASS poses a significant risk to the biota within Trinity Bay's freshwater and marine environments. Although there is no guideline value for Al in marine waters, concentrations in the marine component of Trinity Bay were almost an order of magnitude greater than the guideline value for alkaline freshwaters (pH >6.5) (ANZG, 2018).

The single study which examined Hg concentrations associated with fungicide use in sugarcane fields detected concentrations of approx. 0.085 µg L^{-1}, exceeding the guideline value of 0.06 µg L^{-1} for 99% protection. Even though the system is disturbed, normally on requiring a 95% protection, a higher level of protection is suggested due to the capacity of Hg to biomagnify and insufficient data associated with methyl mercury (ANZG, 2018). Consequently, there is evidence to suggest that Hg may pose an ecological risk to some of the freshwater components of this system.

There is no available evidence to suggest that dissolved metal concentrations within Port Curtis, including the more industrialised parts of the estuary, exceeded national water quality guidelines however some concentrations of metals reported were elevated compared to those found in adjacent coastal waters and estuaries (Angel et al., 2010; Jones et al., 2005). Although data are limited, concentrations of metals appeared to be below guideline values in Townsville Harbour, Magnetic Island and Orpheus Island (da Silva et al., 2004; Esslemont, 2000). However, it is emphasised that the small sample size hinders a valid estimate of the risks. Furthermore, the data is more than two decades old.

In addition to the *in situ* studies described above, there were 12 laboratory ecotoxicological studies which examined the toxicity of dissolved metals on corals sourced from the GBR. From these studies, Cu was shown to impede fertilisation and larval development of corals with an IC50 (half maximal inhibitory concentration) of between 16 and 17.4 µg Cu L^{-1} (Gissi et al., 2017; Negri & Heyward, 2001). No Observed Effect Concentrations (NOECs, i.e., the highest tested concentration where no effect was observed) for Cu in local species has been shown to range between 16.5 µg L^{-1} to 69 µg L^{-1} (Reichelt-Brushett & Harrison, 2005; Reichelt-Brushett & Michalek-Wagner, 2005), although they were generally around the centre of these two values (Reichelt-Brushett & Hudspith, 2016). In an ecotoxicological assay using adult coral and their microbiomes, Gissi et al. (2019), observed bleaching in adult specimens at a Cu concentration of 32 µg L^{-1}. In the same study, bacterial and eukaryotic components of the microbiomes were altered at concentrations of 32 µg L^{-1} and 65 µg L^{-1}, respectively. Collectively, these studies suggest that early life stages of corals are affected at concentrations above the guideline value of 5.5 µg Cu L^{-1} for 95% protection. As such, there is little evidence to suggest that concentrations observed in Port Curtis and Townsville (and adjacent islands) are sufficient to cause toxicity in coral larvae as they are consistently below the guideline values and the IC50s and NOECS from ecotoxicological assays. However, it should be noted that bleaching was observed in adult specimens after a relatively short exposure period (36 hrs) at a concentration of 32 µg L^{-1} (Gissi et al., 2019).

In coral larval assays, no effects were observed at a cobalt (Co) concentration of 2,500 µg L^{-1}, nor did the addition of Ni have any noticeable effect on toxicity (Reichelt-Brushett & Hudspith, 2016). A Ni concentration of 470 µg L^{-1} was shown to discolour an adult species of coral as well as alter its eukaryotic microbiomes, including their zooxanthellae (Gissi et al., 2019). In larval corals, no effects were observed at Cd concentrations of both 1,000 µg L^{-1} and 2,000 µg L^{-1} (Reichelt-Brushett & Harrison, 2005; Reichelt-Brushett & Hudspith, 2016), and a Zn concentration of 500 µg L^{-1} (Reichelt-Brushett & Hudspith, 2016). The mean NOEC for Pb was 2,232 µg L^{-1}, and ranged between 451 and 5,444 µg L^{-1} (Reichelt-Brushett & Harrison, 2005). All NOECS were considerably above guideline values, indicating that concentrations observed in Port Curtis and Townsville are unlikely to be of risk to corals.

One experimental study examined the interaction between dissolved metals, in this case Cu, and temperature (Negri & Hoogenboom, 2011). The study used larval metamorphosis in the endemic corals *Acropora millepora* and *Acropora tenuis* and found that reducing Cu concentrations by half roughly equated protecting the corals from a 2-3°C increase in sea surface temperature. To date, this is the only known study to examine the interactions between temperature and dissolved metals in corals from the GBR.

Sources of metals in water

In the Fitzroy Basin located in the southern region of the GBR, a significant source of metals within the water column was associated with active and inactive coal mines including legacy gold (Au), Cu and silver (Ag) mines (Jones et al., 2019). These metals were predominantly found in the upper catchment (freshwater streams and creeks) and were markedly pronounced in some creeks and streams, e.g., Callide Creek, where Cu and Zn concentrations exceeded guideline values in 98% and 69% of the samples, respectively.

Other known sources of metal enriched waters included sites within the Port Curtis, Rockhampton region, with the primary sources associated with mining and industrial activities within the catchment (Angel et al., 2010). Metal processing and heavy industry were associated with elevated concentrations of metals in the water column from the Townsville region (Esslemont, 2000).

Enriched concentrations of Hg in some areas of the Tully catchment are likely due to the application of the fungicide Shirtan® 120, however, legacy mines are also a possible source in other parts of the catchment (Turull et al., 2018). Consequently, the sources and whether they still exist remains unknown (Turull et al., 2018).

Atmospheric deposition was also identified as a potential source of metals (Strzelec et al., 2020), however, it is unclear what the risks are associated with this source.

Metals in sediments and soils

Spatial patterns in sediments and soils

Fourteen studies were deemed suitable for extracting metal data on soils and sediments. These were predominantly from *in situ* surveys, however, metal data were also extracted from two biogeochemical process studies which used *in situ* sediments (Alongi et al., 1993; 2011). The studies captured a range of regions including: Cairns and Trinity Bay (Brady et al., 1994; Keene et al., 2010; Pratt & Lottermoser, 2007); Townsville and Magnetic Island (Esslemont, 2000; Gibbs, 1993; Inglis & Kross, 2000; Reichelt & Jones, 1994); Port Curtis (Angel et al., 2010; Jones et al., 2005); the Hinchinbrook Channel and offshore islands (Alongi et al., 1993); Mackay and offshore islands (Alongi et al., 1993); and the Tully catchment (Turull et al., 2018).

The highest concentrations of Mn were found in the sediments from Port Curtis (2,700 mg kg^{-1}) (Angel et al., 2010) and Townsville Harbour (1,200 mg kg^{-1}), with the latter associated with a dump site in Cleveland Bay (Reichelt & Jones, 1994). Concentrations in other parts of Townsville were generally lower by approximately a third (Gibbs, 1993). Other studies showed Mn concentrations of around 400-500 mg kg^{-1} in coastal sediments (Alongi et al., 1993), with concentrations substantially lower in offshore sediments (14-80 mg kg^{-1}) (Alongi et al., 1993).

The highest Cd concentrations were associated with ASS from Trinity Bay, where mean values ranged from 5 to 18 mg kg^{-1}, which far exceeded the guideline value of 1.5 mg kg^{-1} (Simpson et al., 2013). In marine sediments, Townsville Harbour had the highest concentrations of Cd (Gibbs, 1993) with a mean concentration of 0.9 mg kg^{-1}, although a maximum concentration of 1.8 mg kg^{-1} was reported, and was therefore above the guideline value. Cd concentrations from Port Curtis, Cairns, Magnetic Island and Orpheus Island were below the guideline value (Esslemont, 2000; Jones et al., 2005; Keene et al., 2010), including sediments associated with the road runoff from Cairns (Pratt & Lottermoser, 2007).

Al concentrations were rarely reported. Concentrations associated with ASS sediments from Trinity Bay, ranged between 1,700 and 4,000 mg kg^{-1} (Keene et al., 2010). In suspended materials from Port Curtis, Al concentrations ranged from 4,400 to 9,600 mg kg^{-1}. No guideline value is available for Al, with no baseline concentrations able to be determined from the extracted studies.

The highest arsenic (As) concentrations were reported in Port Curtis (mean 18 mg kg^{-1}, max: 36 mg kg^{-1}) (Jones et al., 2005). Arsenic concentrations ranged between 2.3 and 18.5 mg kg^{-1} in the ASS from Trinity Bay (Keene et al., 2010). As of December 2022, no Australian sediment guideline exist for As, however, the Canadian guideline values are 6 mg kg^{-1} and 33 mg kg^{-1}, for lowest and severe effect, respectively (Persaud et al., 1990). Consequently, if Port Curtis results were compared to the Canadian guideline values, the arsenic concentrations exceeded the severe guideline, with Trinity Bay exceeding the concentration for the lowest effect level.

Cu concentrations have been shown to be exceedingly high in the sediments from Townsville, especially Ross Creek, where concentrations as high as 1,422 mg kg^{-1} have been reported (Gibbs, 1993). This far exceeds the guideline value of 65 mg kg^{-1} and the Sediment Quality Guideline (SQG)-High of 270 mg kg^{-1}. Exceedances have also been shown near a dumping site in the same harbour (Reichelt & Jones, 1994), however, other locations in the harbour have shown concentrations to be below the guideline value

(Esslemont, 2000). Cu concentrations from the sediments of Port Curtis, Cairns, Magnetic Island, Orpheus Island and Trinity Bay were consistently below the guideline value (Angel et al., 2010; Brady et al., 1994; Esslemont, 2000; Jones et al., 2005; Pratt & Lottermoser, 2007), even in sites exposed to ASS (Keene et al., 2010).

Only one source had particulate Pb concentrations above guideline values. Concentrations of Pb in the Ross Creek which flows into Townsville Harbour had concentrations ranging from 209 to 811 mg kg^{-1} with the latter almost four times greater than the SQG-High of 220 mg kg^{-1} (Simpson et al., 2013). Sediments were markedly less contaminated in the harbour (40-53 mg kg^{-1}), with only one sample over the guideline value of 50 mg kg^{-1} (Simpson et al., 2013).

Port Curtis was the only location from the studies where chromium (Cr) exceeded the guideline value of 80 mg kg^{-1} (Jones et al., 2005). However, this was a maximum value (85 mg kg^{-1}) with the median (52 mg kg^{-1}) being below the guideline.

Particulate concentrations of Ni exceeded the sediment guideline value in sediments from Townsville, Port Curtis and Cairns (Gibbs, 1993; Jones et al., 2005; Pratt & Lottermoser, 2007; Reichelt & Jones, 1994). The highest concentrations were from Cleveland Bay, Townsville (178 mg kg^{-1}) (Reichelt & Jones, 1994) and in freshwater sediments from suburban Cairns (80 mg kg^{-1}) (Pratt & Lottermoser, 2007), where both sites exceeded the SQG-High of 52 mg kg^{-1} (Simpson et al., 2013).

Esslemont (2000) found very high concentrations of Zn (>3,800 mg kg^{-1}) in the sediments from Townsville Harbour. Similarly, Gibbs (1993) also found very high concentrations of Zn in the same system (>1,800 mg kg^{-1}), with both studies having concentrations far exceeding the SQG-High of 410 mg kg^{-1} (Simpson et al., 2013). Zn concentrations were also elevated in Cleveland Bay (up to 460 mg kg^{-1}), although concentrations were low (11 mg kg^{-1}) in other parts of the system away from the dump (Reichelt & Jones, 1994).

Hg was measured in the soils of the Tully Catchment associated with sugarcane fields (Turull et al., 2018). Concentrations were highest in the soils 1-2 m deep, with mean concentration of 0.077 µg kg^{-1}, and a maximum concentration of 0.264 mg kg^{-1} (Turull et al., 2018). The mean concentration in surficial soils was lower (0.064 mg kg^{-1}) with a maximum concentration of 0.199 mg kg^{-1} (Turull et al., 2018). Collectively, this study showed that the mean concentrations of Hg were below the guideline value of 0.15 mg kg^{-1} (Simpson et al., 2013), however, exceedances did occur in both the soils from the surficial and lower layers.

Risk for particulate metals

Whilst Mn is clearly elevated in several of the studies which sampled coastal developed regions, no sediment guideline value has yet to be established for Mn. However, there is a low reliability guideline value for Canada of 450 mg kg^{-1} (Persaud et al., 1990). This suggests that Mn concentrations in both Port Curtis and Townsville may be of sufficient concentration to be of ecological concern.

The highest As concentrations in sediments were reported in Port Curtis (mean 18 mg kg^{-1}, max: 36 mg kg^{-1}) (Jones et al., 2005). Particulate As ranged between 2.3 and 18.5 mg kg^{-1} in the ASS from Trinity Bay (Keene et al., 2010). As of December 2022, no Australian guideline values exist for As, however, the Canadian guideline values are 6 mg kg^{-1} and 33 mg kg^{-1}, for lowest and severe effect, respectively (Persaud et al., 1990). Consequently, Port Curtis exceeded the severe guideline value, with Trinity Bay exceeding the concentration for the lowest effect level.

Cu concentrations have been shown to be exceedingly high in the sediments from Townsville, especially Ross Creek, where concentrations as high as 1,422 mg kg^{-1} have been reported (Gibbs, 1993) far exceeding the guideline value of 65 mg kg^{-1} and the SQG-High of 270 mg kg^{-1}. Exceedances have also been shown near a dumping site in the same harbour (Reichelt & Jones, 1994).

The occasional exceedances of Hg in the soils of Tully catchment suggest that the concentrations in soils do pose an ecological risk (Turull et al., 2018). However, the full extent of Hg exposure and sources with the GBR remain unknown.

Only a single source examined correlative patterns between particulate metals (and hydrocarbons) and coastal macrobenthic communities (Inglis & Kross, 2000). This study was performed in two urban and three rural estuaries near Townsville. The study showed that Pb, Zn, Cu, Cd and total petroleum hydrocarbons (oils) were significantly elevated in the Ross Creek, with the strongest correlates with macrobenthic communities being Cu, Pb and hydrocarbons (Inglis & Kross, 2000). Consequently, this study showed correlative evidence that metals and hydrocarbon concentrations in the sediments of this region were likely altering the composition of macrobenthic communities (Inglis & Kross, 2000).

Sources of particulate metals

The primary sources for particulate metals were similar to those for dissolved metals: urbanisation (Reichelt & Jones, 1994); industry, including legacy and active mines (Angel et al., 2010; Brady et al., 1994; Gibbs, 1993; Inglis & Kross, 2000; Jones et al., 2005); agriculture (Turull et al., 2018); and acid sulfate soils (Keene et al., 2010). Additional sources included a dump site in Townsville Harbour (Reichelt & Jones, 1994) and road runoff (Pratt & Lottermoser, 2007).

Metals in biota

Spatial and temporal patterns of metals in biota

Fourteen studies were used to obtain metal data from biota. Collectively, these included samples taken from: seagrass, algal mats and turtle forage (Jones et al., 2005; Tebbett et al., 2022; Villa et al., 2017); fish (including elasmobranchs) (Hogstrand & Haux, 1996; Jones et al., 2000); cetaceans (Cagnazzi et al., 2020); dugongs (Haynes et al., 2005); marine turtles (Finlayson et al., 2021; Gaus et al., 2019); crustaceans (da Silva et al., 2004; Jones et al., 2000; Negri et al., 2009); molluscs (Jones et al., 2000; 2005); bird feathers (Burger & Gochfeld, 1991); zooplankton (da Silva et al., 2004); and corals (Esslemont, 1999; 2000; Reichelt-Brushett & McOrist, 2003).

The most spatially comprehensive study which examined metals in a biota was that by Negri et al. (2009), who sampled mud crabs from numerous catchments (Normanby, Barron, Johnstone, Tully, Herbert, Gordon Creek, Burdekin, O'Connell, Pioneer, Fitzroy and Burnett) on two occasions (2005 and 2006). In general, this study found no differences in concentrations between years, with the exception of Cu and Zn in crabs from the Johnstone being more elevated in 2005 when compared to 2006. Some spatial differences in metals were also observed. Most notably, As concentrations were more elevated in the Normanby (mean = 101; max = 186 mg kg^{-1}) and Johnstone (mean=64; max=258 mg kg^{-1}) catchments, when compared to the other systems where means ranged from 19-48 mg kg^{-1}, with a maximum of 83 mg kg^{-1}. Hg concentrations were elevated in the Tully (mean=1.38; max=3.5 mg $^{-1}$kg) and Herbert (mean 1.45 and max 5.9 mg kg^{-1}) catchments, compared to the other locations (means ranged from 0.24-0.62 mg kg^{-1}).

In a survey examining Zn concentrations in biota prior to the smelter being established in Townsville, Jones et al. (2000) found fish had a mean Zn concentration of 4.83 mg kg^{-1}, with a similar concentration in sharks. Cuttlefish/squid and prawns/bugs had higher mean concentrations of Zn, 13.89 mg kg^{-1} and 15.24 mg kg^{-1}, respectively.

Mean concentrations of Zn, Cu and Cd from the livers of Squirrelfish sampled from Elford Reef (off Cairns) and Scott Reef were lower than those from Bermuda (Hogstrand & Haux, 1996). However, the mean concentrations of Cd were 5 to 25 times higher (mean ranges 5.8-25 mg kg^{-1}), than Squirrelfish sampled in Bermuda (mean 1.0 mg/kg). A direct comparison of these fish to those sampled by Jones et al. (2000) is not possible as different species and tissues were examined.

Comparisons in the metal concentrations associated with algal turf from Orpheus and Lizard islands found higher concentrations of As, Co, Cr and Cu in the Orpheus Island samples (Tebbett et al., 2022). In Port Curtis, seagrasses in the middle of the harbour were found to be enriched in Al, As, Cd, Cu and Zn when compared to the reference site (Jones et al., 2005). A multi-year (2-3 years) study of green turtle forage did not find exceedance when compared to sediment guideline values (Thomas et al., 2020). However, coastal forage (Cleveland and Upstart bays) had up to two times higher concentrations of Co, iron (Fe) and vanadium (V) than the Howick Island Group (northern GBR), the latter location being three times more enriched in concentrations of strontium (Sr) (Thomas et al., 2020).

Finlayson et al. (2021) measured 26 trace elements in the blood of green turtles from two locations within the GBR (Port Curtis and Hervey Bay) and Moreton Bay. The study found that turtles from the heavily urbanised Moreton Bay (outside of the GBR) had higher concentrations of caesium (Cs), silver (Ag) and Zn than those from the two GBR locations. In another multi-elemental study of green turtles (Gaus et al., 2019), while the data were semi-quantitative, the findings suggested that a range of metals, including many with no known toxicological information, were more elevated in inshore turtles from Upstart Bay and Cleveland Bay when compared to those from the Howick Island Group. Furthermore, Co, tin (Sn) and molybdenum (Mo) were elevated in turtles from Upstart Bay when compared to Cleveland Bay. In another study, coastal turtles were found to have generally higher blood concentrations of Co, molybdenum (Mo), Mn, magnesium (Mg), As, antimony (Sb), and Pb (Villa et al., 2017).

One study opportunistically sampled metal in the livers of freshly deceased dugongs across a wide spatial scale (Haynes et al., 2005). This study found a range of metals (Al, Cd, Fe, Hg and Zn) to be significantly more elevated in the livers of mature dugongs compared to juveniles. Skin samples from snubfin and humpback dolphins showed higher concentrations of Zn and Ni in the snubfin dolphins (Cagnazzi et al., 2020). No differences were found between sexes in the snubfin dolphin (Cagnazzi et al., 2020). Furthermore, no differences in metal concentrations were found between humpback dolphins sampled from Port Curtis and the Fitzroy River (Cagnazzi et al., 2020).

Three studies measured metals in corals (Esslemont, 1999; 2000; Reichelt-Brushett & McOrist, 2003). In a study looking at metals in different components of corals (tissues, skeletons, gametes and zooxanthellae) from Magnetic Island and One Tree Island (Reichelt-Brushett & McOrist, 2003), two key findings were found: zooxanthellae accumulated higher concentrations of metals than coral tissues; and metal concentrations were higher in corals from Magnetic Island (inshore) than from One Tree Island (offshore) (Reichelt-Brushett & McOrist, 2003). Similarly, metals were found to be higher in the corals of Townsville Harbour when compared to the less modified areas of Orpheus and Magnetic Islands (Esslemont, 2000). However, patterns varied between species, tissues and extraction methodology (Esslemont, 2000). In addition, one study examined baseline metals in corals at Heron Island, with metals varying between species and location (reef and harbour) (Esslemont, 1999).

Risks of metals in biota

From the examined studies, determining the risks associated with metal concentrations within biological tissues is challenging due to the lack of studies which examined correlative relationships between body burdens of metals and a biological endpoint, and a paucity of baseline studies over a wide range of taxa and geographical areas.

Two studies found correlative patterns between metals and biological endpoint in green turtles (Finlayson et al., 2021; Gaus et al., 2019). Finlayson et al. (2021) found two *in vitro* endpoints to be correlated with metal concentrations in the blood. However, expression of these endpoints was significantly more pronounced in the turtles from Moreton Bay than those sampled from the GBR (Hervey Bay and Port Curtis). Similarly, correlations between the condition of turtles and metal concentrations from the blood and scutes of green turtles has also been observed (Gaus et al., 2019), with condition being lower in individuals sampled from inshore sites.

Prange and Dennison (2000) found that most metals (excluding Al) increased in seagrass following flood plumes, which may also have trophic implications for the species that feed on them. The same study also showed that metals did elicit sublethal effects (e.g., PSII efficiency), which potentially could be used as an indicator of exposure (Prange & Dennison, 2000).

Baseline data of Zn concentrations in a range of biota was obtained from Townsville Harbour prior to the establishment of the smelter (Jones et al., 2000). This study found that all seafoods had Zn concentrations below the Australian National Food Authority’s Maximum Residual Limit for Human Consumption of 150 mg kg^{-1}, (FSANZ, 1996), with fish having similar concentrations to others studies around the world. In addition, baseline data on mud crab from across a wide geographical range was also available, which clearly showed that metal concentrations were enriched in certain GBR catchments

(Negri et al., 2009), however, the risks of elevated metal concentrations in this species are yet to be elucidated.

Sources of metals in biota

The primary sources for the metals in biota are varied and were likely associated with a range, and often a mixture of, land uses including: mercury from sugarcane farming (Negri et al., 2009); sewage (Negri et al., 2009); a mix of land use sources in land-based runoff (Prange & Dennison, 2000); industry (active and inactive mines) (Jones et al., 2000; 2005; Negri et al., 2009; Tebbett et al., 2022) and diffuse sources from urbanisation (Cagnazzi et al., 2020; Esslemont, 1999; 2000; Finlayson et al., 2021; Gaus et al., 2019; Reichelt-Brushett & McOrist, 2003; Tebbett et al., 2022; Thomas et al., 2020).

Gaps associated with metals

The key knowledge gaps associated with determining the spatio-temporal patterns and risks associated with metals in waters, sediments and biological material include:

- For many metals there are no water or sediment guideline values, and in many cases the confidence associated with these values are low. Most notable is the absence of a sediment quality guideline for manganese.
- Guideline values are not specifically designed for the tropics and are generally derived from temperate species. Tropical species may differ in their toxicological responses to metals (Peters et al., 1997). Further analysis is required to determine the suitability of guidelines for tropical systems.
- In the case of sediment guidelines, the information is predominantly extracted from Canada and the US. These guidelines are very outdated.
- There are very few routine metal monitoring programs for the GBR with the exception of some monitoring within the Regional Report Cards for which the raw data is not publicly available. Consequently, it is not possible to truly understand how metals in all matrices change over space and time. Some studies do provide the basis (Jones et al., 2000; Negri et al., 2009) but have not been repeated for many years. Without a consistent approach (methods, taxa, locations), no patterns can be clearly formed.
- Metal toxicity data for endemic GBR biota were primarily from corals and not coastal/estuarine species. Consequently, there is a dearth of information about how metals may be affecting the coastal species of the region, including benthos and fish. This is a significant data gap given that these taxa are residing in components of the system which are more likely to be exposed to metals than offshore species.
- Vary rarely did studies have a biological or ecological endpoint. Consequently, it is unclear whether elevated concentrations of metals pose a risk.
- Only a single study examined a community endpoint (macrobenthos) with environmental concentrations of metals (sediments) (Inglis & Kross, 2000). No studies examined community level relationships between metals and fish communities.
- There are numerous locations which are affected by ASS, however, Trinity Bay appears to be the only site studied. Given the concentrations in this system, it would seem highly possible that numerous other locations along the coast are being subjected to similar conditions (Kroon et al., 2020).
- Only one study examined the effects of a metal (copper) and temperature on an endemic species (corals) (Negri & Hoogenboom, 2011). The results from this study emphasised the importance of the interactive effects between metals and temperature.
- The extent of mercury use as a legacy fungicide from sugarcane farming is not known (Turull et al., 2018).
- Differences in methods (e.g., metal species and extractions), the type of tissues, including wet and dry weights hinders comparisons among studies.
- The framework used by the Australian water quality and sediment quality guidelines for determining the risks or the ecological condition of system is based on multiple lines of evidence. For example, environmental concentrations of a contaminant, its accumulation, and

biological or ecological endpoints (ANZG, 2018; Simpson et al., 2013). However, studies which used more than one line of evidence were rare, notable exceptions being (Finlayson et al., 2021; Gaus et al., 2019; Inglis & Kross, 2000; Prange & Dennison, 2000). Without an articulate and co-ordinated approach for monitoring metals it is not possible to determine their spatio-temporal patterns or risks within the GBR.

ii. Persistent Organic Pollutants (POPS)

Study characteristics

This section covers relevant studies on persistent organic pollutants (POPs) within the GBR. This includes: PAHs (polycyclic aromatic hydrocarbons), petroleum products (associated with land use), chlorinated PCDDs (polychlorinated-p-dioxins), PCDFs (polychlorinated dibenzofurans), PCBs (polychlorinated biphenyls) and HCB (hexachlorobenzene). It should be noted that in some studies multiple pollutants were measured in conjunction with POPs, e.g., metals (Andersen et al., 2008; Beale et al., 2017; Inglis & Kross, 2000; Melville et al., 2009) and oestrogens (Beale et al., 2017). Given the association between coal and PAHs, some components of coal are captured in this section as well as the following section specifically dedicated to coal. In total, 19 studies were used for the following section, including experimental studies of relevance. All studies captured one or more of the following regions, Mackay, Townsville, Fitzroy and Port Curtis; although some less developed areas along the coast and offshore were also included (Burns, 2014; Haynes et al., 2005; Müller et al., 1999; Shaw & Müller, 2005; Vijayasarathy et al., 2019a).

Summary of evidence to 2022

POPs in sediments and waters

Nine studies were found for POPs in sediments, sediment traps and waters. This included studies which looked at the diffuse dispersal of POPs (e.g., (Burns, 2014; Müller et al., 1999; Shaw & Müller, 2005), as well as more localised studies, e.g., following an oil spill in the Gladstone region (Andersen et al., 2008; Melville et al., 2009).

In a survey of Port Curtis one month after an oil spill (2006), POPs (and metals) were measured in the sediments near the spill site and reference sites (Andersen et al., 2008). A wide range of organics were significantly enriched in the impact sites, sometimes more than a magnitude greater than the reference sites. Acenaphthene, Fluorene, Phenanthrene, Pyrene all exceeded the High-SQG (H-SQG) (Simpson et al., 2013). Total PAHs, total low molecular weights, total high molecular weights, 2-Methylnaphthalene, Acenaphthylene, Anthracene, Benz(a)anthracene and Chrysene all exceeded the Low Sediment Quality Guideline (Low-SQG) (Simpson et al., 2013). After six months, total PAHs were below their guideline values, suggesting a reduction over time (Melville et al., 2009). No correlations between organic contaminants and macrobenthic community composition and abundance were observed at either one month or six months after the spill (Melville et al., 2009). Crab-hole density was initially negatively affected (Andersen et al., 2008), although appeared to have recovered after six months (Melville et al., 2009). However, mangrove health was negatively affected six months after the spill, as evident by an increase in seedling mortality and defoliation (Melville et al., 2009).

As previously indicated in the metals section, Inglis and Kross (2000), examined benthic communities along a polymetallic and total petroleum hydrocarbon (oil) gradient in Townsville Harbour, including Ross Creek. This study found strong correlations between the co-correlated contaminants (Cu, Pb and oil) and macrobenthic community structure.

In a multi-omics study which examined metals, organics and oestrogens in sediments from Gladstone Harbour, Fitzroy Reef and Heron Island, the authors found all sediments had concentrations of organics (and metals) below guideline values (Beale et al., 2017). However, oestrogen concentrations were more elevated in sites away from Gladstone Harbour (Beale et al., 2017). For example, (estrone) E1 at a sediment depth of 10 cm from Fitzroy Reef was 0.19 $\mu g\ g^{-1}$, with Heron Island having sediment concentrations of E1 ranging between 0.02–5.59 $\mu g\ g^{-1}$ (Beale et al., 2017). In contrast, concentrations of E1 in the sediments from Gladstone Harbour ranged between 0.07–0.4 $\mu g\ g^{-1}$ (Beale et al., 2017).

In a reinterpretation of the dataset obtained by Burns and Brinkman (2011), Burns (2014), evaluated the cumulative toxicity of a wide range of organic contaminants from sediments and sediment traps sampled in a gradient from the Mackay region. This included coastal, offshore and reef sites. This study demonstrated that the coastal sediments offshore from the Hay Point coal port were already contaminated with coal residues. Furthermore, when examined collectively, PAHs in the suspended sediments were higher in coastal sites, close to coal stockpiles and loading facilities and were still detectable 40 nautical miles from the coast.

Müller et al. (1999) sampled sediments from five sites from Mackay to Far North Queensland (Newry Bay, Upstart Bay, Pallarenda (Townsville), Cardwell and Flinders Island) for dioxins, i.e., highly chlorinated PCDDs (polychlorinated dibenzodioxins), PCDFs (dibenzofurans), selected PCBs and HCBs. A range of PCDD's and PCDF's were detected in all sites. Octochlorobdibenzo-p-dioxin was the dominant PCDD/PCDF in all cases, with concentrations ranging from 17,500 pg g^{-1} in Upstart Bay to 130,000 pg g^{-1} in Cardwell, although concentrations were less than half of those sampled in the least contaminated Brisbane site. Concentrations of all PCDD/PCDE congeners were lower in the GBR sites than the Brisbane sites. The concentrations varied greatly among the GBR sites, as indicated by the Σ PCDDs/PCDFs Upstart Bay (18,000); Flinders Island (28,000); Pallarenda (91,000); Cardwell (149,000); and Newry Bay (210,000). PCBs and HCBs were below detection in all samples.

As a means of examining the potential of PCDDs in the diets of dugongs, McLachlan et al. (2001) sampled seagrass and sediments as well as the blubber from three stranded dugongs. Sediment and seagrass samples were taken from five sites from Mackay (Newry Island) to Far North Queensland (Flinders Island), and included Upstart Bay, Pallarenda and Cardwell. Dugongs were only obtained between Mackay and Townsville, and it is emphasised that only one individual was sampled at each location. In sediments and seagrass, concentrations of PCDD/F were predominantly associated with Cl8DD, approximately 90 % of the 3,7,8-substituted congeners in all samples, with PCDFs and 2,3,7,8-Cl4DD being below detection. Sediment concentrations of Cl8DD varied greatly across the sites, for example, Cardwell had a mean concentration of 1,200 pg g^{-1}, compared to Upstart Bay (14 pg g^{-1}). Concentrations in Newry Bay were approximately half of those from Cardwell but were still almost an order magnitude higher than Pallarenda and Flinders Island. Concentrations of Cl8DD in the seagrass were strongly correlated with the sediment and ranged from 49 pg g $^{-1}$ (Upstart Bay) to 1,300 pg/g (Cardwell). Given the small sample size and lack of replication, the relationship between sediment and seagrass and the concentrations of PCDDs in the dugongs is not discussed in this review.

Using passive samplers, Shaw and Müller (2005) sampled the water columns of eight sites from Townsville to Port Douglas (Double Island, Fitzroy Island, High Island, Normanby Island, Russell-Mulgrave River, Johnstone River, South Barnard and Dunk Island), for PAHs (and pesticides) during the dry (November 2003) and wet season (January 2004). PAH concentrations were consistently below their detection limits. Although this suggests that concentrations are very low in the sampled locations, it is emphasised that the samplers were only placed in the environment for a short duration (8-11 days), and when placed in the river mouths for 50 days (in the late wet season), low concentrations (pg L^{-1} levels) of higher molecular weight PAHs were detected (Shaw & Müller, 2005).

POPS in biota

A suite of organic compounds was measured from biopsies taken from live humpback and snubfin dolphins from the Fitzroy and Mackay Whitsunday regions (Cagnazzi et al., 2013). In addition to pesticides, POP analysis included PCBs, HCBs, and a wide range of PAHs. Whilst the small and unequal sample size (species and catchment) did not permit statistical comparisons, the findings of this study suggested that low-molecular weight (water soluble) PAHS were the most abundant POP, with these being dominated by naphthalene and pyrene (Cagnazzi et al., 2013). Furthermore, concentrations generally appeared to be higher than cetaceans surveyed overseas (Cagnazzi et al., 2013). Speculatively (given the sample size), concentrations of POPs appeared to be higher in the Fitzroy sampled dolphins than those from the Mackay Whitsunday region (Cagnazzi et al., 2013). Temporal and spatial trends of these two species have also been examined, specifically comparing individuals from Port Curtis and the Fitzroy estuary before and after the 2010 floods and the expansion of Port Curtis (Cagnazzi et al., 2020).

All 30 measured PCB congeners and HCB were above detectable levels in all 35 samples, the ΣPCBs varied greatly among individuals, however, HCBs were generally low. No differences in POPs were found between male and female humpback dolphins, and no statistical comparison could be made between the sexes of the snubfin dolphins. In general, no differences were found between the humpback dolphins from both catchments, however HCB was higher in the humpback dolphins from the Fitzroy estuary when compared to the snubfin dolphins from the same catchment. PCBs in both species collected post-flood (2014-16) in the Fitzroy were higher than those collected in 2009-10 (Cagnazzi et al., 2020). HCB concentrations were also higher in dolphins from both systems in the later sampling period. PCBs in humpback dolphins from Port Curtis were similar before and after the expansion/floods. Overall, significant increases in the concentrations of PCBs (2.2 times higher), and HCB (7.0 times higher) were observed between the pre (2009–2010) and post (2014–2016) flood and port expansion sampling periods (Cagnazzi et al., 2020).

Vijayasarathy et al. (2019b) sampled PCDD/F and PCB levels in a range of tissues from five dugongs from Townsville and Hinchinbrook and compared these to southeast Queensland. PCDDs were detected in all samples, although PCDFs were near or below levels of quantification. Although no statistical comparisons can be made due to the small sample size, the data suggest, that in these individuals, concentrations of all measured PCDFF/ and PCB were lower in the tissues from the individuals sampled in the GBR when compared to southeast Queensland. In opportunistic collection of dugong samples (described above in the metals section), HCB was only detected in one of the 38 samples (Haynes et al., 2005). Whilst PCBs were analysed, the authors never mentioned the findings, and hence it is assumed that concentrations were below detection or of environmental insignificance.

Baseline PAH concentrations from the blood of green turtles were obtained from three populations, reflecting different land uses: the Howick Island Group (remote and offshore); Cleveland Bay (Townsville, urban and industrial); and Upstart Bay (agricultural runoff from the Burdekin River) (Vijayasarathy et al., 2019a). In general, concentrations were low and below those observed around the world (Vijayasarathy et al., 2019a). In all three locations, the PAHS were predominantly three ringed (50–60%) and four ringed PAHs (25–40%). Five and six ringed PAHs were detected in both the Cleveland and Upstart Bay turtles, but not in the turtles sampled from the Howick Group (Vijayasarathy et al., 2019a). In a study looking at the relationships between proteomic patterns and anthropogenic pollutants in the blood of green turtles from the Port of Gladstone and Hervey Bay, the authors generally only found low concentrations of POPs, and these were most likely not leading to any differences in protein expressions (Chaousis et al., 2023).

van Oosterom et al. (2010) measured metabolite concentrations of naphthalene and benzo(a)pyrene in mud crab (*Scylla serrata)* hepatopancreas, haemolymph and urine from the Normanby, Herbert, Burdekin and Fitzroy Rivers. No differences in naphthalene metabolite concentrations measured in crab urine were found between the four estuaries. However, some differences in the mean concentrations of the benzo(a)pyrene metabolite were observed. Concentrations were lowest in the Burdekin (0.47 ± 0.04 μg mg_{-1} protein), the Normanby (0.83 ± 0.25 μg mg^{-1} protein) and Herbert River had similar concentrations (0.90 ± 0.15 μg mg^{-1} protein), with the highest mean concentration occurring in the Fitzroy River (1.1 ± 0.1 μg mg^{-1} protein).

Risks of POPs

Several studies based on ecotoxicological experiments were used to aid in understanding the risk of organic contaminants to the GBR's biota (Ashok et al., 2020; 2022; Johansen et al., 2017; Nordborg et al., 2018). For example, the exposure of six fish species to crude oil at ≤5.7 µg L^{-1}, which is considered to be an environmentally relevant concentration for the GBR (Johansen et al., 2017), had a range of toxic effects including increased mortality and retardation of growth rates (Johansen et al., 2017). The study also found indications that oil exposure affected cognitive processes, as reflected in anti-predatory behaviour and habitat choice selection (Johansen et al., 2017). Consequently, survivorship may be further reduced beyond traditional toxicology (Johansen et al., 2017). With respect to marine fuels (both heavy fuel oil and diesel), a coral settlement success assay found that ultraviolet radiation increased heavy fuel oil toxicity, reducing the EC50 by approximately 50% (Nordborg et al., 2018). Although less toxic, diesel toxicity was similarly increased by the presence of ultraviolet radiation. These findings suggest that surface water species and life stages (including coral gametes, larvae and embryos) may be more susceptible to fuel spills, and therefore the risk may be underestimated if ultraviolet radiation is not taken into consideration (Nordborg et al., 2018). Experimental studies have also aided in understanding the trophic transfer of PAHs. For example, using labelled PAHs, it has been shown that phenanthrene can be accumulated from phytoplankton to coral (Ashok et al., 2020), and furthermore its accumulation in corals may be driven by the length of the food-chain (Ashok et al., 2022).

The study by Burns (2014) clearly showed that more than a decade ago, coastal and offshore sediments from Port of Hay Point had concentrations of PAHs which were detectable. However, it is unclear what the current concentrations in the region are, and whether they have spread further out into the GBR. The author highlighted that the current sediment guidelines used to assess PAH risk does not include biphenyl and dibenzothiophene series, and if included, the estimated toxicity value would be higher. Consequently, current approaches may be underestimating the risk of PAHs. Whilst concentrations of PAHs were low in the water of the GBR (Shaw & Müller, 2005), this is not unexpected given that these compounds are hydrophobic (Müller et al., 1999).

Based on the studies from this review, the risk of PAHs in the sediments from Port Curtis was directly linked to an oil spill event and appears to have diminished over time (Melville et al., 2009), although the long-term effect on mangrove condition was not documented beyond six months (Müller et al., 1999).

While it is difficult to extrapolate the risks, Cagnazzi et al. (2020) suggest that either in isolation or collectively, large flood events and port expansion may be increasing the concentrations of some POPs in dolphins. However, given that these two events happened simultaneously, it is not possible to determine which was the primary contributor. In contrast, while limited, the data from the studies suggest that the risk of POP exposure to green turtles was low in the GBR region in comparison to southeast Queensland and overseas (Vijayasarathy et al., 2019a).

The spatial and temporal patchiness of the data from the studies hinders extrapolating the risks associated with POPs in the GBR. For example, it is unclear whether the sources of PCDDs in seagrass and sediments were legacy or from more recent sources (McLachlan et al., 2001). Whilst PCBs and other POPS including HCB have been restricted in Australia for around four decades, they can still be imported under consent, and as such, it is unclear whether these pollutants are still entering the GBR environment (Cagnazzi et al., 2013). The persistence of PCBs, and to a lesser extent HCB, in the GBR was also raised in a review by Haynes and Johnson (2000). However, given the current lack of recent data, the risks for many POPs remain unknown.

Sources of POPs

The primary identified potential sources of POPs were associated with industry (Andersen et al., 2008; Burns, 2014; Cagnazzi et al., 2013; 2020; Haynes et al., 2005; Inglis & Kross, 2000; McLachlan et al., 2001; Müller et al., 1999; van Oosterom et al., 2010; Vijayasarathy et al., 2019a), oil spills (Andersen et al., 2008; Melville et al., 2009), coal (Burns, 2014), floods (Cagnazzi et al., 2020) and urbanisation (Haynes et al., 2005). However, some sources remain unclear, including whether restricted products, e.g., some PCB’s which can be imported with consent from the Department of Home Affairs, are still being used within the GBR (Cagnazzi et al., 2013; McLachlan et al., 2001).

Gaps in POPS

As illustrated here, there are some significant gaps associated with the diversity, spatial and temporal patterns, and risks of POPS across the GBR region. These include:

- A lack in spatial-temporal studies across the breadth of the GBR. Currently, no temporal trends on POPs are available and the distribution of data is very patchy. Data are predominantly from urbanised and industrialised environments, although there are indications that they occur in offshore environments (Burns, 2014).
- It is not known if restricted POPs are still being used under consent in the GBR, and if so, the types, volumes and locations of use (Cagnazzi et al., 2013).

- No studies were available on the interactions between POPs and temperature.
- No studies were available on the endocrine effects of POPS and their metabolites.
- The ecotoxicology of POPs has only been examined in very few species and life-stages.
- Further research is required to understand the interaction between ultraviolet radiation and toxicity, especially to surficial biota (Nordborg et al., 2018).
- The influence of floods and plumes on the distribution and risks of POPS, including their accumulation in cetaceans (Cagnazzi et al., 2020).
- The effect of Port of Hay Point and other expansions and initiatives on POP inputs and their exposure to biota (Burns, 2014).
- The current national sediment quality guidelines underestimate toxicity, and currently excludes biphenyl and dibenzothiophene. Sediment quality guidelines are old and need reassessing.
- It is not known if oestrogen levels detected in the sediments of islands are associated with endocrine disrupting POPs, or other sources, including natural (Beale et al., 2017).

iii. PFAS/Fire Retardants

Study characteristics

This section looked at studies associated with PFAS and flame retardants (PBDEs) in the GBR. After studies that were not relevant to the question were excluded, only one peer reviewed report "Queensland Ambient PFAS Monitoring Program 2019-2020" (Baddiley et al., 2020) and one scientific paper were retained (Hermanussen et al., 2008). However, in the case of the latter, which compared concentrations of PBDE's in marine turtles, only a single specimen was obtained from the GBR (Bundaberg region), with this being a Flatback turtle, and differing from the other species examined in the study. Consequently, no robust statement can be made with the exception that PBDE's were detected (ΣPBDEs=8.70 ng g^{-1} lipid weight) (Hermanussen et al., 2008). There were some additional scientific papers which examined PFAS in the freshwater turtle *Emydura macquarii macquarii* (Beale et al., 2022a; 2022b), however, for confidentiality reasons no details on the collection sites were provided. Furthermore, this is a freshwater species whose main distribution range is not within the GBR region, although it does occur in some freshwater rivers inland from the GBR (Atlas of Living Australia, 2023).

Summary of evidence to 2022

Given that the "Queensland Ambient PFAS Monitoring Program 2019-2020" was the only study considered suitable for this question, the following section summarises the findings of this report within the context of the GBR. Sampling was carried out in three Natural Resource Management (NRM) regions of interest to the current review, with the number of locations for each region provided in brackets: Wet Tropics (6), Mackay Whitsunday (7) and the Fitzroy (5) (Baddiley et al., 2020).

The Wet Tropics locations included the Daintree River (Cape Kimberley), Daintree River (Daintree), Armit Creek; Moresby River; Hinchinbrook Channel (North) and Hinchinbrook Channel (South). Water samples were collected on six occasions between May 2019 and March 2020. It should be noted that these sites were not adjacent to intensive land use (Baddiley et al., 2020). PFAS was rarely detected in any of the sites from the Wet Tropics. PFOS was reported at around the level of reporting (LOR) of 0.001 µg L^{-1} on at least one occasion in each location, with the highest PFOS concentration (0.004 µg L^{-1}) being reported on one occasion in Hinchinbrook (North). However, waters, including those from this site were generally below the limit of reporting (LOR). Only one sample, also from the northern end of Hinchinbrook had a reportable concentration (0.002 µg L^{-1}). Concentrations were too low in the Wet Tropics to determine whether there was a seasonal pattern. Sediment samples were taken from the Daintree River (Kimberley), with PFAS being below the LOR (0.001 mg kg^{-1}). No biota was sampled for PFAS in these regions.

PFAS was sampled in the water six times between May 2019 and March 2020 from seven locations within the Mackay Whitsunday region: Gregory River (Cape Gloucester); St Helens Creek; Vines Creek (Mackay); Sandy Creek (Sandiford); Sandy Creek (Eton); Rocky Dam Creek; and Carmila Creek. Across the sampling period, PFAS were only reported in Vines Creek, Sandy Creek (Eton) and Sandy Creek (Sandiford). The highest concentrations of PFOS were at Vines Creek (0.0047 µg L^{-1}), near an industrial area. PFOS was detected at this location on most sampling occasions, and was more pronounced after rainfall events, potentially associated with industrial runoff (Baddiley et al., 2020). In comparison, the sites located within Sandy Creek had concentrations around an order of magnitude lower than those reported for Vines Creek. Of the Vines Creek and Sandy Creek (Sandiford) samples, 50% contained low concentrations (just above LOR) of other PFAS (PFHxA, PFOA and PFHxS). No PFAS was detected in a sediment sample from Vines Creek, nor were precursors detected in the waters. The study detected PFOS above LOR in five out six fish species and in a prawn. The highest concentrations were in sea mullet (average=0.019 mg kg^{-1}; max=0.003 mg kg^{-1}).

In the Fitzroy region, two locations in the Fitzroy River (Barrage and Nerimbera), Auckland Creek, Calliope River and Boyne River were sampled. PFOS was the only PFAS reported in these systems, with concentrations consistently around the LOR. Water samples from the Auckland Creek, the Boyne River and Calliope River had no precursor PFAS, and sediments were below the LOR. Two out of the three fork-tailed catfish sampled in the Fitzroy River had reportable concentrations of PFOS (0.001 – 0.002 mg kg^{-1}), with no other PFAS being reported.

In summary, the report did not show any indications that PFAS were ubiquitous in the sampled areas of the GBR, and where reported were generally low, most likely as the locations were predominantly near conservation, agricultural and forestry areas. Concentrations were too low in the GBR to identify any seasonal patterns. While still low, long chain PFCAs were in biota and not water, with this being consistent with the literature. However, due to the capacity for PFAS to be transported great distances, there is the potential for estuaries to contain PFAS from a variety of sources, especially in estuaries which receive inputs from multiple sources. It is pertinent to note that this study did not examine highly industrialised regions of the GBR, e.g., Cleveland Bay and Port Curtis, consequently, it remains unclear if PFOS concentrations in these areas pose a risk.

iv. Plastics (including microplastics and fibres)

Study characteristics

This section provides an overview of the studies from the GBR associated with plastics in their various forms, i.e., large plastics, microplastics and fibres. A total of 19 studies were selected for this component of the review. These included surveys of plastics associated with marine debris in the environment (water and beaches), plastics in biota (birds, fish, turtles, macrobenthos and zooplankton) and experimental studies.

Summary of evidence to 2022

Plastics in water and sediments

Roman et al. (2021) performed extensive anthropogenic debris (AD) surveys of Queensland's marine environments, covering 13 uninhabited offshore islands, four inhabited/touristed coastal islands and 81 mainland beaches, including coastal and offshore sites in the GBR. The debris was classified as: hard plastic, soft plastic, plastic strap, fishing debris, cloth, glass, metal, rubber, foam, timber, paper and other debris (Roman et al., 2021). In contrast to southeast Queensland, debris was significantly lower on Heron Island, with Coral Sea sites containing significantly less items (per m^2) than coastal islands or the mainland. For the Coral Sea and coastal islands, debris was dominated by hard plastics. Although not specifically pertaining to the GBR region, as the source included data from southeast Queensland, findings of this study showed that geographic factors were more strongly correlated with density on islands than with mainland beaches, and that hard plastic density was linked with wind forcings and sea surface currents. On islands, beach width and onshore/side-shore forcing were the most important factors influencing hard plastic loads. Furthermore, there was an inverse relationship between beached plastic and nearby sea-float plastic, indicating that islands are like a repository for buoyant plastic (Roman et al., 2021).

The potential influence of tourism on marine debris was assessed by sampling shoreline debris over a three-year period on two isolated islands (Wreck and Tryon) and two popular tourist destinations (Heron and Northwest), all located in the Capricorn-Bunker Group east of Rockhampton (Wilson & Verlis, 2017). The largest number of items recovered during a sampling event was 706, from Wreck

Island, with Tryon Island having the lowest (130 items). The accumulation rate was highest on the windward side of Wreck Island, equating to approximately 0.1 items m^2. In contrast, 0.01 items m^2 were observed on the leeward side of Northwest Island. Overall, windward sites of the islands accumulated significantly more debris than leeway sides, adding credence to the above study by Roman et al. (2021). Plastics were the most common debris (68-92%). Northwest and Heron islands had debris which was indicative of visitors, e.g., plastic wrappers and cigarette butts, and in general, inland sourced debris loads were higher in Heron (47%) and Northwest (25%) islands, than Tryon and Wreck (3% each). About 20-23% of the waste for Tryon and Wreck was associated with commercial shipping and boating, as well as commercial and recreational fishing. Collectively, the study indicates that tourism is major source of debris in the islands with high tourism, and in many cases, this is associated with the incorrect disposal of waste (Wilson & Verlis, 2017).

In a three-year survey of debris from the Ross River (Townsville), almost 28,000 debris items were collected, with the vast majority (92%) of these items being plastics (Bauer-Civiello et al., 2019). The plastics consisted mainly of food packaging, straws, drink bottles and bottle caps (Bauer-Civiello et al., 2019). While differences were observed over time and between the sampled sites, marked increases (often threefold) were observed in most types of plastics after a rain event. Although sampling only occurred over three years, there was a decline in the amount of waste collected (per effort) over time. The study also found that inland sources outside of the river systems themselves were a major source, including adjacent parklands (Bauer-Civiello et al., 2019). This emphasises the potential that on-ground actions, e.g., programs to reduce littering, may be beneficial (Bauer-Civiello et al., 2019).

In a survey of the surface waters of the Whitsunday region, the most common morphologies of plastics were fibres (47%) and fragments (32%), with the colours mostly commonly being blue (47%), clear (16 %) and black (12%) (Carbery et al., 2022). The mean surface concentration of plastics was 0.23 ± 0.03 particles m^3. The most common size fractions were 50-300 μm (49%) and 300 μm – 1 mm (46%), with only 5% of the plastics being between 1 and 5 mm. Microbeads and pre-production plastic pellets were not present in the sampled surface waters (Carbery et al., 2022). The most common plastic polymers were polyethylene terephthalate (PET) (24%), high density polyethylene (HDPE) (18%) and polypropylene (PP) (18%).

In two surveys (2010 and 2012) trawling a number of sites, including several locations in the GBR, marked changes in the types of plastics were seen between the two years (Acampora et al., 2014). While a significant decline in hard plastics (almost 70%) and balloons was observed, increases were observed in rope/string (approximately tenfold), and rubber and soft plastics (approximately sixfold). Whilst the types of debris differed between inshore and offshore trawls, no differences were observed in the colours of the plastics.

The longest temporal sampling program for plastics (33 sampling months, with two replicates per event) in the water column was that performed at the SS Yongala National Reference Site between 2016 and 2019 (Miller et al., 2022). Across the study, 533 pieces of plastics were examined, with plastics being present in all but one sample. The most common polymers were polypropylene and polyethylene, with approximately 13% and 50% of these being synthetic fibres and fragments, respectively. While mean plastics concentration varied over months, there was no difference in concentrations over time. Concentrations of plastics were correlated with windspeed, salinity and river discharge volumes, however, no relationship was found with surface current speed or temperature.

Seawater and lemon damselfish (*Pomacentrus moluccensis*) were extensively sampled from the Townsville region, including inshore (1-30 km from the mainland) and reefs (60-100 km for the mainland) (Jensen et al., 2019). The study showed that microdebris contamination was widespread and was primarily made up of microfibres (86%). The study also found that contamination in coastal waters was likely caused by river discharge, with the effect being less pronounced offshore. Offshore sources could not be confirmed, with the authors suggesting that these were likely associated with sewage from vessels, general discard, ocean transport or atmospheric transport. Although, total median concentrations of microdebris were double in inshore samples compared to offshore samples, no significant difference was detected. However, microfibre concentrations, specifically, synthetic ones, were higher in the surface waters from offshore sites when compared to inshore reefs. There was no difference in the debris ingested by the fish between inshore and offshore samples. The most abundant colours of marine microdebris items were black, blue, white, and red, comprising ≥80% of the colours in both surface water tows and lemon damselfish. Importantly, 11% of the items in the fish were transparent, with these not being detected in the surface tows. Furthermore, the plastics in the fish differed in composition and shape to that from the surface water tows, indicating that microdebris intake by the fish was not random (Jensen et al., 2019).

The presence of microdebris was examined in juvenile coral trout from Lizard, Orpheus, Heron and One Tree Islands (Kroon et al., 2018). Marine debris fibres and particles were found in all but one of the 20 sampled individuals. Of these, 97% were semi-synthetic and naturally-derived fibres, with the authors suggesting that the synthetics were likely from textiles. Mean marine debris items in fish was greater in Heron Island than Lizard Island. However, no differences in mean number of synthetic particles or fibres, or naturally-derived fibres was found between the four islands.

Comparisons between microplastics in wild-caught and commercial (unverified wild-fish) seafoods have been performed (Dawson et al., 2022). This study found that the total amount of microplastic particles was significantly higher in the commercially obtained fish fillets, while being barely detected in the wild caught individuals, with only two of the ten coral trout containing two fibres each (Dawson et al., 2022). In the samples used in this study, tissues from wild-caught barramundi, scallops and prawns were also free of microplastics. In contrast, commercially obtained barramundi contained significant levels of microplastics (0.02 – 0.19 microplastics g^{-1}) (Dawson et al., 2022).

The relationship between microplastics and three trophic levels (zooplankton, benthic crustaceans and fish) was studied in two reefs (Backnumbers and Davies), east of Townsville (Miller et al., 2023). Of the 57 plastic items sampled, all semi-synthetic items were fibres, with synthetic items being roughly equally made up of fibres and fragments. Microplastics were higher in concentration in the water column of Backnumbers Reef compared to Davies Reef, with the opposite being the case for the sediments. However, replication for both matrices were low. In general, microplastic (MP) concentrations were much lower in the water column (mean 0.005 MP kg^{-1}) when compared to the sediment (mean = 3.22 MP kg^{-1}). Fibres were the dominant shape in the water column, sediment, and all three trophic groups (zooplankton, benthic crustaceans and fish) examined. Reef fish had a higher ratio (4:1 fibres/fragments) than both waters and sediment (both approx. 2:1). Blue, transparent and white microplastics were dominant in the water column, with black and blue being the more dominant colours in the sediment. Black items were in higher abundance in benthic crustaceans than the other trophic levels, however, no relationships between the dominant colours and their respective environmental matrices were found. Whilst copepods (zooplankton) were the most contaminated trophic level, there was no evidence of bioaccumulation or biomagnification in the three examined trophic levels (zooplankton, benthic crustaceans and fish).

Plastics consumed by five marine turtle species (from both the GBR and Western Australia) were examined from deceased specimens collected over 26 years (1993-2019) (Duncan et al., 2021). The following summary pertains only to the GBR specimens from this study. The study found a high incidence of plastic ingestion in green (83%), loggerhead (86%), flatback (80%) and olive ridley turtles (29%), with no incidence of consumption in hawksbill turtles. The ingested plastics were primarily made of hard fragments (52%), with the most consumed colours being clear (36%), white (36%), blue (16%) and green (16%). From a polymer perspective, those most commonly ingested plastics were polyethylene (58%) and polypropylene (20%). There was no clear significant pattern to demonstrate that consumption had changed over time, as determined by the year of stranding. While it is unclear whether some of these specimens were used in the previous study (Duncan et al., 2021), Duncan et al. (2019) also showed that green turtles had the highest consumption of plastics (n=7) out of the six species of turtle. However, the sample sizes of the other species were too small to compare. Plastic was detected in the single individual hawksbill turtle, although the number of particles was at the lower end of the range to that found in green turtles (Duncan et al., 2019). Again, it is emphasised that the sample size hinders any direct comparisons between species. In general, approximately 60% of the plastics were fibre (mainly blue and black), 20% fragments, and 18% beads (Duncan et al., 2019).

Several studies have examined the consumption and nesting use of plastics in birds (Acampora et al., 2014; Verlis et al., 2013; 2014; 2018). The nest of the brown booby (*Sula leucogaster*) and adjacent beaches in the Swain Reefs were surveyed on three occasions (2012-2013) for plastics (Verlis et al., 2014). More than 58% of nests contained marine debris, with on average four items per nest. Hard plastics were the most common form in both nests (57%) and beaches (73%), with 9% and 1% of the plastics in the nest being from rope plastic and sheet plastic, respectively. On average, four marine debris items were found per nest (n = 96). The average size of nest debris was 8.6 ± 7.1 cm with a mean weight of 6.2 ± 10.9 g. Several toiletry items (4%), e.g., toothbrushes, razors and combs, and pens/markers (4%) were found in the nest; although nests were absent of medical, fibrous and foamed plastics. The colour of the materials in the nest and the beaches differed, with nests having high amounts of yellow and silver/grey coloured items. The major sources of debris in the nest were associated with fishing (31%) and land-based sources (26%). In general, the debris in the nest did not represent the colour or composition of that sampled in the environment.

In a survey (February and May, 2012) of wedge-tailed shearwaters (*Ardenna pacifica*) from Heron Island, no plastic fragments were found in adult birds (Verlis et al., 2013). However, 21% of the sampled chicks contained fragments (average of 3.2 fragments). These fragments had a mean size of 0.17 ± 4.55 mm, with a mean weight of 0.056 ± 0.051 g. The ingested plastics were predominantly off-white/white (37.5%), green (31%) and yellow (12.5%). Whilst the results were preliminary, they illustrate that plastics are being fed to the chicks by adult birds. However, more information is required about the extent of ingestion and the preferences, accidental or not, of plastics (Verlis et al., 2013). In another study also examining plastics in wedge-tailed shearwaters, Verlis et al. (2018) sampled birds from Heron Island and Northwest Island reefs and compared these to coastal birds from outside of the GBR. Consequently, no direct comparison between offshore and coastal birds within the GBR is possible. In contrast to Verlis et al. (2013), 8% of the sampled birds from the offshore GBR sites contained plastics (Verlis et al., 2018). In comparison, 20% of the birds from coastal sites (not in the GBR) contained plastics. Of those birds that ingested plastics, the mean number of items was similar between offshore (1.1 ± 0.1) and inshore birds (1.0 ± 0.0), however the mean weight (offshore 0.009 g; inshore 0.03 g) and mean size (offshore 0.6 cm; inshore 4.3 cm) of the items was substantially different. Debris found at the offshore sites was predominantly associated with land use (tourism), commercial shipping, fishing (commercial and recreational) and stormwater; however, land use, and stormwater were more the dominant sources of debris in the coastal sites (Verlis et al., 2018).

Risks of plastics

A number of experimental, both laboratory and *in situ*, studies have been performed to examine the risks of plastics on the GBR's biota. Using the stomach and intestinal fluids harvested from freshly deceased green and loggerhead turtles, an experimental study examined the degradation of biodegradable, standard and degradable plastics (Müller et al., 2012). After 49 days, there was no significant breakdown of the standard and degraded plastic bags. Biodegradable bag mass was reduced by 3 to 9% during this period, however, it was much slower than the composting rates (100% in 49 days in compost) stated by manufacturers. Differences were observed between the two species, with the carnivorous loggerhead having a lower capacity to breakdown the plastics than the herbivorous green turtle. Whilst biodegradable plastics do breakdown more rapidly, the authors believe that is not rapid enough to prevent mortality. Furthermore, they emphasised the need to understand how biodegradable plastics break down both in terrestrial and aquatic systems (Müller et al., 2012).

Berry et al. (2019) experimentally examined the effects of plastics on coral (*Acropora tenuis*) fertilisation and larvae. The study used fifteen different treatments using weather polypropylene particles and spherical polyethylene microbeads; with the treatments ranging from five to 50 polypropylene pieces per litre, and 25 to 200 microbeads per litre (Berry et al., 2019). Only the largest weathered microplastics (2 mm^2) were shown to affect fertilisation, with the effect being independent of dose. Larval development and settlement were not affected by the plastic treatments (Berry et al., 2019). Overall, the study suggested that moderately high levels of <2 mm marine plastics has little effect on this coral species (Berry et al., 2019). Although the study was comprehensive, it is emphasised that it was limited to one species of coral. In a review assessing the risks of microplastics that examined ecotoxicology through various modes of action (e.g., accumulation and bioavailability), a notional mean hazardous dose metric concentration for 5% of the species (HC_5) of 75.6 particles per litre was obtained for aquatic species (Koelmans et al., 2022). However, it is emphasised that this value was derived from only nine studies, and did not capture species relevant to the GBR.

McCormick et al. (2020) experimentally exposed the Ambon damselfish *Pomacentrus amboinensis* to polystyrene microplastics and monitored their behaviour after being placed in live or dead/degraded coral patches. Fish were bolder (more active and straying further) when exposed to microplastics or poor habitat. Plastics appeared to have a more pronounced effect on behaviour than poor habitat, although no synergism between the two was found. However, it can be argued that the exposure concentrations (and doses based on their pilot study) were high and likely above conditions present within the GBR. Using environmentally relevant concentrations of plastics, wild-caught damselfish (*P. amboinensis*) were exposed to irregular shaped blue polypropylene (PP) particles (longest length 125–250 µm), and regular shaped blue polyester (PET) fibres (length 600–700 µm) to examine ingestion and clearance rates (over 128 h) (Santana et al., 2021). Whilst both plastics were consumed by the fish, concentrations, body burden, and depuration rates of PET fibres were significantly larger and longer than those associated with PP particles. Furthermore, for both treatments, body burdens and clearance rates were influenced by concentration. This study emphasises that in this case, the type of plastic and their concentrations has a bearing on body burden and depuration rates, and hence affects the recovery of exposed fish. It is also noted, that despite depuration, extraneous microplastics were still present in the experimental fish, emphasising the ubiquitous nature of plastics and the challenges of using wild-caught specimens in ecotoxicological assays.

The observational studies in the previous section above clearly illustrate the ubiquity of plastics in the GBR environment. Given the incongruity between the compositions of plastics in the environment and those used (e.g., nesting material) or consumed by species, there is evidence to suggest that some species consume, either selectively or non-selectively, specific types of plastics based on size, shape and colour. Consequently, risk may vary markedly among species and environments and across biological season (e.g., feeding of chicks).

Sources of plastics

The sources of plastics and their types appears to vary with geographical position. Coastal sites are more likely influenced by catchment sources (e.g., parks and stormwater runoff) (Bauer-Civiello et al., 2019; Roman et al., 2021). Islands are often the repository of wind-borne plastics, as well as general waste associated with tourism activities (fishing, boating and presence on islands), commercial boating and fishing, and localised stormwater runoff (Kroon et al., 2018; Miller et al., 2022; Roman et al., 2021; Verlis et al., 2014; Wilson & Verlis, 2017). However, the source of plastics from some offshore sites (e.g., SS Yongala NRS), appears to be correlated with inshore river discharges (Miller et al., 2022).

Gaps in plastics

- Greater understanding on the risks of plastics to biota in coastal, offshore and high tourism areas.
- To assist our understanding of plastics, it has been suggested that a more consistent approach for classifying microdebris, which includes synthetic, as well as semi-synthetic and naturally derived fibres , be used (Kroon et al., 2018).
- Information on how biodegradable plastics break down both in terrestrial and aquatic systems is required to help understand their risks and options for managing their disposal (Müller et al., 2012).
- The ecotoxicology of plastics is poorly understood, including the effects on the breakdown products.
- Links between plastic exposure and endocrine disruption remain unknown.
- The types of plastics, their colours, chemical composition and size is diverse, making understanding exposure, dose and risk exceedingly complex. Considerable research is needed to understand this risk to a wide range of biota from consumption and ecotoxicological perspectives.

- Overseas research has shown that different species of corals respond differently to plastics (Reichert et al., 2018). Consequently, there is a deficiency on how GBR species are affected.
- No studies were reported that examined the interaction between plastics and temperature.
- Research in southeast Queensland showed that there are a number of attributes associated with the probability of turtles consuming plastics (Schuyler et al., 2012). This includes the species of turtle, whether it is a pelagic or benthic feeding phase, and the colour and morphology of the plastics. More information is required on differences in exposure between species and life stages in order to aid in determining risk of plastics to biota.
- Only a few bird species have been sampled. More extensive knowledge is required about the effects of plastic on different species and life stages, and how plastics are consumed in different environments.

v. Pharmaceuticals, Veterinary Products and Personal Care Products (PVPs)

Study characteristics

There is a dearth of studies associated with the types, distribution and risks associated with pharmaceutical, veterinary and personal care products (hereon abbreviated to PVPs). In summary, there was only one survey detecting these compounds in the environment (Gallen et al., 2019), one study examining these compounds in green turtles (Heffernan et al., 2017), and two research papers examining antibiotic resistance (Ahasan et al., 2017) and antibiotic treatment (Sweet et al., 2011).

Summary of evidence to 2022

PVPs in water and sediments

Waters, sediments and passive samplers were used to detect a range of contaminants at three turtle foraging sites: Upstart Bay (Lower Burdekin), Cleveland Bay (off Townsville) and the Howick Island Group (Cape York midshelf area off Cape Melville), with the latter being an offshore ‘control’ (Gallen et al., 2019). Although not quantifiable due to a lack of available calibration data, a range of PVPs were detected via passive sampling in the water column and sediments in Cleveland Bay, but were not detected in either the Howick Island Group or Upstart Bay.

The chemicals/compounds were associated with:

- Medications: carbamazepine (anti-seizure drug), venlafaxine and citalopram (antidepressants), codeine and tramadol (opioids for pain relief); paracetamol (pain relief) and hydrochlorothiazide (diuretic medication).
- Medical imaging: iopromide (non-ionic x-ray contrasting chemical).
- Food additives: acesulfame (artificial sweetener).
- Anti-microbial additives: triclosan.

In addition, a number of other PVPs were tentatively identified from water and passive samplers from Cleveland Bay: allopurinol (urate-lowering medication, para-aminomethyl-benzoic acid (haemostatic medication), azelaic acid (acne treatment), cyclopentamine (nasal decongestant), DEET (insect repellent), milrinone (heart medication), salicylic acid (face cleanser) and viloxazine (anti-depressant). The diversity and composition of the PVPs reflects that some of the Cleveland Bay samples (passive water samplers) were placed near a wastewater treatment plant (Gallen et al., 2019). A range of tentatively identified PVPS were collected in the sediment samples (both passive and collected) from Cleveland Bay: azomycin (antibiotic), clozapine (antipsychotic), enalapril (hypertension), fenfluramine (serotonergic seizure medication), imipramine (antidepressant), remoxipride (antipsychotic), sertraline (antidepressant) and arginine (used as a body protein supplement). Tentatively detected PVPs in Upstart Bay were: cyclopentamine, DEET, azomycin, imipramine, phenytoin (seizure medication), physostigmine (antimuscarinic toxicity and glaucoma) and risperidone (antipsychotic). With naproxen (pain treatment), perphenazine(antipsychotic), pyrazinamide (antibiotic), ribavirin, DEET and salicylic acid being tentatively detected in the offshore Howick Island Group.

The analysis of turtle blood from the same three sites (Heffernan et al., 2017), identified azelaic acid in the blood of turtles from both Cleveland Bay and Upstart Bay. In addition, allopurinol and milrinone were detected in turtles from Cleveland Bay. Of particular note was that both DEET and salicylic acid were detected in all three sites as well as in the blood of turtles from Cleveland Bay (Heffernan et al., 2017). No other co-detections were found between PVPs measured in the environment and turtle blood. However, it is emphasised that the detection of many of these PVPs is challenging due to database limitations and access (Heffernan et al., 2017). While a range of biomarkers in turtles were detected, especially in turtles from Cleveland Bay, numerous anthropogenically derived pollutants were detected (metals and organics) and consequently these endpoints were not able to be tied specifically to PVPs.

Using cloacal swabs, Ahasan et al. (2017) sampled 73 green turtles (2015/2016) for antibiotic resistance from three populations: Toolakea Beach and Ollera Creek (north of Townsville) and Cockle Bay (Magnetic Island). More than 150 gram-negative isolates were identified as Enterobacteriale, capturing nine genera and 16 species, with dominant isolates being *Citrobacter* (31%), *Edwardsiella* (22%) and *Escherichia* (12%). These isolates were shown to have resistance to 12 antibiotics belonging to six different classes. Most notable, was resistance to lactam antibiotics (79%), quinolone (50%) and tetracycline classes (46%). More than one third of the isolates (38%) were found to exhibit multi-drug resistance. Furthermore, rehabilitated turtles (from a local turtle hospital) had a significant higher level of multi-drug resistance. Importantly, the study found a higher percentage (22%) of multi-drug resistant isolates from the turtles sampled from Cockle Bay, with the city and port of Townsville being potential sources. It should be noted that this is the first and only baseline dataset for antibiotic resistance in turtles within the GBR, and clearly shows that there is a significant gap in understanding both the level and range of antibiotic resistance in the region's biota, including areas which are less significantly impacted by anthropogenic activities (Ahasan et al., 2017).

In an experimental study, corals (*Acropora muricata*) were exposed to the broad-spectrum antibiotic Ciprofloxacin (Sweet et al., 2011). The results showed that exposure to the antibiotic did not eliminate all bacteria. Following exposure, corals were placed in natural seawater to enable bacterial recolonisation. During the initial stages the communities were dominated by natural antibiotic resistant bacteria which survived the application. The bacterial communities generally reached a similar stage to the controls after 96 hours, suggesting resistance to a short-term exposure event, although some difference did occur. However, potential pathogens (e.g., *Clostridium*) were more abundant in the treated corals, albeit in relatively low numbers.

Sources of PVPs

While the number of selected studies was very limited, potential sources for PVPs identified from this review are: wastewater treatment plants (Ahasan et al., 2017; Gallen et al., 2019; Heffernan et al., 2017); urban surface runoff (Ahasan et al., 2017; Gallen et al., 2019; Heffernan et al., 2017); and tourism, e.g., DEET, salicylic acid and oestrogens (Beale et al., 2017; Gallen et al., 2019; Heffernan et al., 2017). In the case of the green turtles, antibiotic resistance in some cases may be inherent, however, the extent of this has yet to be ascertained (Ahasan et al., 2017).

Gaps in PVPs

Given the diversity of PVPs and the potential sources, there are significant gaps in this area. These include:

- Fundamental information on the types of PVPs, their occurrence and distributions in both the GBR environment and biota. To date, this is limited to three sites with a few environmental replicates.
- A greater understanding of the inputs and discharge of PVPs associated with wastewater treatment plants and wet weather overflow events.
- No information is currently available on the types and quantities of PVPs associated with agricultural and veterinary products.
- Quantification and identification of many PVPs is currently constrained by technical limitations, including access to databases (Gallen et al., 2019; Heffernan et al., 2017).
- Ecotoxicological information on GBR species to well distributed PVPs, e.g., DEET and antibiotics.

- An understanding on the relationship between PVPs and temperature in terms of exposure, dose and response.
- The processes associated with antibiotic resistance in the environment, including its transference.
- Natural resistance to antibiotics in biota. It is emphasised that DNA sequencing technologies have advanced rapidly since the publication of Sweet et al. (2011) (Taberlet et al., 2018). As such there is now far greater opportunity to understand the interactions between microbiomes, e.g., those associated with corals and other biota, and PVPs.
- A greater understanding of natural and anthropogenic oestrogens in the environment including their concentrations, sources and risks to biota.

vi. Coal and fly ash

Study characteristics

There were five studies associated (indirectly or directly) with coal, and no studies were found associated with fly ash in the GBR.

The studies included: a PAH dataset (Burns, 2014), a study examining water quality data from a catchment with extensive mines (coal, metals and legacy) (Jones et al., 2019), which was discussed in the section on metals, as no coal specific data is provided; a modelling study quantifying the predicted spread of coal from a Central Queensland Coal Project in the Styx Basin (Saint-Amand et al., 2022), and an ecotoxicological study (Berry et al., 2017).

Summary of evidence to 2022

Berry et al. (2017) studied the effects of suspended coal, coal smothering and coal leachate on the embryos, larvae and juveniles of the coral *Acropora tenuis*. The study found that suspended coal (>50 mg L^{-1}) reduced fertilisation success, with fertilisation being the most sensitive measured endpoint. Furthermore, increasing concentrations of suspended coal, and its duration, had an increasingly negative effect on embryo survivorship. In contrast, leachate had minimal effect on larval settlement and fertilisation. Collectively, the findings suggest that plumes of suspended coal have the capacity to affect coral recruitment via its interaction with newly spawned gametes and embryos.

Modelling was performed to examine the Central Queensland Coal Project, a proposed open-cut coal Styx basin (approx. 130 km north west of Rockhampton) (Saint-Amand et al., 2022). The modelled data found that finer sediments (<32 µm) have the capacity to reach a dugong sanctuary and meadows of dense seagrass within a short timeframe (weeks). The authors postulated that tidal circulation patterns will result in the long-distance dispersal of sediment along the coast, becoming concentrated in areas of high conservation value. Consequently, this could negatively impact seagrass communities via smothering and a reduction in light. The long-distance effects of the Hay Point coal port terminal have been demonstrated using PAH data, with the chemical composition of the PAHS likely being those associated with the coal terminal and were also detected 40 nautical miles from the coast (Burns, 2014).

Gaps in coal

Given the very limited number of studies there are considerable knowledge gaps associated with coal and fly ash. In the case of the latter, there is no information at all regarding its spatio-temporal data, concentrations or risks. To date only three studies examined the ecotoxicology of coal, and hence the information is constrained to the early life stages of a single species. Potential knowledge gaps include:

- Ecotoxicology of coal (particulate, physical and leachate) to a wider range of species, including those which are most like to be affected by exposure (e.g., fish and benthos).
- Spatial and temporal data on the dispersal and settlement of coal and its associated products.
- The effects of coal on seagrass (e.g., smothering or reduced light) and its ecotoxicological effects on the species which use seagrass meadows.
- The ecological implications of habitat lost to smothering.
- A more thorough understanding of the downstream effects of coal mines in areas beyond the GBR (Saint-Amand et al., 2022).

vii. Sunscreen

Study characteristics

No single source was found associated with sunscreen in the GBR. Only a single individual study was found relating to the dissipation and occurrence of UV filters in a Brisbane freshwater system (O'Malley et al., 2021).

Summary of evidence to 2022

In the US, the primary studies are from surface contact with waters during recreation activities and release from stormwater waste (National Academies of Science, 2022). This is likely similar in Australia given that 2.5 million Australians purchase sunscreen within a four-week period (Research, 2016). In Australia, there are 28 organic and two mineral UV filters permitted for use in sunscreen (TGA, 2016). For the most detailed and current review, readers are advised to see “Review of Fate, Exposure, and Effects of Sunscreens in Aquatic Environments and Implications for Sunscreen Usage and Human Health” (National Academies of Science, 2022). Given the large breadth of information conveyed in this report it is not possible to distil this into the current review. However, it should be noted there are significant complexities associated with assessing the risks of sunscreens. These include highly varied toxicity results, inconsistent methods, and wide range of behaviours of the filters in the environment.

In summary, overseas studies have found that most filters have little or no environmental exposure data, and that there are frequently conflicting results about whether specific filters do or do not pose a risk under specific conditions. This information is summarised in several reviews associated with the effects of UV filters on corals (Mitchelmore et al., 2021; Watkins & Sallach, 2021). A global survey of experts from governments, non-governmental organisations (NGOs), researchers, academics and industry identified the following needs for better understanding the ecological risks associated with sunscreens on corals (Watkins & Sallach, 2021). It should be noted that the information below has been taken verbatim from Table 3, Watkins & Sallach (2021).

Effects of UV-filter exposure on different biotic parameters

- Coral species type (soft, hard)
- Life-cycle stage of test species (larvae, adult structure)
- Planulae larval production (brooding, broadcast spawning, settled, swimming)
- Test species origin (farmed or wild)
- Structural sample regions of coral polyp (stalk, tip)
- Ecosystem structure reflective test species (ecologically important species, indigenous species)

Effects of UV-filter exposure on different study

- Natural vs. artificial sea water condition parameters
- Natural vs. artificial sunlight
- Diurnal differences (light or dark)
- Functional complexity of ecosystem mesocosms
- *In situ* studies

Effects of different spatial and temporal parameters

- Seasonal variation (wet and dry)
- Depth in the water column at which test species is harvested
- Occurrence and distribution in surface water of UV filters with regards to geographical location
- Water conditions (wastewater, coastal recreational activities, and low water renewal)
- Chronic exposure (long-term monitoring)
- Accumulation rate in ocean food chains/trophic transfer

Effects of UV filters when coinciding with additional climate-induced environmental stressors

- Temperature, pH, salinity, ocean acidification

Effects of pulse exposure to marine organisms

- Ability to recover and build resilience to previous exposures (physiological acclimation)

Effects of whole product/co-exposure testing

- Ecotoxicity of UV-filter degradation products and metabolites
- Mixture toxicity of UV filters and other concomitant chemical exposure (inorganic, organic, additional sunscreen products)
- Bioavailability boosting of UV filters from other sunscreen ingredients

Effects of UV-filter exposure on ossification of organisms

- Coral species (and other calcium structured organisms) skeletal organism formation under acute and chronic exposure of UV-filter chemicals

Effects of UV-filter exposure on organism biological processes

- Metabolic capabilities, viral infection rates oxidative stress, endocrine processes disruption processes

Gaps identified by survey respondents:

- Potential significant contributors of UV filters to marine environment other than sunscreen (packaging, plastic, textiles, fishing equipment, paints, coatings, etc.)
- Appropriate population endpoints for coral species in laboratory environments
- Optimal exposure conditions for corals in laboratory environments
- Cost–benefit analysis or socioeconomic analysis of UV-filter removal from the environment and using alternatives for UV protection (hats, protective clothing, etc.)
- Increasing risks of coral disease
- Photosynthesis-important light levels for wild corals.

The highest weighted knowledge gaps rated by the participants in the above survey were: coral species (and other calcium structured organisms) skeletal formation under acute and chronic exposure of UV-filter chemicals; mixture toxicity of UV filters and other concomitant chemical exposure biotic parameters (e.g., coral type, life-cycle stage) appropriate to evaluating risk in actual reef ecosystems; and effects of spatial and temporal parameters of UV-filter chemical exposure on coral reef ecosystems (Watkins & Sallach, 2021).

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

Chapters 1, 2 and 3 of the 2017 SCS provided an overview of ‘other pollutants’, their distributions, sources and their risks. The notable difference between the 2017 SCS update and the present one is that antifoulants are not covered in the current review, as they are derived from offshore activities. Furthermore, the current SCS review aimed to provide a more detailed focus on POPs, PVPs, PFAS and sunscreen. Many of the limitations emphasised in the 2017 SCS still remain. These include: a lack of data; the need to conduct targeted campaigns for pollutants; and a need to understand the ecological impacts of plastics and PVPs on the GBR’s organisms and ecosystems. Since the 2017 SCS, there have been a range of studies which has aided the information contained in the present review. This includes: a single extensive PFAS sampling program; a number of studies looking at the distribution of plastics and their effects on selected biota; experimental studies on the effects of coal on marine organisms; and some significant advancements in the ecotoxicological tools for assessing the effects of pollutants on turtles. However, given the dearth of studies across all pollutant classes, the present review jointly assessed studies captured both in the 2017 SCS and those more recently published. Collectively, there is no substantial change between the 2017 findings and the current review, with the gaps for the key pollutants still remaining which continues to hinder a comprehensive understanding of the spatial and temporal distributions of other pollutants, their sources and risks.

4.1.3 Key conclusions

This Evidence Summary synthesised evidence from 92 studies. The information was biased towards several groups of pollutants, most notably metals and plastics. Of particular note was the lack of long-term datasets and hence no temporal trends could be determined for any pollutant groups. Consequently, no direct comparisons are made between the current data and evidence from the 2017 SCS. The majority of the datasets (including different pollutant groups) came from the same systems including: Port Curtis, Townsville and Cairns, and collectively the data was very coastal focused. Furthermore, only relatively few offshore environments were sampled, and these varied greatly amongst the different types of pollutants. It is important to note that many of the results reported are from single studies.

The key conclusions from each pollutant group are summarised below.

Metals

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

Persistent Organic Pollutants (POPS)

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

Per- and poly-fluoroalkyl substances (PFAS)

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

Plastics

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

Pharmaceuticals, veterinary products and personal care products (PVPs)

- Only four studies were available on PVPs in GBR waters and biota.
- Only one survey, with limited replication, examined a suite of PVPs.
- There are insufficient data to provide insights about spatial or temporal patterns and/or the ecological consequences of PVPs in the Great Barrier Reef.
- The sources of PVPs remain unclear, however, the limited evidence suggests that PVPs are more dominant near wastewater overflows and stormwater discharges.

Coal

- Five studies were available on coal in GBR waters and biota. There were no studies for fly ash.
- There are insufficient data to provide insights about spatial or temporal patterns of coal and fly ash in the Great Barrier Reef.
- Polycyclic aromatic hydrocarbons (PAHs), which are most likely derived from coal, were detected in coastal sites near Hay Point (Mackay) and up to 40 nautical miles from the coast.

Sunscreen

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

4.1.4 Significance of findings for policy, management and practice

Collectively, the review highlights that pollutant data are very patchy and lack temporal replication. In contrast to programs for assessing nutrients, sediments and pesticides in the Great Barrier Reef, there are very few routine monitoring programs for pollutant groups assessed in this review, with the exception of some monitoring of metals and marine litter within the Regional Report Cards (e.g., Gladstone, Dry Tropics and Mackay Whitsunday) for which the raw data is not publicly available. Consequently, it is not possible to accurately determine their concentrations, distributions or temporal changes. As there are GBR-wide coordinated programs, research for each group of pollutants is generally focused on a particular environment or region, and does not take into consideration the effect of co-occurring pollutants.

There is a dearth of studies which examined the relationships between exposure, dose and response. For example, pollutants were measured in an environmental matrix, but their concentrations were rarely measured in the residing biota. In cases where both were measured, it was generally unclear what this meant, with the exception that the pollutant was accumulated. Furthermore, links between environmental concentrations and biological (and ecological) endpoints were rare, and often associated with studies which examined a suite of co-occurring pollutants, hindering the capacity to determine which pollutant was likely driving any perceived changes. Without substantial links between exposure, dose and a biological (or ecological) endpoint, it not possible to confidently determine risks.

Fundamental data for most pollutant groups in the GBR are lacking, most notably for coal, PVPs, PFAS and sunscreen. This prevents any reliable assessment of spatial patterns, temporal trends or exposure risk for ecosystems and individual biota. Water and sediment guidelines values are not established for most of the ’other pollutant’ groups including coal, per- and poly-fluoroalkyl substances, pharmaceutical, veterinary, and personal health care products, sunscreens and pesticides and their degradation products. Arguably, the sediment quality guidelines are outdated and lack sufficient breadth of contaminants to assess risks within the GBR. Sediment guideline values still need to be established for some metals (e.g., manganese, aluminium). This limits the ability to assess ecological risks, particularly for tropical ecosystems, as guidelines are predominantly derived from temperate taxa. Furthermore, in the case of both water quality and sediment quality guidelines, guideline values are not generally derived from tropical species and therefore it is unclear how valid they are for predicting the risks of exceedances to the GBR’s biota. Consequently, there is a pertinent need for the guidelines (both sediment and water) to be refined and updated using toxicity tests specifically derived from GBR organisms.

While guidelines are an important screening tool, as indicated in this review, many of the pollutants co-occur, and consequently, there is a need for more ecotoxicological assays (field and *in situ*) which can assess the risks of cumulative pollutants.

Fundamental data for several key pollutant groups are lacking. For example, there is only a single isolated study on PVPs, and it is unclear how potentially significant sources (such as boats, stormwaters and wastewater) are contributing to these environments across the GBR, including islands with high recreational use. The available data are also presence/absence and often tentatively assigned to the PVP due to the costs and availability of databases. Of particular note was the lack of research on the ecological effects (and distribution) of coal, and the complete lack of studies examining the effects of UV filters (sunscreen) in the GBR.

Importantly, there was only a single study which examined the effects of a pollutant (copper) and temperature. While it is not possible to draw trends from a single study, the findings of this study suggested lower pollutant levels increased the capacity for corals to deal with sea temperature rise.

An additional noticeable gap was the absence of any studies examining the effects of pollutants on coastal fish communities. This was surprising given the importance of this biotic group (ecologically, socially and environmentally) and their close association with coastal activities.

It is emphasised that the above limitations are not a reflection of the research or science per se, but rather highlight the limitations of synthesising data which are not collected in a co-ordinated manner, and the lack of regionally relevant tools and guidelines to confidentially assign risks.

4.1.5 Uncertainties and/or limitations of the evidence

- There are no guideline values or baseline measurements for many of the pollutants.
- Data were often centred around known potential sources.
- No temporal data were available, with the exception of plastics.
- Approaches used to measure pollutants often varied, including metals and plastics.
- Sample size was often small due to the opportunistic nature of many studies (e.g., turtles and cetaceans). Sample size was also often small due to logistics and costs (e.g., measuring POPs and PVPS).
- For most pollutants there was not sufficient information to address the questions, most notably for PFOS, PVPs, coal and sunscreen.
- Data from non-primary literature (such as those associated with the Regional Report Cards) were rarely externally peer reviewed and publicly available and consequently excluded.

4.2 Contextual variables influencing outcomes

Table 8. Summary of contextual variables for Question 6.1.

Contextual variables	Influence on question outcome or relationships
Climate change (or climate variability)	Flood and expansion of Port Curtis. There was some evidence, that either the 2010 flood or the expansion of Port Curtis was increasing the concentrations of POPs in dolphins (Cagnazzi et al., 2020). Another study examined larval metamorphosis in the endemic corals *Acropora millepora* and *A. tenuis* and found that reducing copper concentrations by half roughly equates to protecting the corals from a 2-3ºC increase in sea surface temperature (Negri & Hoogenboom, 2011). To date, this is the only known study to examine an interaction between dissolved metals and corals from the GBR.

4.3 Evidence appraisal

Relevance

The relevance of each class of pollutant was examined separately due to the variation in the number of studies between pollutant classes.

Metals: The relevance of this body of evidence was Moderate (5.3 out of 9.0). Of the 44 studies used in this section, 52% were given a relevance to the question score of 3 (out of 3.0), 34% rated as 2 and 18% rated as one, the remainder were laboratory studies. The lowest scores were from those studies which provided *in situ* metal data for biogeochemical studies, with sample replication being low. Those with a score of two were field studies with low replication and/or used unstandardised approaches for extracting metals. The higher scored studies were replicated and examined an environmental matrix or metals with a biota of interest. Overall, the score for the spatial scale was Moderate (1.6 out of 3.0). Forty-one percent of the studies scored a spatial relevance to the question of one (out of 3.0), indicating that samples were only obtained from one site. Twenty-five percent received a score of 2, indicating that multiple sites were sampled within a distance of 500 km. Seven percent were scored 3 for their spatial scale, indicating multiple sites were sampled over >500 km, however, these were all patchy. The remainder were laboratory studies. The overall score for temporal relevance to the question was Moderate (1.6) and this reflects the 47% of studies which only collected data at a single time point. Sixteen percent collected data on two occasions, with only 7% of studies collecting data on three or more occasions, although this was generally within a two-year period. Several studies were opportunistic, e.g., used stranded animals and hence were not given temporal scores.

POPs: The overall relevance of this body of evidence to the question was rated as Moderate (6.5 out of 9.0). Of the 19 studies used in this section, 89% were rated three for the relevance of the study approach and reporting of results to the question, the remaining two studies, both rated two, were experimental studies which the aided in understanding the transfer of POPs through trophic interactions. The overall spatial relevance to the question was rated as Moderate (2.2). Using the same criteria as above, 15% were rated 1, with 32% of the samples each scoring 2 and 3. The remainder were experimental studies, which were excluded from the temporal and spatial scores. The overall temporal relevance to the question was rated at the lower end of Moderate (1.5). Forty-eight percent were rated 1, 16% rated 2 and 11% rated 3, reflecting that most studies only sampled on one occasion.

PFAS: Only one study was used for this section. It was of high relevance to the question (3), a high spatial scale (3) and a low temporal scale (1) - only occurring on one occasion. Overall, this section was rated High (7 out of 9) however, this is clearly irrelevant given the score is based on a single study.

Plastics: Nineteen studies were used in this section. The overall relevance of this body of evidence to the question was rated as Moderate (6.7 out of 9.0). Ninety-five percent of the studies were rated 3 with relevance to the question, with one source rated 2 as it the concentrations of plastics were not considered to be environmentally relevant within the GBR. The rating of the relevance of the study approach and reporting of results to the question was on the higher end of High (2.9 out of 3.0). The spatial relevance to the question was rated as Moderate (1.8 out of 3.0), with 32% of the studies each receiving spatial scores of 2 and 16% of the studies a spatial score of 3. The remainder were experimental studies. The temporal relevance to the question was rated as Moderate (2.0 out of 3.0). This relatively high score, in comparison to the other pollutant classes was because 32% of studies collected data, generally plastics surveys, over three or more sampling events. A similar percentage was rated 1 temporally (only sampled once), and 16% percent of the studies obtained data on two events.

PVPs: Only four studies were used in this section, the overall relevance of this body of evidence to the question was rated as Moderate (5.8 out of 9.0). The relevance of the study approach and reporting of results was scored as High (2.8 out of 3.0), with three out of the four papers being ranked 3. The other source was ranked 2 which was an experimental study where the microbiome data was outdated compared to current approaches. The spatial relevance to the question was Moderate (2.0 out of 3.0), with all three *in situ* studies receiving a score of 2. The temporal relevance to the question was rated as Low (1.0 out of 3.0), with all studies being spatially discrete.

Coal: Only five studies were used in this section, the overall relevance of this body of evidence to the question was rated as Moderate (6.0 out of 9.0). The relevance of the study approach and reporting of results was rated as High (3), with all three studies being ranked 3. The spatial relevance to the question was ranked Moderate (1.5), with one study being ranked 2 and the other 1, the remaining one source was a laboratory experiment. The temporal relevance to the question was ranked Moderate (1.5), with one study being ranked 2 and the other ranked 1, the remaining one source was a laboratory experiment.

Sunscreen: No rankings are provided as no studies were deemed eligible for this synthesis.

Consistency, Quantity and Diversity

Metals: The quantity of the studies was Moderate (44 studies). There was a strong agreement between studies which examined similar regions and generally indicated that metals are low in the GBR, with the exception of some industrialised catchments. The diversity of studies was Moderate capturing a range of observational and experimental studies. A notable area where data were insufficient was estuarine systems, with no data on fish communities and minimal data on macrobenthos. Another notable gap was the lack of multiple lines of evidence, rarely were two lines of evidence available, e.g., metals in the environment and a biological or ecological endpoint.

POPs: The quantity of studies was Low (19 studies), these were predominantly observational studies. The diversity was Low, with concentrations measured in only a few species, notably dugong, turtles, cetaceans and mud crabs. No statement can be made about consistency since there was little overlap between studies. Again, a notable gap was the lack of multiple lines of evidence.

PFAS: The quantity of studies was insufficiently Low (one source). No relevant comments can be made about consistency and diversity, with the latter being restricted to waters and few fish and crustacean from the same study.

Plastics: The quantity of studies was Low (19 studies), these were predominantly observational studies. The consistency was High, reflecting both the ubiquity of plastics and their harm to the region's biota. Diversity was Low given the extent of the issue, with studies based on few fish species, a few bird species, a coral (experimental) and turtle species. Consistency was constrained due to different approaches in measuring and categorising plastics, however, the impact and distribution were clear.

PVPs: The quantity was exceedingly Low (four studies). Consequently, the diversity and consistency cannot be estimated. This emphasises the large knowledge gap with regards to these pollutants.

Coal: The quantity was exceedingly Low (five studies). Consequently, the diversity and consistency cannot be estimated. This emphasises the large knowledge gap with regards to these pollutants.

Sunscreen: No comments are provided as no studies were deemed eligible for this synthesis. This emphasises the large knowledge gap with regards to these pollutants.

Confidence

What is the spatial and temporal distribution and risk of other pollutants in GBR ecosystems?

There is a Moderate level of confidence associated with the spatial distributions of metals, POPs and plastics within the GBR. However, metal and POP data are temporally deficient, and have a very Low levels of confidence. There is a very Low level of confidence for PFAS, PVPs and coal, with the data being far too insufficient to provide any insights into spatial or temporal patterns. There were no studies on sunscreen and hence the spatial and temporal distribution of UV blockers within the GBR remains completely unknown.

What are the primary sources of the other pollutants?

There is a High level of confidence regarding the primary sources of metals and plastics, less so for POPs as it is unclear whether some restricted products, e.g., some PCBs which can imported under consent of the Department of Home Affairs, are still being used in the region or whether the sources are legacy. One exception for metals are acid sulfate soils because although they are, e well distributed across the coastal fringes of the GBR, the metal data derived from acid sulfate soils are restricted to Trinity Bay (Cairns), and hence, the issue could be far more widespread than currently recognised. While it can be assumed that PVPs are more dominant near wastewater overflows and stormwaters, the extent of these sources remains unknown. The primary sources of PFAs into the GBR remain unknown due to the paucity of data from industrialised sites and sites know to be of high risk (e.g., fire stations and air force bases). For sunscreen, the international data suggests that recreational use and wastewater are the primary sources.

What evidence is there for risk?

From the sourced studies, the risk from metals appears to relatively low, and constrained to a few small areas. However, there is a lack of recent data, including post development of the Zn smelter in Townsville. One of the challenges associated with all pollutant classes is the lack of studies which link exposure to any ecological or biological endpoint, consequently, risk is not truly measurable. To fully understand the risks of pollutants there is dire need for ecotoxicological studies which employ multiple lines of evidence. As previously emphasised, an additional constraint to measuring risks is the lack of reliable guideline values for both sediments and waters, with this especially being true for sediments. A more cohesive approach which examines the interplay of multiple pollutants and stressors, including climate change is needed. To date, the evidence from this review clearly illustrates that these issues have been overlooked, with only a single study examining the interactions between metals and temperature.

Table 9. Summary of results for the evidence appraisal of the whole body of evidence used in addressing Question 6.1. The overall measure of Confidence (i.e., Limited, Moderate and High) is based on the overall relevance and consistency.

Subgroups (e.g., pollutants groups)	Relevance				Quantity of items	Diversity of items	Consistency	Confidence
	To the Question	Spatial	Temporal	Overall				
Metals	Moderate	Moderate	Low	Moderate	44	High	High	Moderate
Persistent Organic Pollutants (POPs)	High	Moderate	Moderate	Moderate	19	Moderate	Moderate	Moderate
PFAS	High	High	Low	High	1	Low	N/A (only one source)	Limited
Plastics	High	Moderate	Moderate	Moderate	19	Moderate	High	Moderate
Pharmaceutical, veterinary and personal care products	High	Moderate	Low	Moderate	4	Low	Low	Limited
Coal	High	Moderate	Moderate	Moderate	5	Low	Low	Limited
Sunscreen	Low	Low	Low	Low	0	Low	N/A	Limited

4.4 Indigenous engagement/participation within the body of evidence

Only a single study acknowledged Indigenous engagement (Miller et al., 2023).

4.5 Knowledge gaps

Several knowledge gaps have been identified for each of the pollutant groups within Section 4.1. A selection of these have been presented in the context of potential outcomes for policy/management if these gaps were addressed in Table 10.

Table 10. Summary of knowledge gaps and potential management outcomes for Question 6.1.

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
All pollutants		
Assessment of spatial and temporal distribution of all pollutant groups is required.	Fundamental baseline and temporal variations in all pollutant groups capturing a wide range of matrices, biomes and species.	Essential information which can be used to determine the diversity, concentrations, distributions, sources and risks of pollutants in a coordinated manner. This information can assist in determining whether concentrations vary over time due to management actions and changes in policies.
Standardised methods for the measurement and analysis (including any processing such as extractions) is required.	This is not a research question but rather requires guidance and consensus for all pollutant groups.	The capacity to compare studies from the same pollutant group. This will assist in determining risks and how pollutants change over space and time.
The effects of multiple abiotic stressors on the accumulation and toxicity of pollutants.	Ecotoxicological testing (lab and field) to understand how temperature, and other abiotic variables (e.g., pH, dissolved oxygen and sediment type) interact and influence the uptake and toxicity of pollutants. This will need to include the cumulative effect of these abiotic controlling variables and stressors.	The ecotoxicology of pollutants is influenced by the interactions of pollutants with a range of abiotic variables which do not occur in isolation. In some cases these interactions may increase or decrease toxicity, or one stressor may. This would help understand the effects of pollutants under the increasing influence of climate change, as well how toxicity may change across different biomes and regions within GBR.
Extent to which wastewater and flood events are important sources of contaminants.	Routine measuring of wastewaters and floodwaters across the GBR for a diverse range of pollutants.	Identify the types and concentrations of pollutants associated with these sources. This will help understand their sources, regional influence, dispersal and potential risk.
The suitability of water and sediment guidelines for assessing the risks of pollutants to GBR taxa.	Refinements and updates of the water and sediment quality guidelines using GBR taxa and sediment types.	A greater capacity to determine the risks of GBR biota to pollutants and an increase in the applicability of the guidelines to capture tropical environments.

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
No guidelines or suboptimal values for many pollutants (water and sediment).	Derivation of guideline values (waters and sediments) for a wider range of pollutants than is currently available. As stated above, to be relevant to the GBR, these will need to be derived from an appropriate number of GBR taxa.	Increased capacity to determine the risks of *in situ* concentrations of pollutants within the waters and sediments of the GBR.
Metals		
Water and sediment guideline values for metals that don't have existing guidelines or have guidelines of low reliability. Refinement of the existing guidelines to recognise tropical species. Most notable is the absence of a sediment quality guideline for manganese.	What are the threshold values for water and sediment concentrations of metals found in the GBR? How do metals as a mixture affect the GBR's biota?	Improved certainty that the risks posed by all metals identified in the GBR waters are accounted for, including their risks as a mixture.
Establishment of routine coordinated water and metal monitoring programs for the GBR, with adoption of a consistent approach to monitoring (methods, taxa, locations) to allow for assessment of environmental concentrations of a contaminant, its accumulation, and biological or ecological endpoints.	What is the spatial and temporal distribution of metals in the GBR, what is its accumulation, and biological or ecological endpoints? What are the most appropriate methods to be consistently applied to support metal analysis (e.g., metal species and extraction)? How can monitoring programs be better coordinated to ensure that multiple lines of evidence are captured in assessing results?	Improved spatial understanding of the presence, distribution and potential risks posed by individual metals to GBR ecosystems.
Understanding of how metals may be affecting the coastal species of the GBR, including benthos and fish. This is a significant data gap given that these taxa are residing in components of the system which are more likely to be exposed to metals than offshore species.	How do metals affect coastal species of the GBR and what is the toxicity of individual metals to these species? What are the community level relationships between metals and fish and macrobenthic communities?	Improved spatial understanding of the presence, distribution and potential risks posed by metals to ecological communities within the GBR's ecosystems.
Current assessment of the presence and impact of acid sulfate soils in GBR coastal areas.	To what extent do acid sulfate soils pose a risk to GBR coastal ecosystems?	Improved spatial understanding of the presence, distribution and potential risks posed by acid sulfate soils to GBR ecosystems.
Interactive effects between metals and elevated temperature with regards to exposure, dose and response.	What are the interactive effects between individual metals and elevated temperature with regards to exposure, dose and response?	Likely cumulative impacts of metals combined with other stressors in the GBR in the future.
POPs		
Assessment of spatial and temporal distribution of POPS in the GBR,	What is the spatial and temporal distribution of POPs in the GBR,	Improved spatial understanding of the presence, distribution and

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
including a consistent approach to monitoring (methods, taxa, locations) to allow for assessment of environmental concentrations of a contaminant, its accumulation, and biological or ecological endpoints. This should extend beyond urban and industrialised areas in the GBR.	what are the baseline concentrations in biota, and how are they manifested as biological and ecological endpoints?	potential risks posed by individual POPs and mixtures of POPs to GBR ecosystems.
Examination of the ecotoxicology of POPs in an expanded suite of species and life stages.	How do POPs impact a range of species and life stages of those species in the GBR?	Improved understanding of the potential risk posed by POPS to a broader range of GBR species and ecosystems.
Understanding of the interactive effects between POPs and elevated temperature, and between ultraviolet radiation and toxicity with regards to exposure, dose and response.	What are the interactive effects between individual POPS and elevated temperature with regards to exposure, dose and response? What are the interactive effects between ultraviolet radiation and toxicity of POPS on GBR species?	Likely cumulative impacts of POPs combined with other stressors in the GBR in the future.
Understanding of endocrine effects of POPS and their metabolites.	What are the endocrinal effects of POPS and their metabolites?	Improved understanding of the potential risk posed by POPs, including reproductive effects, to a range of GBR species and ecosystems.
Current use of POPs in the GBR and the types, volumes and locations of use.	What are the sources of POPS in the GBR?	Identification of management opportunities for the sources of POPs.
The influence of floods and flood plumes on the distribution and risks of POPS, including their accumulation in cetaceans.	How do floods and river plumes influence the distribution and risks of POPs on GBR ecosystems and biota, including accumulation in cetaceans?	Improved understanding of the potential risk posed by POPs to a range of GBR species and ecosystems.
Investigation of whether oestrogen levels detected in the sediments of islands are associated with endocrine disrupting POPs, or other sources (e.g., sewage), including natural.	Are oestrogen levels detected in the sediments of islands associated with POPs or other sources?	Improved understanding of the sources of oestrogens in GBR ecosystems.
Review of sediment guideline values for POPs found in the GBR, including the addition of biphenyl and dibenzothiophene.	What are the threshold values for sediment concentrations of POPs found in the GBR?	Improved certainty that the risks posed by all POPs identified in the GBR are accounted for.
The effect of Port of Hay Point and other expansions and initiatives on POP inputs and their exposure to biota.	What is the likely effect of port and industrial expansion in the GBR on POP inputs and their exposure to biota?	Improved understanding of the influence of future expansion of industrialised areas on the presence and distribution of POPs in the GBR.
Plastics		
Understanding of the risks of plastics to biota in GBR coastal and offshore areas and areas of high tourism.	What are the risks of plastics to biota in GBR coastal and offshore areas and areas of high tourism?	Improved understanding of the potential risk posed by plastics to GBR species and ecosystems.

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
Understanding of the ecotoxicology of plastics, including the effects on the breakdown products, and how biodegradable plastics breakdown both in terrestrial and aquatic systems.	What is the ecotoxicology of plastics on GBR ecosystems, including breakdown products?	Improved understanding of the potential risk posed by plastics to GBR species and ecosystems.
More extensive knowledge is required about the effects of plastics on a wider range of taxa, especially in coastal and estuarine environments. Additional research is also required on how plastics affect different types of fish, bird, turtle species, including various life stages. In all cases this should include how plastics are consumed in different environments and whether different characteristics of plastics influence ingestion and toxicity.	What are the effects of plastics on a wider breadth of species, and research on how the different characteristics of plastics and their associated chemicals affect ingestion and toxicity.	Improved understanding of the potential risk posed by plastics to GBR species and ecosystems.
Understanding of the interactive effects between plastics and elevated temperature with regards to exposure, dose and response.	Are there interactive effects between individual plastics and elevated temperature with regards to exposure, dose and response?	Likely cumulative impacts of plastics combined with other stressors in the GBR in the future.
PVPs		
Assessment of the spatial and temporal distribution of different types of PVPs in the GBR environment and biota, including their concentrations, sources and risks to GBR biota. DEET, antibiotics, natural and anthropogenic oestrogens are of particular interest.	What is the spatial and temporal distribution of PVPs in the GBR, and the associated risks to GBR ecosystems?	Improved spatial understanding of the presence, distribution and potential risks posed by individual PVPs to GBR ecosystems.
A greater understanding of the types, quantities, inputs and discharge of PVPs associated with wastewater treatment plants and wet weather overflow events, agricultural and veterinary products.	What are the primary sources, quantities and types of PVPS in GBR waters?	Improved spatial understanding of the source of individual PVPs to GBR ecosystems.
Understanding of the ecotoxicology of PVPs especially those that are widely available and used such as DEET and antibiotics, and including antibiotic resistance in biota.	What is the ecotoxicology of PVPs, especially DEET and antibiotics, on GBR biota?	Improved understanding of the potential risk posed by PVPs to GBR species and ecosystems.
Understanding of the interactive effects between PVPs and elevated temperature with regards to exposure, dose and response?	Are there interactive effects between individual PVPs and elevated temperature with regards to exposure, dose and response?	Likely cumulative impacts of PVPs combined with other stressors in the GBR in the future.

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
Coal		
Assessment of spatial and temporal distribution of coal and fly ash in the GBR environment and biota, including their concentrations, sources and risks to GBR biota, and dispersal and settlement characteristics.	What is the spatial and temporal distribution of coal and fly ash in the GBR, and the associated risks to GBR ecosystems?	Improved spatial understanding of the presence, distribution and potential risks posed by coal and fly ash to GBR ecosystems.
Greater understanding of the ecotoxicology of coal (particulate, physical and leachate) to a wider range of species, including those which are most like to be affected by exposure (e.g., fish and benthos).	What is the ecotoxicology of coal on wider range of GBR biota?	Improved understanding of the potential risk posed by coal to GBR species and ecosystems.
Sunscreens		
Assessment of spatial and temporal distribution of sunscreen in the GBR environment and biota, including the risks to GBR biota.	What is the spatial and temporal distribution of sunscreens in the GBR, and the associated risks to GBR ecosystems?	Improved spatial understanding of the presence, distribution and potential risks posed by sunscreen to GBR ecosystems.
No toxicity information of GBR biota.	Toxicity testing across a range of species and abiotic conditions using commonly formulated products.	The capacity to determine the risks associated with sunscreen on GBR biota. This information could help advise on what products can or should not be widely used in areas of high recreational use.

5. Evidence Statement

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

Summary of findings relevant to policy or management action

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

Supporting points

Metals

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

to complete this assessment and available studies rarely considered metal speciation which is an important factor for determining metal bioavailability and ecological risk.

Persistent Organic Pollutants (POPs)

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

Per- and poly-fluoroalkyl substances (PFAS)

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

Plastics

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

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

- There are insufficient data to provide insights about spatial or temporal patterns and/or the ecological consequences of PVPs in the Great Barrier Reef.
- The sources of PVPs remain unclear, however, the limited evidence suggests that PVPs are more dominant near wastewater overflows and stormwater discharges.

Coal and fly ash

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

Sunscreens

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

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.

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Appendix 1: 2022 Scientific Consensus Statement author contributions to Question 6.1

Theme 6 – Other pollutants

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

Author team

Name	Organisation	Expertise	Role in addressing the Question	Sections/Topics involved
1. Anthony Chariton	Macquarie University	Ecotoxicology, marine and estuarine ecology, risk assessment.	Lead Author	All Sections
2. Natalie Hejl	Macquarie University	Environmental assessment and stressors.	Contributor	Searches and conceptual model.