2022 Scientific Consensus Statement

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

Michelle Templeman[1], Sarah McDonald[1]
[1]Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER), James Cook 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.

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

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

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

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

Two methods were developed for the 2022 SCS:

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

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

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

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

[2] Collins A, Coughlin D, Miller J, & Kirk S (2015) The production of quick scoping reviews and rapid evidence assessments: A how to guide. UK Government. https://www.gov.uk/government/publications/the-production-of-quick-scoping-reviews-and-rapid-evidence-assessments

[3] Richards R, Pineda MC, Sambrook K, Waterhouse J (2023) 2022 Scientific Consensus Statement: Methods for the synthesis of evidence. C_2O Consulting, Townsville, pp. 59.

[4] https://libguides.jcu.edu.au/systematic-review/define

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

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

Guidance for using the synthesis of evidence

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

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

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

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

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

Peer Review and Quality Assurance

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

Contents

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Executive Summary

Question

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

Three sub-questions were developed to address the linkages between aspects of the main question.

- What are the major sources / land uses of pesticides across Great Barrier Reef ecosystems?
- What are the key pesticides and pesticide mixture loads that have been found in the Great Barrier Reef catchment area?
- What factors and processes influence the delivery and timing of delivery of pesticides into these ecosystems?

Background

Catchments draining to the Great Barrier Reef (GBR) cover 424,000 km^2 of north and central Queensland, from Cape York to the Bundaberg region. For management purposes, the GBR catchment area includes 35 basins across 6 Natural Resource Management (NRM) regions. The major land use areas are grazing (73%), national parks/conservation areas (15%), forestry (4.6%), dryland cropping (2.4%), water (2%), sugarcane (1.2%), urban (0.7%), irrigated cropping (0.4%), and horticulture (0.2%).

Annual freshwater flows into the GBR average around 73,500 gigalitres (GL) but can vary from as low as 20,000 GL in dry years to as high as 1,160,000 GL under extremely wet years. Depending on location and climatic patterns, riverine flows are highly variable in timing and intensity across the different basins.

Water quality issues have been recognised and monitored in GBR catchments since the 1990s, with pesticides being a key focus during the 2000s. The first Reef Water Quality Protection Plan (RWQPP) was developed in 2003. The RWQPP was updated and revised in 2009 and 2013, and most recently in 2018 to become the current Reef 2050 Water Quality Improvement Plan (WQIP). The goal of the Reef 2050 WQIP is to improve water quality at end-of-catchments (EOC) to reverse declines in ecosystem health in the GBR with targets to assess progress towards improvements in water quality.

Pesticides were identified as being a possible risk to the health of the GBR as far back as the 1990s. During the 2000s, sugarcane production, grazing and other agricultural activities were identified as key contributors to pesticide exports across many GBR catchments. The Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (Paddock to Reef Program) was established in 2008 and included monitoring of pesticides at EOC as well as incorporating management practice adoption, a process which expanded over time. Prior to 2016, reporting was restricted to the five major Photosystem II inhibiting (PSII) herbicides - ametryn, atrazine, diuron, hexazinone and tebuthiuron.

In 2017, the assessment methodology for pesticide reporting shifted to a risk–based profile. This approach focused on concentrations of pesticides at EOC to estimate Pesticide Mixture Toxicity. The revised approach was designed to establish the proportion of aquatic species protected at current levels of pesticide exposure at a catchment level with a goal of achieving 99% species protection. With the shift in approach, there was also an expansion of the pesticide suite to include additional PSII herbicides as well as herbicides with different modes of action (non-PSII) and insecticides. Currently 22 pesticides are monitored using this approach.

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

[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

search effort, quality appraisal of evidence and the amount of data extracted. The process has well-defined steps enabling fit-for-purpose evidence to be searched, retrieved, assessed and synthesised into final products to inform policy. For this question, an Evidence Summary method was used.
- Search locations included Web of Science and Scopus. This was supplemented with relevant peer reviewed reports from the Great Barrier Reef Catchment Loads Monitoring Program (GBRCLMP) and Queensland Government website.
- The main source of evidence was studies focused on the GBR as studies outside the GBR had limited applicability.
- The initial keyword search for all questions returned 2,130 results for Web of Science and 707 for Scopus. After initial screening by title and removing duplicates, 239 were shortlisted for full-text screening. In addition, 52 relevant peer reviewed reports from the Queensland Government publications portal and the authors' personal collections were manually added. Following full-text screening, 109 papers met the eligibility criteria and were included in the synthesis.

Method limitations and caveats to using this Evidence Summary

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

- Only studies written in English were included.
- Two academic databases, one government portal and an initial screen of Google Scholar were used for the searches.
- Studies published prior to 1990 were excluded.
- With the exception of background summaries on mode of action and chemical properties of pesticides, only GBR derived studies were included. Studies outside the GBR offered limited additional information of relevance.
- A total of 20 reports and papers that were held behind a paywall or were not readily accessible by an Inter-Library Loan (ILL) were excluded.

Key Findings

Summary of evidence to 2022

Pesticides are found across almost all monitored catchments in the GBR. The key factors that influence export of pesticides to the GBR are pesticide application rates, the timing between pesticide application and rainfall, irrigation regimes, and pesticide properties such as persistence. Other factors that can influence delivery of pesticides to the GBR include soil characteristics, pesticide formulations, climatic conditions and particularly extreme weather events, and catchment characteristics.

Currently, 22 pesticides, comprising 9 PSII herbicides, 10 non PSII herbicides and 3 insecticides, are monitored as the priority suite for the GBR Catchment Loads Monitoring Program (GBRCLMP).

- Overall, there is no substantive evidence to indicate that the main land use contributions to pesticide concentrations in the GBR catchment area have significantly changed since the 2017 SCS.
- Sugarcane areas are the largest contributor to end-of-catchment pesticide concentrations, dominated by photosystem II inhibiting herbicides (PSII herbicides). While pesticides are used over large areas of grazing lands, the relative ecological toxicity of the dominant pesticide, tebuthiuron, is low compared to other PSII herbicides. Other land uses including, horticulture, banana growing and urban areas can be large users of some pesticides, but their total area within the GBR catchment area is relatively small.
- Herbicides, specifically PSII herbicides, are the most common and abundant pesticide type measured in end-of-catchment monitoring followed by other herbicide types and insecticides. Catchments with minimal agricultural activity, such as the Ross and Kolan basins, have the lowest PSII herbicide contributions.

- Application rate and time between application and rainfall continue to be the biggest drivers of pesticide export from sugarcane. A range of studies have identified that the critical time period for pesticide runoff is 1-25 days after application. The longer the timeframe from application to runoff rainfall the lower the relative amount of pesticide exported.
- The first rainfall event of the wet season (typically described as the ‘first flush’ event) often delivers the greatest proportion of pesticides to the GBR. The proportion delivered is enhanced where short timeframes between application and rainfall occur. Pesticide contributions typically reduce with subsequent rainfall events. Similarly for irrigated areas, the greatest losses tend to be associated with the first irrigation event.
- Pesticide export profiles from irrigated sugarcane are similar to rainfall events, but irrigation can lead to higher ecological risk in receiving systems due to extended periods of exposure and limited flushing or dilution.
- Although most pesticide export to the Great Barrier Reef is via surface runoff, pesticide export via groundwater may be a contributor in some basins. While export via groundwater has been measured in a few studies in the Wet Tropics region and Lower Burdekin floodplain, the overall proportion of groundwater pesticide contributions is unknown. Groundwater contributions can also have significant lag effects from the timing of application, with pesticide export potentially continuing for years after application, leading to uncertainties in the understanding of pesticide migration.

Recent findings 2016-2022

Of the 109 studies included in this Evidence Summary, 38 (35%) were published between 2016 and 2023. Findings from these studies are:

- There have been no significant changes to land use sources of pesticides since the 2017 SCS. Sugarcane continues to be the largest single contributor to toxic load at EOC. There are smaller scale influences from other land uses including bananas and urban activities but their overall relative land use contributions are small.
- Across all monitored basins between 2016 and 2020, the relative contribution of PSII herbicides to the overall pesticide risk increased from 47% to 57%, other herbicides increased from 32% to 35%, while insecticides decreased from 17% to 7%. These findings do not necessarily indicate a reduction in the use of insecticides, but their relative contribution to the overall pesticide risk is lower.
- PSII herbicides are strongly linked with agricultural activities, particularly sugarcane. Only catchments with little agricultural activity did not have a major contribution from PSII herbicides.
- Imidacloprid is the most commonly detected insecticide in GBR catchment area and is associated with banana, sugarcane and urban activities. However, the relatively small proportion of land for bananas and urban areas reduced the proportion of imidacloprid delivered to the EOC from these land uses.

Significance for policy, practice, and research

The outcomes indicate that despite efforts by all levels of government, industry and stakeholders, there has been no significant change in the primary sources of pesticides since 2016. Sugarcane remains the dominant source in terms of toxic equivalent load at EOC. Smaller scale contributions from bananas and urban activities have also been identified, particularly for imidacloprid detection but the small relative land use contribution minimises EOC contributions.

PSII herbicides continue to be the greatest relative contributor to EOC pesticide concentrations. The relative contribution of insecticides has reduced between 2016 and 2020. Imidacloprid is the most commonly detected insecticide, largely delivered from bananas, sugarcane and urban activities.

On-farm studies are identifying confounding influences of pesticide formulations and adjuvants. The use of adjuvants is designed to reduce pesticide mobility off-farm. However, some studies have shown these effects are variable across soil types and climatic zones, leading to inconsistent results. Extreme weather events continue to be a risk for pesticide exports. Other challenges include capital costs and infrastructure changes to implement new management practices (see Question 5.3, Davis et al., this SCS).

Key uncertainties and/or limitations

The limited temporal data available (2016-2020) since the transition to the PRM at EOC restricts the capacity to determine if improvements in pesticide management and water quality outcomes are occurring. Year–on-year assessments are influenced by climate factors including weather extremes and can reflect short-term variations.

While application rates and timing are considered the major drivers of pesticide export at the local level, other factors including soil characteristics, soil sorption properties, and pesticide formulations can influence retention and export. However, these processes can be challenging to manage at the local level and often deliver confounding results.

Evidence appraisal

Overall, the relevance of the body of evidence for sources of pesticides was considered to be High. Collectively 64 of the 109 studies were considered to be of High overall relevance to the question with only 8 considered to be Low relevance. In contrast, the spatial relevance of the studies to the question was Moderate. Of the 109 studies, 43 covered multiple locations or a wide spatial context and were ranked High for spatial relevance, whereas 25 studies were focused on a single site or had limited spatial extent and therefore rated Low. Similarly, temporal relevance was rated as Moderate as most studies were temporally limited with only 25 of the 109 studies covering an extensive time period (i.e., multiple years). This outcome is consistent with expectations. Experimental studies, which accounted for 29% of the evidence, tend to be more constrained both spatially and temporally due to resourcing limitations. Monitoring and observational studies comprised 31% of the evidence, 23% were reviews and 17% were other types of studies including modelling. Overall, the spread of literature sources represents multiple lines of evidence and provides a balanced assessment of the pesticide influence on GBR catchments. The confidence in the body of evidence used to address the primary question is Moderate-High. In the evidence appraisal, the relevance of the studies to the main question was considered High, while the diversity of approaches was also High. Out of the 291 studies that were included in the second screening stage, 109 met the eligibility criteria and were used in the Evidence Summary. There was a level of variation among experimental studies in identified outcomes, which were justified based on fine scale contextual elements underpinning these approaches.

1. Background

Catchments draining to the Great Barrier Reef (GBR) cover 424,000 km^2 of north and central Queensland, from Cape York to the Bundaberg region (Australian & Queensland Government, 2021). For management purposes, the GBR catchment area includes 35 basins across 6 Natural Resource Management (NRM) regions. The major land use areas across GBR catchments comprise national parks/conservations area (15%), grazing (73%), forestry (4.6%), dryland cropping (2.4%), water (2%), sugarcane (1.2%), urban (0.7%), irrigated cropping (0.4%) and horticulture (0.2%) (Australian & Queensland Government, 2021). Mining and industrial activity is also present across multiple basins but represents less than 0.2% of area. Anthropogenic point and non-point source pollutants enter waterways of the GBR catchments from many of these activities and ultimately get discharged to the GBR. Pollutants detected in GBR catchment waterways include nutrients, hydrocarbons, pesticides, sediment, metals, plastics and personal care products with variable sources between regions and industries.

Annual freshwater discharge into the GBR averages around 73,500 gigalitres (GL) but can vary from as low as 20,000 GL in dry years to as high as 1,160,000 GL under extremely wet years (Australian & Queensland Government, 2021; Devlin et al., 2012). Depending on location and climatic patterns, riverine discharges are highly variable in timing and intensity across the different basins. Pollutants discharged to these areas have the potential to impact the ecology of both the freshwater and marine systems, and identifying the primary source, timing and volume of loads can influence management activities that can minimise impacts on aquatic ecosystems of the GBR (see Question 5.1, Negri et al., this Scientific Consensus Statement (SCS)).

Water quality issues have been recognised and monitored in the GBR catchment area since the 1990s (e.g., Cavanagh et al., 1999; Johnson & Ebert, 2000; Müller et al., 2000). The accumulating evidence of water quality decline and the risk this poses to the GBR resulted in the development of the first Reef Water Quality Protection Plan (RWQPP) in 2003 (The State of Queensland & Commonwealth of Australia, 2003). This plan underpinned processes and initiatives to halt and reverse the decline in water quality in the GBR from the adjacent GBR catchment area. The RWQPP was updated and revised in 2009 and 2013, and in 2018 was updated to become the current Reef 2050 Water Quality Improvement Plan (WQIP; Australian & Queensland Government, 2018). The 2050 outcome of the Reef 2050 WQIP is 'Good water quality sustains the Outstanding Universal Value of the Great Barrier Reef, builds resilience, improves ecosystem health and benefits communities' (Australian & Queensland Government, 2018).

Pesticides were identified as a potential risk to the health of the GBR as far back as the 1990s. During the 2000s, sugarcane production, grazing and other agricultural activities were identified as key contributors to pesticide exports across many GBR catchments (e.g., Bainbridge et al., 2009; Davis et al., 2008; Haynes et al., 2007; Mitchell et al., 2005; Packett et al., 2009; among others). During this period, grazing, agriculture and sugarcane production in particular, were identified as major contributors to pesticide exports (Mitchell et al., 2005).

The Paddock to Reef Integrated Monitoring Modelling and Reporting Program (Paddock to Reef program) was established in 2008 and included monitoring of pesticides at EOC as well as incorporating management practice adoption, a process which expanded over time. This is being achieved through a combination of incentives and initiatives at farm scale to encourage improvements in management practices as well as the introduction of regulations targeting agricultural land uses (King et al., 2013).

To provide better dissemination of the changes in water quality and progress towards improved management practices, the Reef Water Quality Report Card was established in 2009 to understand and monitor change in the quantity of sediments, nutrients and pesticides being delivered to EOC, the adoption of management practices in major land uses and the current catchment condition (Australian & Queensland Government, 2018). Between 2009 and 2016, pesticides were reported as a reduction in load at EOC with a target of 50% reduction in the overall load of the five priority Photosystem II (PSII) herbicides – ametryn, atrazine, diuron, hexazinone and tebuthiuron (Huggins et al., 2017).

In 2017, the assessment methodology shifted to a risk–based profile. The new approach focused on concentrations of pesticides at EOC to estimate the Pesticide Mixture Toxicity (PMT) rather than the previous loads-based approach (Australian & Queensland Government, 2018; 2022). The revised approach was designed to establish the proportion of aquatic species protected at measured pesticide mixture concentrations at a catchment level with a goal of achieving 99% species protection (Smith et al., 2017a; Warne et al., 2020b). With the shift in approach, there was also an expansion of the pesticide suite to include additional PSII herbicides as well as herbicides with different modes of action (non-PSII) and insecticides. Currently 22 pesticides are monitored using this approach (Australian & Queensland Government, 2018; 2021; 2022).

1.1 Question

Primary question	**Q5.2** What are the primary sources of pesticides that have been found in Great Barrier Reef ecosystems and what are the key factors that influence pesticide delivery from source to ecosystem?

The question was interpreted with the following sub-questions:

1) What are the major sources / land uses of pesticides across GBR ecosystems?
2) What are the key pesticides and pesticide mixture loads that have been found in the GBR catchment area?
3) What factors and processes influence the delivery and timing of delivery of pesticides into these ecosystems?

The scope and interpretation of these sub-questions is explained below.

What are the major sources / land uses of pesticides across GBR ecosystems?

Unlike other ecosystem stressors (e.g., nutrients and sediments), pesticides do not have a natural origin in GBR catchments. They are however, employed across a range of land uses and industries in the GBR catchments to manage weeds and pests. In this question, the main sources of pesticides are assessed for a number of identified land uses including sugarcane production, grazing, banana growing, horticulture, dryland and irrigated cropping and urban systems. While other land uses, including mining may use pesticides as part of their operational activities, the current relative contributions are considered to be very small and largely non-detectable within the downstream areas.

What are the key pesticides and pesticide mixture loads that have been found in the GBR catchment area?

The use of a particular pesticide or pesticide group differs among land use types and accordingly the types of pesticides and their relative proportions can differ among basins, depending on the upstream land uses. The review considers the different pesticide mixtures that are found within different basins and how they relate to land use sources.

What factors and processes influence the delivery and timing of delivery of pesticides into these ecosystems?

The export contribution of a given pesticide or pesticide mixture to the EOC is a function of land use, rainfall and climate factors, farm management techniques and catchment characteristics. These factors can be highly variable in both time and space and influence how much of an applied pesticide / mixture is delivered to the EOC.

1.2 Conceptual diagram

The conceptual diagram (Figure 1) provides a level of context to the primary question (i.e., What are the primary sources of pesticides that have been found in GBR ecosystems and what are the key factors that influence pesticide delivery from source to ecosystem?). This sets out the scope of the primary question and where the boundaries of the question lie. The sub-questions as set out above provide additional context to the primary question. The primary land use sources of pesticides included in the review are sugarcane, grazing, bananas, horticulture, dryland and irrigated cropping and urban. Herbicides, insecticides and fungicides are included, as well as consideration of pesticide mixtures. Delivery and timing of pesticide export is dependent on the source and several factors including pesticide chemistry properties, application rates and timing, climate factors and rainfall, and catchment characteristics. The diagram also demonstrates how the other questions within Theme 5 (Pesticides – catchment to reef) integrate into the conceptual model including distribution, impact and risks (Question 5.1, Negri et al., this SCS) and the minimisation of risk and land management (Question 5.3, Davis et al., this SCS).

1.3 Links to other questions

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

Links to other related questions	Q5.1 describes the spatial and temporal distribution of pesticides across all aquatic GBR ecosystems, the ecological impacts of these pesticides and evidence of risk from pesticide exposure. **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? Q5.3 identifies the most appropriate farm management practices that have been shown to be effective at reducing pesticide export to end-of-catchments. **Q5.3** What are the most effective management practices for reducing pesticide risk (all land uses) from the Great Barrier Reef catchments, and do these vary spatially or in different climatic conditions? What are the costs of the practices, and cost-effectiveness of these practices, and does this vary spatially or in different climatic conditions? What are the production outcomes of these practices?

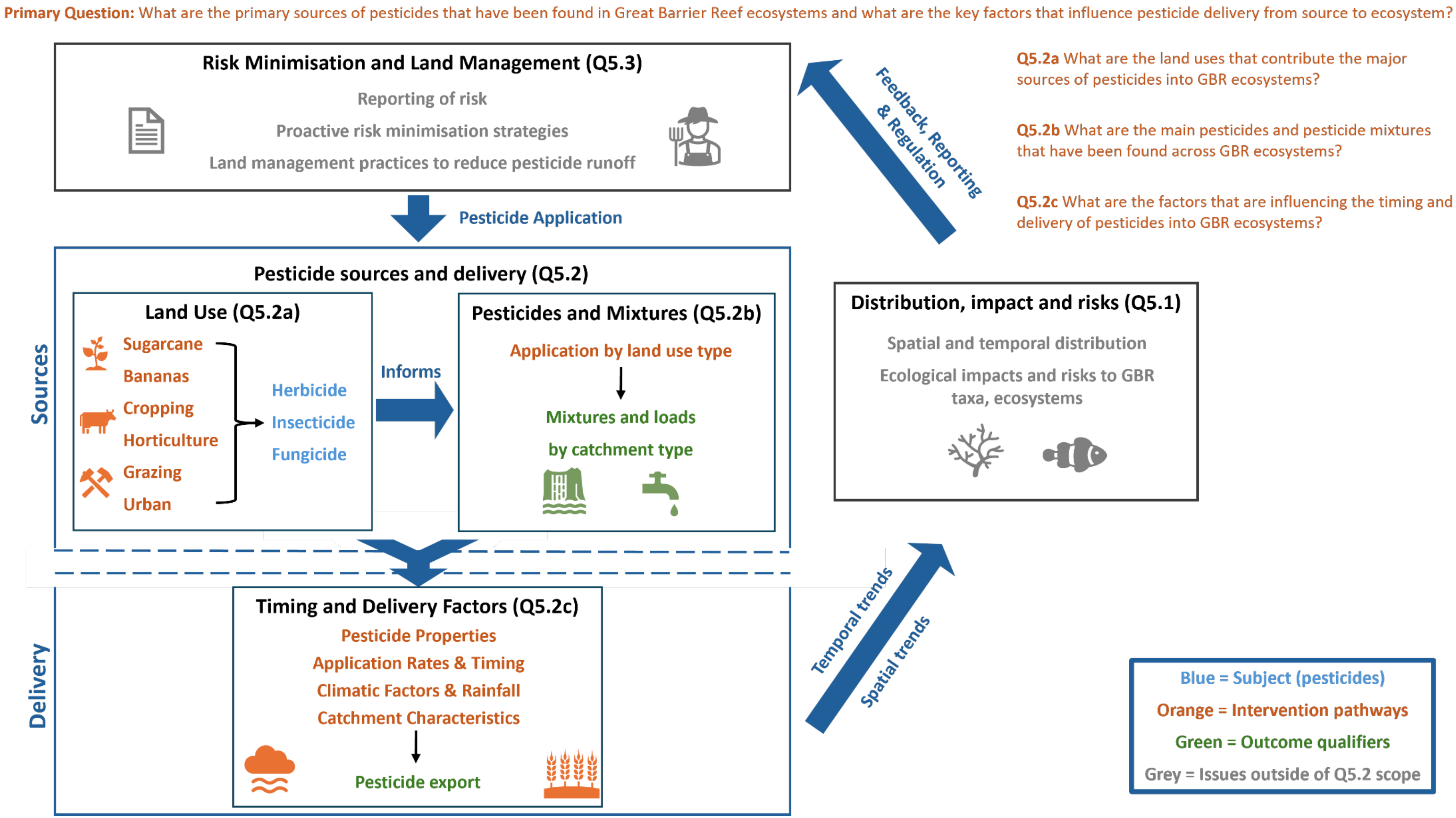


Figure 1. Conceptual diagram of drivers of pesticides into GBR ecosystems. The key processes identified in the review comprise land use sources including a range of agricultural and other activities (Q5.2a), the key pesticides and mixtures being measured at EOC (Q5.2b) and the processes that influence pesticide migration from source to EOC (Q5.2c). Links to other related questions (Questions 5.1, Negri et al., and 5.3, Davis et al., this SCS) are identified (see also below).

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

This question has been separated to three sub-questions:

1) What are the major sources / land uses of pesticides across GBR ecosystems?
2) What are the key pesticides and pesticide mixture loads that have been found in the GBR catchment area?
3) What factors and processes influence the delivery and timing of delivery of pesticides into these ecosystems?

The question elements are described in Table 1. Definitions are presented in Table 2.

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 5.2.

Question S/PICO elements	Question term	Description
Subject/Population	Pesticides in GBR catchments	The pesticides of concern are herbicides, insecticides, and fungicides.
Qualifier	Sources of pesticides in GBR catchments	Agriculture comprising sugarcane production, grazing, banana production, horticulture and dryland and irrigated cropping. Non-agricultural sources include urban activities.

[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
Intervention, exposure & qualifiers	Mixtures, timing and pathways of migration	Pesticide types, mixtures, preferential pathways of migration and climate / weather influences will be considered for loads being delivered into GBR ecosystems. Freshwater and groundwater pathways are the primary routes to be assessed. This section will not assess risk associated with pesticide exposure at an ecosystem level as this is covered in Question 5.1 (Negri et al., this SCS). It will also not focus on management processes designed to mitigate pesticide migration which is addressed in Question 5.3 (Davis et al., this SCS).
Comparator	Spatial and temporal variation in pesticides	Comparison of pesticides among catchments and upstream land use. Effect of seasonality, climate and weather on pesticide export.
Outcome & outcome qualifiers	Regional and catchment level sources and loads of pesticides	Primary sources of pesticides by land use. Key pesticides and pesticide mixtures in GBR catchments. Criteria influencing timing and export of pesticides to GBR catchments.

Table 2. Definitions for terms used in Question 5.2.

Definitions	
Pesticides	Pesticide is a generic term for any substance that is used to control animals, plants or other organisms regarded as an unacceptable threat to an activity or lifestyle. Pesticides for this review include herbicides, insecticides and fungicides. For the purposes of this review pesticides refer to active ingredients only and not commercial pest control formulations or trade names.
GBR catchment area / GBR catchments	Freshwater catchments discharging into the Great Barrier Reef World Heritage Area (GBRWHA).
Land use	The purpose for which an area of land is being used. For this review land use has been separated to eight main types – sugarcane, bananas and horticulture, grazing, dryland and irrigated cropping, urban, natural (including wetlands), and forestry.
Pesticide Mixtures	A pesticide mixture is considered a substance containing more than one active ingredient in its makeup (excluding water which is generally used as the primary solvent).
Adjuvant	A compound or substance that improves solubility, efficacy or potency of a pesticide.
Migration paths	Migration pathways include sorption to soil, movement into groundwater, movement across land surface, movement in surface water and movement via air as aerosols.

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 and Web of Science
- Google Scholar
- Queensland Government publications database and a manual search of the Reef 2050 WQIP website, plus authors' personal collections.

b) Search terms

Tables 3a-3c show a list of the search terms used to conduct the online searches.

Table 3(a). Sub-question 1- What are the major sources / land uses of pesticides across GBR ecosystems?

Question element	Search terms
Population (or Subject)	Pesticide, herbicide, insecticide, fungicide
Exposure/Intervention	Crops, agriculture, horticulture, forestry, grazing/pastoral, urban, industry, ports, sewage treatment plants (STP)
Outcome	Pesticide type, pesticide application, crop type, land use type, ports activities, urban stormwater, STP outfalls, groundwater.

Table 3(b). Sub-question 2- What are the key pesticides and pesticide mixture loads that have been found in the GBR catchment area?

Question element	Search terms
Population (or Subject)	Pesticide, herbicide, insecticide, fungicide,
Exposure/Intervention	Freshwater, catchments, mixtures of pesticides
Outcome	Catchment loads of pesticides, pesticide mixture types

Table 3(c). Sub-question 3- What factors and processes influence the delivery and timing of delivery of pesticides into these ecosystems?

Question element	Search terms
Population (or Subject)	Pesticide, herbicide, insecticide, fungicide
Exposure/Intervention	Application rate, season, rainfall, irrigation, flood, leaching, groundwater, half-life, pesticide matrix, mode of action, biological degradation, UV degradation, sediment sorption, dissolved fraction.
Outcome	Degradation products, mobility, persistence, release

c) Search strings

Table 4a – 4c show a list of the search strings used to conduct the online searches.

Table 4(a). Sub-question 1- What are the major sources / land uses of pesticides across GBR ecosystems?

Search strings
VERY BROAD PESTICIDES (Pesticide* OR herbicide* OR insecticide* OR fungicide*) AND (“Great Barrier Reef” OR “GBR”) AND (catchment*)
INCLUDE AGRICULTURE, HORTICULTURE, URBAN, INDUSTRY: (B) (Pesticide* OR herbicide* OR insecticide* OR fungicide*) AND (“Great Barrier Reef” OR “GBR”) AND (agric* OR hort* OR urban* OR graz* OR past* OR forest* OR storm* OR sewage* OR groundwater* OR port*)
INCLUDE CROPS: (Pesticide* OR herbicide* OR insecticide* OR fungicide*) AND (“Great Barrier Reef” OR “GBR”) AND (sugar* OR banana* OR cattle* OR plant* OR cotton* OR weed* OR crop*)
INCLUDE HABITAT: (Pesticide* OR herbicide* OR insecticide* OR fungicide*) AND (“Great Barrier Reef” OR “GBR”) AND (river* OR creek* OR fresh* OR estu* OR coast* OR chan* OR lagoon*)

Table 4(b). Sub-question 2- What are the key pesticides and pesticide mixture loads that have been found in the GBR catchment area?

Search strings
VERY BROAD GBR (Pesticide* OR herbicide* OR insecticide* OR fungicide*) AND (load*) AND (“Great Barrier Reef” OR GBR)
INCLUDE GBR CATCHMENT: (Pesticide* OR herbicide* OR insecticide* OR fungicide*) AND (load*) AND (“Great Barrier Reef” OR GBR) AND (catch*)
INCLUDE HABITAT: (Pesticide* OR herbicide* OR insecticide* OR fungicide*) AND (“Great Barrier Reef” OR “GBR”) AND (river* OR creek* OR fresh* OR estu* OR coast* OR chan *)

Table 4(c). Sub-question 3- What factors and processes influence the delivery and timing of delivery of pesticides into these ecosystems?

Search strings
VERY BROAD: (Pesticide* OR herbicide* OR insecticide* OR fungicide*) AND (“Great Barrier Reef” OR “GBR”) AND (application* OR rate* OR matrix*)
ADD MOBILISATION: (Pesticide* OR herbicide* OR insecticide* OR fungicide*) AND (“Great Barrier Reef” OR “GBR”) AND (applic* OR matrix* OR rainfall* OR groundwater* OR irrigation*)
INCLUDE CHEMISTRY: (Pesticide* OR herbicide* OR insecticide* OR fungicide*) AND (“Great Barrier Reef” OR “GBR”) AND (half-life* OR mode* OR degrad* OR diss* OR sorp* OR Kow*)
INCLUDE SEASON, SOILS: (Pesticide* OR herbicide* OR insecticide* OR fungicide*) AND (“Great Barrier Reef” OR “GBR”) AND (flood* OR season* OR run-off* OR irrig* OR soil*)

d) Inclusion and exclusion criteria

Several criteria were used to determine if a study or report was suitable for inclusion in the review (Table 5).

Table 5. Inclusion and exclusion criteria for Question 5.2 applied to the search returns.

Question element	Inclusion	Exclusion
Subject/Population	Studies relating to pesticides and pesticide usage in the GBR catchment area since 1990.	Historical studies and studies published before 1990. Studies not relevant to the GBR. Studies not relevant to the question. Studies focused on GBR marine systems. Studies focused on ecosystem or species risk assessment or stress. Studies with no pesticide linkages. Studies focused on social or risk practices.
Exposure or Intervention	Pesticide types and mixtures Application timing Catchment characteristics Pesticide chemistries	Pesticides of no relevance to GBR catchments. On-farm management studies. Studies with a post-harvest focus. Studies with a sediment movement focus.
Comparator	Spatial and temporal distribution among GBR NRM regions and catchments.	Studies not relevant to the GBR.
Outcome	Pesticide and pesticide mixtures by land use source. Pesticide mixtures at end-of catchment.	Pesticide risk at EOC
Language	English only	Non-English
Study type	Monitoring reports, modelling studies of transport and pesticide degradation processes, review studies, observational and experimental field studies.	Theoretical, modelling, statistical or laboratory studies with no linkage to field applications. Studies not available or behind a paywall.

3. Search Results

A total of 2,430 studies were identified through online searches for peer reviewed and published literature. Of these, 249 studies passed the initial screening phase. An additional 55 studies / datasets were identified manually through expert contact and personal collections, which represented 18% of the evidence. Following the second screening, 109 studies met the eligibility criteria and were included in the synthesis of evidence (Table 6) (Figure 2). Twenty studies were unobtainable (e.g., behind paywall) and were therefore excluded.

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

Date (d/m/y)	Search strings	Sources	
A) Academic databases		Scopus	Web of Science
16/02/2023	*5.2aA: (Pesticide* OR herbicide* OR insecticide* OR fungicide*) AND ("Great Barrier Reef" OR "GBR" OR "Queensland")*	*138 of 661*	*141 of 2131*
16/02/2023	*5.2aB: (Pesticide* OR herbicide* OR insecticide* OR fungicide*) AND ("Great Barrier Reef" OR "GBR" OR Queensland) AND (agric* OR hort* OR urban* OR graz* OR past* OR forest* OR storm* OR sewage* OR groundwater* OR port*)*	*107 (104) of 305*	*100 (97) of 1092*
17/02/2023	*5.2aC: (Pesticide* OR herbicide* OR insecticide* OR fungicide*) AND ("Great Barrier Reef" OR "GBR" OR Queensland) AND (sugar* OR banana* OR cattle* OR plant* OR cotton* OR weed* OR crop*)*	*105 (104) of 387*	*80 (76) of 1201*
17/02/2023	*5.2aD: (Pesticide* OR herbicide* OR insecticide* OR fungicide*) AND ("Great Barrier Reef" OR "GBR" OR Queensland) AND (river* OR creek* OR fresh* OR estu* OR coast* OR chan* OR lagoon*)*	*106 (102) of 278*	*113 (110) of 801*
17/02/2023	*5.2bA (Pesticide* OR herbicide* OR insecticide* OR fungicide*) AND ("Great Barrier Reef" OR GBR OR Queensland) AND (load*)*	*47 of 59*	*46 of 86*
17/02/2023	*5.2bB (Pesticide* OR herbicide* OR insecticide* OR fungicide*) AND (load*) AND ("Great Barrier Reef" OR GBR OR Queensland) AND (catch*)*	*33 (33) of 37*	*35 (35) of 44*
17/02/2023	*5.2bC (Pesticide* OR herbicide* OR insecticide* OR fungicide*) AND ("Great Barrier Reef" OR "GBR" OR Queensland) AND (load*) AND (river* OR creek* OR fresh* OR estu* OR coast* OR chan *)*	*27 (26) of 31*	*33 (31) of 42*
17/02/2023	*5.2cA (Pesticide* OR herbicide* OR insecticide* OR fungicide*) AND ("Great Barrier Reef" OR "GBR" OR Queensland) AND (appl* OR rate* OR matrix*)*	*92 of 316*	*99 of 1164*
17/02/2023	*5.2cB (Pesticide* OR herbicide* OR insecticide* OR fungicide*) AND ("Great Barrier Reef" OR "GBR" OR*	*116 (111) of 334*	*124 (122) of 1119*

Date (d/m/y)	Search strings	Sources	
	Queensland) AND (appl OR matrix* OR rain* OR ground* OR irrig*)*		
17/02/2023	*5.2cC (Pesticide* OR herbicide* OR insecticide* OR fungicide*) AND ("Great Barrier Reef" OR "GBR" OR Queensland) AND (half * OR mode* OR degrad* OR diss* OR sorp* OR Kow*)*	*12 (12) of 17*	*104 (99) of 736*
17/02/2023	*5.2cD (Pesticide* OR herbicide* OR insecticide* OR fungicide*) AND ("Great Barrier Reef" OR "GBR" OR Queensland) AND (flood* OR season* OR run* OR irrig* OR soil*)*	*135 (134) of 293*	*135 (133) of 670*
B) Search engine (e.g., Google Scholar)			
	(Pesticide OR herbicide* OR insecticide* OR fungicide*) AND ("Great Barrier Reef" OR "GBR" OR "Queensland")*	*59 of 17,100 (first 100) (43 already identified)*	
	Total items online searches	***249 (82 %)***	
C) Manual search			
Date/time	Source	Number of items added	
20/02/2023	*Detailed specific searches – Queensland Government Publications Portal*	*41*	
20/02/2023	*Personal Library Sources*	*11*	
02/05/2023	*External literature submissions*	*3 (none met inclusion criteria for Q5.2)*	
	Total items manual searches	***55 (18 %)***	

Web of Science (WoS) returned a greater number of items but the number of studies that were considered relevant was similar to Scopus. A Google Scholar search returned a very large number of hits but relevance was limited in the initial scan of 150 items and did not offer any additional items that had not previously been identified through WoS, Scopus, Qld Government Portal or personal collections.

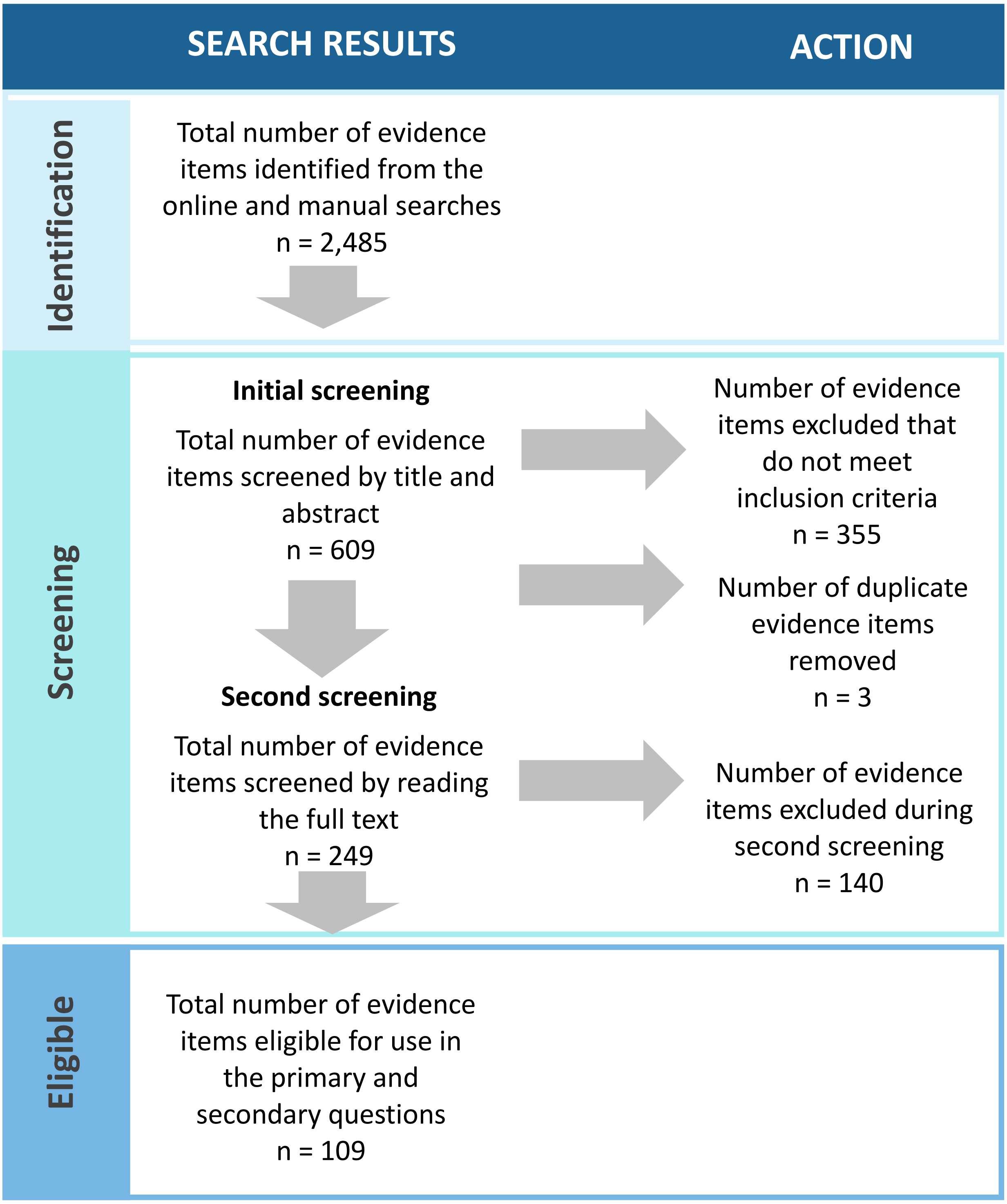


Figure 2. Flow chart of results of screening and assessing all search results for Question 5.2.

4. Key Findings

4.1 Narrative synthesis

4.1.0 Summary of study characteristics

A total of 109 eligible studies were found for Question 5.2. Almost all of the studies included GBR catchments, with the exception being a few papers highlighting land use links to pesticide sources that had indirect relevance to the GBR (e.g., southeast Queensland urban catchments).

Most evidence came from peer reviewed scientific journal articles post-1990, although several peer reviewed technical reports and conference proceedings were also included due to their direct relevance to the topic. Where technical reports were superseded by peer reviewed journal articles, the article was used for the review.

The papers comprised a mix of primary (experimental, observational/monitoring or modelled), secondary (reviews) and mixed studies (comprising a mixture of review and experimental processes). Primary studies (experimental and observational / monitoring) dominated and accounted for 60% of the literature included in the synthesis, although only 28% of the primary studies had a GBR-wide focus (Table 7).

A total of 54 studies included sources of pesticides as a characteristic in their assessment while 64 considered pesticide type / mixture and /or load considerations. In addition, 60 papers focused on the key factors that influence delivery of pesticides off-farm to the end-of-catchments (Table 7). Many of these papers covered elements of multiple characteristics e.g., reference to both land use type and pesticide types.

Collectively, 46% of studies had a GBR-wide scope with most coming from reviews. Ten of the studies had no temporal component, either being a one-off experimental approach or a modelled aspect with no temporal element (Table 7).

*Table 7. Summary of the primary characteristics evaluated, and the study approach used. *Export factors are factors that can influence pesticide migration. Note: some studies can include multiple factors so numbers may not always equal the total.*

	Location			Factors			Total
Study Type	GBR wide	GBR Catchment/s	Other	Land Use / Source	Pesticide Type / Loads	Export Factors*	
Experimental	3	21	8	14	18	26	**32**
Observational/ Monitoring	15	17	2	18	27	16	**34**
Review	18	2	5	14	10	11	**25**
Other	14	3	1	8	9	7	**18**

4.1.1 Summary of evidence to 2022

The focus of this review is to synthesise the key contributions of pesticides to end-of-catchment (EOC) in the GBR and their key drivers and migration influences. Pesticides, by definition, are environmentally active compounds designed to control unwanted plants and pests. Many pesticides, particularly older formulations can persist in soil, water and tissue for long periods, with residual effects caused by long-term accumulation in non-target plants and animals, often taking years to be detected and also persisting many years after use has been phased out (Cavanagh et al., 1999; Schneider, 2021; Thompson & Chauhan, 2022).

This review is constrained to the freshwater catchments of the GBR. Assessments pertaining to estuarine and marine waters are contained in Question 5.1 (Negri et al., this SCS), while management practices to reduce or remove pesticide use are detailed in Question 5.3 (Davis et al., this SCS).

Pesticides originate from a range of sources and land uses across GBR catchments. In 2012, it was estimated that 30,000 kg of PSII herbicides were delivered to EOC each year (Kroon et al., 2012). This was considered to be an underestimate of total contributions as many other pesticides are routinely used in the GBR catchment area (Brodie et al., 2015). The Reef Water Quality Protection Plan 2009 (Queensland Government, 2009) set a target of 50% EOC reduction in five priority PSII herbicides (ametryn, atrazine, diuron, hexazinone and tebuthiuron) by 2013 and management was focused on overall pesticide quantity at EOC. The initial loads-based approach did not account for the different ecological risk posed by each pesticide (Australian & Queensland Government, 2018). Investigation of the relative risk posed by different pesticides led to development of the Toxic Equivalent Load (TEL) or Toxic Equivalent Load diuron equivalent (TEq_{diuron}) (Smith et al., 2017a; 2017b) which accounted for a relative toxicity for each of the measured pesticides to provide an estimate of the level of risk posed to ecosystems.

Under the Reef 2050 Water Quality Improvement Plan (WQIP) 2017-2022 (Australian & Queensland Government, 2018), pesticide targets transitioned to an EOC concentration-based target rather than a loads based target (Warne et al, 2020b). This aligns directly with the outcome of the Reef 2050 WQIP, to have greater ecological relevance for protecting aquatic ecosystems of the GBR from pesticide impacts, and is compatible with the Australian and New Zealand Guidelines for Fresh and Marine Water Quality. The target is based on the concentrations required to protect at least 99% of aquatic species at the river mouth (Australian & Queensland Government, 2018). The rationale for the shift was to improve measurement of ecosystem risk and capture risks associated with other non-PSII herbicides (Smith et al., 2017a; 2017b; Waterhouse et al., 2017). This approach recognises that not all pesticides pose the same level of risk to aquatic ecosystems and allows programs to target improvements to reduce ecosystem risk rather just reducing overall pesticide quantity (Smith et al., 2017a; Warne et al., 2020b). While the new approach provides greater understanding of risk at EOC, data are not directly comparable to load estimates pre-2016 due the change in the targets and associated pesticide reporting strategy. Accordingly, change and /or improvement over time is difficult to determine across the two assessment types.

Pesticides and mixtures vary by basins and are associated with a range of factors including upstream land use, distance from source, pesticide type, rainfall, catchment topography, degradation processes and management strategies (Davis et al., 2014; Mitchell et al., 2005; Shaw et al., 2014). Collectively, working across industry, stakeholders, landholders, researchers and all tiers of government, a significant level of effort has gone into identifying, monitoring and managing sources and loads of pesticides across different land uses in the GBR catchment area (Telford et al., 2017; Waterhouse et al., 2012). Pesticide retention and/or migration is strongly influenced by a combination of pesticide chemistry and associated adjuvants, watering /irrigation regimes (e.g., furrow irrigation) and the climatic conditions under which it is used (e.g., Dollinger et al., 2018; Fillols & Davis, 2021a; Shaw et al., 2014). The pesticide chemistry can also determine the proportion of pesticide found in the dissolved or particulate phases. Most studies measure total concentrations which includes all phases. The tropical and subtropical conditions such as those found in the GBR catchment area have a strong influence on pesticide migration, degradation and persistence (Lewis et al., 2016; Shaw et al., 2014).

A baseline assessment in 2016 associated with the shift from a loads-based approach to risk-based assessed the 35 basins (Australian & Queensland Government, 2018). Seventeen of the basins (in 5 NRM regions) were assessed to have already met the 2025 target of 99% species protection and were not monitored for the 2020 condition in the Reef Water Quality Report Card 2020 (Table 8). Collectively this amounts to approximately 47% of the overall GBR catchment area. The Mackay Whitsunday NRM region currently has no basins meeting the 2025 target.

The Cape York and Burdekin NRM regions have the greatest proportion of basin area that is considered to have met the 2025 target for pesticides (Table 8). Two basins (Mossman in the Wet Tropics and

Calliope in the Fitzroy) did not meet the target in the 2016 baseline survey, but are not currently monitored for pesticides (Australian & Queensland Government, 2021).

Table 8. GBR EOC meeting baseline 99% aquatic species protection in 2016 (Australian & Queensland Government, 2021). https://reportcard.reefplan.qld.gov.au/home?report=overview&year=611f443aba3074128316eb07

Region	Total No. basins	Total Basin Area (km^2)	No. Basins ≥ 99% aquatic species protected	% Regional Basin Area Meeting Target
Cape York	7	42,982	7	100
Wet Tropics	8	21,693	2	19.8
Burdekin	5	140,593	3	96.1
Mackay Whitsunday	4	9,005	0	0
Fitzroy	6	155,494	4	7.0
Burnett Mary	5	53,015	1	7.7

What are the major sources / land uses of pesticides across GBR ecosystems?

Land use across the GBR catchment area is variable and includes a range of activities. Land uses that potentially contribute pesticides to EOC include agriculture and grazing, forestry, mining and urban centres. Sugarcane production, dryland and irrigated cropping and horticulture (including bananas) comprises 4.2% of overall GBR catchment area while grazing comprises 73% (Australian & Queensland Government, 2021). Forestry covers around 4.6% and urban areas 0.7% while mining is <0.1%.

Land use is a key driver of the types of pesticides used in production. Some land uses have a limited suite of pesticides associated with their activities. For example, in the GBR catchment area, tebuthiuron is primarily linked with grazing activities, while bananas tend to be glyphosate and glufosinate-ammonium dominated (Devlin et al., 2015). Other industries such as sugarcane, horticulture and urban areas use a much wider range of pesticides comprising PSII and non-PSII herbicides and insecticides (Bainbridge et al., 2009; Devlin et al., 2015; Lewis et al., 2009; Warne et al., 2020a). As such, primary land use may not always be a key indicator of pesticide risk contribution (Rippy et al., 2017; Wijesiri et al., 2021). Monitoring in GBR basins however, has shown that sugarcane and grazing are the greatest overall contributors to gross overall pesticide loads (e.g., Bartley et al., 2017; Brodie & Landos, 2019; Brodie et al., 2015; Kroon et al., 2012; Murphy et al., 2013; Smith et al., 2012; Thorburn et al., 2013; Warne et al., 2020a; among others). Both these land uses are considered major contributors to pesticides at EOC, although the contributions are not evenly spread across basins or sources.

Modelling reported in the 2017 SCS identified sugarcane as the greatest land use source of pesticides (>97%) across the Wet Tropics, Burdekin, Mackay Whitsunday and Burnett Mary NRM regions, with no significant contributions from the Cape York and Fitzroy NRM regions where most contributions are from grazing (77%) and dryland cropping (23%) (Bartley et al., 2017). The toxic equivalent load (TEL), which incorporates a measure of ecological relevance to the pesticide load, was greatest for the Wet Tropics and Mackay Whitsunday NRM regions (Bartley et al., 2017; Smith et al., 2017a; 2017b). Although the Fitzroy NRM recorded high loads of tebuthiuron, which is primarily associated with grazing activities, it has a relatively low TEL compared to other PSII herbicides resulting in an overall lower TEL at EOC for the Fitzroy. There are no indications that the main sources of pesticide contributions have changed significantly since the 2017 SCS (Bartley et al., 2017; Warne et al., 2020a; Waterhouse et al., 2017).

Sugarcane is a dominant source of EOC pesticides (e.g., Bartley et al., 2017; Spilsbury et al., 2020; Warne et al., 2020a). Due to the large number of pesticides registered for use in sugarcane growing, waterways downstream of significant sugarcane growing areas have reported the greatest number of pesticides in mixtures (Spilsbury et al., 2020; Warne et al., 2020a).

Other agricultural land uses including dryland and irrigated cropping, horticulture and banana growing can also use large amounts of pesticides. However, with the exception of the Fitzroy and Burnett Mary NRM regions, their relative contribution to EOC pesticide loads is negligible (Bartley et al., 2017). This is in part due to their relatively small land use proportion in the catchments where they are present (Warne et al., 2020a).

Similarly, urban areas have not been considered a major source of pesticides to the GBR, although localised hot spots are considered to occur (Brodie et al., 2019). Catchment specific pesticide patterns are understood to be a common characteristic of urban catchments in Australia even though overall loads and concentrations are generally lower than North American and European catchments (Rippy et al., 2017). In addition, as many urban and industrial activities are point source contributors, they can be actively managed through water treatment and other processes (Brodie et al., 2015; Rippy et al., 2017).

What are the key pesticides and pesticide mixture loads that have been found in the GBR catchment area?

At the commencement of the GBR Catchment Loads Monitoring Program (GBRCLMP) in 2009, attention was focused on PSII herbicides which were considered to have the greatest contribution to the EOC pesticide loads (The State of Queensland & Commonwealth of Australia, 2003). The earlier (2009-2016) monitoring programs reported load contributions from the five major PSII herbicides: ametryn, diuron, atrazine, hexazinone and tebuthiuron (Wallace et al., 2014).

In 2015-16, the GBRCLMP measured EOC PSII herbicides in all GBR basins (Huggins et al., 2017). The GBR-wide 2015-16 annual loads were: tebuthiuron (1,000 kg), atrazine (780 kg) and diuron (660 kg) (Huggins et al., 2017). Atrazine and diuron were detected in all monitored basins, while hexazinone was detected in all basins except the Burdekin and Haughton basins. Collectively these overall loads translated to 750 kg TEL diuron equivalent (TEq_{diuron}) with diuron contributing around 87%, hexazinone 7.4%, atrazine 3%, tebuthiuron 2.6% and ametryn 0.4% (Huggins et al., 2017).

The current (post-2016) GBRCLMP monitors a suite of 86 pesticides and degradation products in 24 basins, the basins that have already met the target are not monitored and include all Cape York basins, Black, Don, Styx, Shoalwater, Waterpark, Boyne and Baffle. Pesticide risk will be reassessed with the next baseline assessment or when there are major land use changes that might affect pesticide run-off (Australian & Queensland Government, 2018; 2022). There is insufficient data to report condition for the Mossman and Calliope basins. The suite of pesticides (referred to as 'reference' pesticides) used for the risk assessment (Tables 8-9) is restricted to 22 pesticides comprising 19 herbicides (including 9 PSII herbicides) and 3 insecticides monitored at EOC (Australian & Queensland Government, 2022). The GBRCLMP Pesticide Reporting Portal[8] includes two additional pesticides in its guidelines (Water Quality & Investigations, 2020). No fungicides are currently included in the EOC risk assessments.

Overall, PSII herbicides continue to have the greatest contribution to EOC pesticides. In 2020, PSII herbicides accounted for around 57% of total contributions across all GBR catchments, with other herbicides contributing 35% and insecticides 7% respectively (Neelamraju et al., 2020). This represents an increase in the relative contribution of PSII herbicides to the overall pesticide load at EOC since 2016 (Table 9). A wider review of monitoring data from 2011 and 2016 found that 15 of the 16 pesticides contributing to the overall EOC ecological risk were herbicides, with imidacloprid (an insecticide) the only non-herbicide (Spilsbury et al., 2020).

At a basin level, the relative pesticide contribution varies depending on upstream land use. Under the 2019/20 GBRCLMP basins could be separated to five major groups based on the relative contributions of different pesticide types (Neelamraju et al., 2020; Table 9). PSII herbicides either dominated or were a major contributor (>25%) in 13 of the 16 monitored basins. The Ross (Burdekin NRM region) and Kolan (Burnett Mary NRM region) basins had ≤1% contributions from PSII herbicides, with non-PSII herbicides dominating. This reflects the respective land use differences in these basins compared to other GBR basins. Both basins are reasonably small and have limited sugarcane or other agricultural land use

[8] https://storymaps.arcgis.com/stories/c0f0c6d7d88a4fd3a5541fe59f41ff75

(Australian & Queensland Government, 2021). Five basins recorded ≥20% relative contribution from insecticides (Table 9).

*Table 9. Relative contribution (%) of pesticide type to overall pesticide risk at end-of-catchment (using the Pesticide Risk Metric) *2016 Baseline data for all GBR basins from Warne et al., 2020b (does not add to 100% due to use of median contribution). NOTE: Those basins that are already meeting 2025 target (i.e., all Cape York basins, Black, Don, Styx, Shoalwater, Waterpark, Boyne and Baffle) or those that have insufficient data (Mossman and Calliope) have not been included. All other data from the 2020 Reef Water Quality Report Card (Australian & Queensland Government, 2021, Neelamraju et al., 2020). '-' indicates no data.*
https://reportcard.reefplan.qld.gov.au/home?report=overview&year=611f443aba3074128316eb07

Region	Basin	2016 Baseline			2020 Contribution		
		PSII	Other Herbicides	Insecticides	PSII	Other Herbicides	Insecticides
		47*	**32***	**17***	**57**	**35**	**7**
Wet Tropics	Herbert	61	22	17	71	24	5
	Johnstone	50	32	18	62	38	<1
	Mossman	53	36	11	-	-	-
	Mulgrave-Russell	46	26	27	42	25	33
	Murray	63	23	14	64	13	23
	Tully	59	20	21	68	32	<1
Burdekin	Haughton	61	34	5	59	39	2
	Ross	1	79	20	1	77	22
Mackay Whitsunday	O'Connell	60	27	13	69	31	<1
	Pioneer	59	24	17	59	22	19
	Plane	62	26	12	55	37	8
	Proserpine	48	28	24	50	30	20
Fitzroy	Calliope	24	70	6	-	-	-
	Fitzroy	35	65	<1	31	69	<1
Burnett Mary	Burnett	51	43	6	67	27	6
	Burrum	34	60	6	28	72	<1
	Kolan	19	56	25	<1	69	31
	Mary	23	69	23	25	66	9

Insecticides have only been included in the GBRCLMP since 2016, when the pesticide suite was expanded (Australian & Queensland Government, 2022). However, several insecticides have been monitored since 2009. Imidacloprid, is the most commonly detected insecticide across GBR catchments and has been detected in around 54% of samples since 2009 (Warne et al., 2022). Increased detection of imidacloprid is linked to sugarcane, banana growing and urban areas. Banana farming had a greater effect on imidacloprid detection compared to sugarcane but its relatively small and use area in these basins reduced the overall contribution at EOC. Urban land use was also considered a higher contributor to imidacloprid detection, but like bananas, the relatively low land use area masked EOC proportions (Warne et al., 2022).

Fungicides have rarely been reported as a major contributor to EOC pesticide loads and are not included in the Reef Water Quality Report Card reporting (Australian & Queensland Government, 2022).

What factors and processes influence the delivery and timing of delivery of pesticides into these ecosystems?

Factors influencing export of pesticides from a given land use are complex and driven by a range of interacting influences. Pesticide properties including degradation profiles, application rates and timing in conjunction with intensity of rainfall post-application are considered to be key drivers (e.g., Silburn et al., 2023). Other factors including irrigation activities, climatic conditions - particularly extreme weather events, catchment characteristics and size can all contribute to pesticide export (e.g., Devlin et al., 2012; 2015; Fillols & Davis, 2021a; 2021b; Rippy et al., 2017; Thorburn et al., 2013).

Pesticide properties

Variations in pesticide chemistry, use of alternate pesticides and associated adjuvants can influence off-farm contributions under similar conditions (Davis et al., 2014; Silburn et al., 2023). Typically, pesticides with more polar chemistries (water-soluble) such as hexazinone and 2,4-D have lower sorption rates and are more vulnerable to dispersal, particularly under rainfall or irrigation events (Silburn et al., 2023).

In contrast, those pesticides with less polar chemistries bind more readily to soils but soil composition, including organic carbon and clay content can very strongly influence their binding to soil (Lewis et al., 2016). One study reported up to 33% of measured diuron was found to be particle-bound (Davis et al., 2012). Most reporting of pesticide concentrations off-farm and at EOC are reported as total concentrations, incorporating both the dissolved and particulate phases. In addition, the sorption characteristics can vary over time with the potential for subsequent migration of pesticides both laterally and through the soil profile and into shallow groundwater (Karim et al., 2021; Thornton & Elledge, 2016). Soil binding potential can also vary with the use of adjuvants. Fillols and Davis (2021a; 2021b) found contrasting results in soil binding capacities with the use of adjuvants under varying conditions.

Although generally considered to be a lower risk option, the transition from PSII herbicides to 'newer' alternative herbicides including imazapic and fluroxypyr still carries risk. In many cases although these newer pesticides meet regulatory safety requirements (APVMA, 2019), ecological risks are generally less well known and, in many cases, can carry a similar environmental risk profile to older chemistries (Davis et al., 2014).

Degradation rates, through a combination of soil pH, photolysis, hydrolysis and microbial degradation are generally greater under tropical conditions, although this is not consistent across all regions or all soil types (Thorburn et al., 2013). For example, drier conditions and associated lower soil moisture has been shown to reduce degradation rates for some pesticides (Shaw et al., 2014). However, in terms of overall pesticide persistence, enhanced degradation processes tend to be more rapid under tropical conditions. This can lead to farmers adjusting the on-farm application rates in an attempt to overcome these issues, which can lead to perverse outcomes (Lewis et al., 2016).

The fundamental chemical properties of the active ingredient/s in pesticides are often further complicated due to variations in contributions from adjuvants including surfactants, along with tweaks to pesticide formulations to improve wettability or solubility for application purposes. For some "off the shelf" pesticides, the branded formulations comprise a mix of more than one active ingredient (e.g., Barrage, Grazon) which can influence solubility and/or sorption factors.

Application timing & rates

Farm and catchment scale assessments of pesticide partitioning between dissolved and particulate phases found that the majority of pesticide load was transported in the dissolved fraction but there was relatively wide variability in outcomes, even for the same pesticide (Davis et al., 2012). Variability in pesticide runoff appears more closely related to the residual pesticide concentration at the time of a rainfall event than the particular properties of the pesticide (Thorburn et al., 2013). Residual concentrations at time of export are also strongly linked with application rates, with a number of studies highlighting the relationship between application rate and proportion of pesticide exported (e.g., Nachimuthu et al., 2016; Oliver et al., 2014).

A range of studies have identified that the critical time period for post-application pesticide runoff is in the 1-25 days post-application period (e.g., Davis et al., 2013; Ross et al., 2017). These effects have been measured under both natural and simulated conditions across a range of GBR catchments. Rainfall simulation studies (e.g., Fillols & Davis, 2021b; Melland et al., 2016; Silburn et al., 2013) have demonstrated that pesticide runoff is enhanced in the period immediately after application. Additionally, for many of the tested herbicides, runoff was in the dissolved phase, irrespective of their reported partitioning coefficients (Melland et al., 2016; Silburn et al., 2023).

For irrigation programs, runoff effects post-application are considered to be similar to rainfall events. Irrigation strategies can be a major contributor to pesticide runoff with furrow irrigation being identified as a source of off-farm pesticide migration (Carroll et al., 2012). Shifts in pesticide application regimes (e.g., from broad acre to spot or band application techniques have been identified as effective in reducing herbicide runoff (Davis & Neelamraju, 2019; Oliver et al., 2014, see also Question 5.3, Davis et al., this SCS). The greatest losses tend to be associated with the first irrigation event, with subsequent export reduced (Davis et al., 2013). The ecological risk is potentially greater under irrigated conditions though, as full flushing of the receiving environment (and associated diluting regimes) may not occur, and local systems may suffer longer exposure periods (Davis et al., 2013).

The challenges associated with out-of-season rainfall as well as unpredictable intense localised storm events mean optimising application timing can be difficult to manage in real-time. These challenges are greater in many of the catchments that are subject to the higher pesticide risk (Lewis et al., 2016).

Climatic factors & rainfall

Overall, across GBR catchments, pesticide export loads tend to be higher in wetter than average years while pesticide export concentrations tend to be higher across average to drier years (Davis et al., 2016; Devlin et al., 2015). This can be explained by a combination of factors governing solute transport and volumes.

The higher rainfall, coastal catchments in the Wet Tropics and Mackay Whitsunday NRM regions have year-round base flows, more frequent runoff events and typically short flow transit times compared to dryland grazing catchments in the Burdekin and Fitzroy NRM regions. Solute and sediment exports from all these catchments are influenced by climate patterns and associated effects on vegetation cover, runoff intensity and streamflow thresholds (Brodie et al., 2012; Davis et al., 2016; see Questions 3.4, Wilkinson et al., and 4.5, Burford et al., this SCS).

Those systems with higher rainfall intensities have increased risk of pesticide migration. Monitoring in the Barratta Creek catchment using multiple techniques reported high levels of a number of pesticides at the onset of first wet-season rainfall events with subsequent decreasing concentrations with additional wet season rainfall events. However, the effects are complex as there was a level of pesticide specificity, with not all pesticides reflecting the same 'first-flush' influence (O'Brien et al., 2016). Similar effects were reported for the lower Burdekin floodplain across a five-year monitoring period indicating 'first-flush' and early wet season rainfall events are responsible for a significant proportion of herbicide load export (Davis et al., 2012).

Intense weather events such as cyclones and floods, also increase the potential for pesticide migration. This has been demonstrated in studies measuring pesticides in first flush flows and under extreme weather events (e.g., Brodie et al., 2017; Devlin et al., 2012). Small scale in-depth studies have demonstrated the temporal nature of pesticide concentrations through a flood event. Novic et al. (2017) reported 86% of measured herbicide load was delivered during a 4-day flood event, with 11% delivered pre-flood (40 days) and 3% delivered post-flood (22 days) in the lower Burdekin floodplain, further highlighting the influence severe weather events can have on pesticide export (Novic et al., 2017).

Although most pesticide export to EOC is via surface water under early wet season 'first-flush events, some export occurs via groundwater pathways (Davis et al., 2016). This is both catchment and climate dependent as there are large variations in aquifer connectivity and size across different catchments. During low- or no- flow periods in surface water systems, groundwater connectivity can be important and any associated stress inducing compounds can influence aquatic ecosystem health (Davis et al., 2016).

Unlike surface water flow patterns, groundwater contributions can have significant lag effects from the timing of on-farm application, causing a mismatch between source and sink in terms of understanding pesticide migration. Pesticide seepage to groundwater from surface application has been documented in both the Wet Tropics catchments and the lower Burdekin floodplain (Karim et al., 2021; Shishaye et al., 2021; Vardy et al., 2015). Migration to groundwater is typically slower and dependent on soil characteristics and underlying geology which can influence migration rates (Shishaye et al., 2021; Vardy et al., 2015). Karim et al. (2021) detected several herbicides and their respective degradation products in groundwater in Wet Tropics catchments up to six years post-application. In addition, degradation processes in groundwater rarely reflect surface processes, resulting in varying half-lives for many pesticides (Karim et al., 2021; Lewis et al., 2016). While there is some, albeit limited information on groundwater migration, there are no identified studies on the potential impact of pesticides on groundwater based (stygofauna) communities.

Catchment characteristics & size

Catchment activity and land use is strongly related to pesticide contributions. Recent studies have shown a strong correlation between the number of measured pesticides in GBR wetlands and the percentage of intensive sugarcane agriculture within 1 km of the wetland (Vandergragt et al., 2020). Other studies also recognise the importance of distance from source to pesticide concentration (Lewis et al., 2016; Thorburn et al., 2013; Warne et al., 2020a). Other studies have demonstrated similar relationships between land use and pesticide concentrations (e.g., Nahar et al., 2023; Warne et al., 2022).

Relative land use area for a given activity is also a key influence on pesticide contributions. Banana growing is recognised as being a large user of pesticides, however the relative land use area within a catchment or basin is generally small, reducing their overall EOC contributions. This is similar for urban activities (Warne et al., 2022).

Both within and across catchments, basins and Regions, soil composition is highly variable. These variables include carbon composition, clay fractions, and soil pH, which can influence pesticide sorption characteristics. Minor changes in soil composition can lead to variability in sorption rates and binding capacities that are considered unpredictable and can occur at a within paddock scale as well as across catchments and regions (e.g., Grant et al., 2015; Lewis et al., 2016; Shaw et al., 2014).

Uncertainties associated with pesticide export processes

A range of uncertainties exist that continue to be associated with managing pesticide export at a farm scale. The greatest challenge with these issues is they tend to be localised issues that require specific approaches. These factors are highly inter-related such that a modification in one approach can often result in unintended management outcomes, despite best efforts. For example, comparison of the use of a surfactant as part of the pesticide spray mixture reduced lateral movement to a greater extent but increased vertical transport through the soil profile when compared to surfactant use in the irrigation water (Dollinger et al., 2018). Similarly, contrasting responses to the use of soil binding adjuvants when applied to trash and bare soil demonstrates the challenges associated with managing pesticide export at the farm level (Fillols & Davis, 2021a). These highlight the complexity of the interactions occurring at a paddock level, which only increase when moving to a catchment or basin level. Collectively the range of issues underpinning pesticide transport processes can make effective management strategies at the paddock challenging (e.g., Davis et al., 2014).

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

Thirty-five of the 109 papers reviewed were published between 2016 and 2023, comprising almost a third of the studies. Findings from these studies include:

- There have been no significant changes to land use sources of pesticides since the 2017 SCS. Sugarcane continues to be the largest single contributor to toxic load at EOC. There are smaller scale influences from other land uses including bananas and urban activities, but their overall relative contributions are small.

- Between 2016 and 2020, the relative contribution of PSII herbicides to the overall pesticide risk has increased from 47% to 57%, other herbicides have increased from 32% to 35% while insecticides have decreased from 17% to 7%. These findings do not necessarily indicate a reduction in the use of insecticides but their relative contribution to the overall influence is lower. The shifts in relative contributions are not consistent across all catchments.
- PSII herbicides are strongly linked with agricultural activities, particularly sugarcane. Only catchments with little agricultural activity did not have a major contribution from PSII herbicides.
- Imidacloprid was the most commonly detected insecticide in GBR catchments. Sugarcane, bananas and urban activities were identified as the major contributors. However, the relatively small land use proportion from bananas and urban areas reduced the proportion of imidacloprid delivered at EOC.
- Reducing pesticide export at the paddock scale can be challenging due to unpredictable localised rainfall and intensity, and intrinsic pesticide properties. Variations in pesticide chemistry, use of alternate pesticides and associated adjuvants can influence export of pesticides off-site. Typically, pesticides with more polar chemistries (water-soluble) such as hexazinone and 2,4-D have lower sorption rates and are more vulnerable to dispersal, particularly under rainfall or irrigation events. First flush conditions are responsible for the greatest pesticide migration risks. Application rates and timing are both negatively correlated with runoff risk.

4.1.3 Key conclusions

The most recent information on the sources, types and timing of pesticide delivery into GBR catchments has been captured under the GBR Catchment Loads Program which reports annually on a financial year scale.

- Overall, there is no substantive evidence to indicate that the main land use contributions to pesticide concentrations in the GBR catchment area have significantly changed since the 2017 SCS.
- Sugarcane areas are the largest contributor to end-of-catchment pesticide concentrations, dominated by photosystem II inhibiting herbicides (PSII herbicides). While pesticides are used over large areas of grazing lands, the relative ecological toxicity of the dominant pesticide, tebuthiuron, is low compared to other PSII herbicides. Other land uses including, horticulture, banana growing and urban areas can be large users of some pesticides, but their total area within the GBR catchment area is relatively small.
- Herbicides, specifically PSII herbicides, are the most common and abundant pesticide type measured in EOC monitoring followed by other herbicide types and insecticides. Catchments with minimal agricultural activity, such as the Ross and Kolan basins, have the lowest PSII herbicide contributions.
- Imidacloprid is the most commonly detected insecticide in GBR catchment area and is associated with banana, sugarcane and urban activities. However, the relatively small proportion of land for bananas and urban areas reduced the proportion of imidacloprid delivered to the EOC from these land uses.
- The key factors that influence export of pesticides to the GBR are pesticide application rates, the timing between pesticide application and rainfall, irrigation regimes, and pesticide properties such as persistence. Other factors that can influence delivery of pesticides to the GBR include soil characteristics, pesticide formulations, climatic conditions and particularly extreme weather events, and catchment characteristics.
- The 2009 to 2016 GBR Catchment Loads Monitoring Program focused on end-of-catchment loads with a target of 50% reduction in five key PSII herbicides (ametryn, atrazine, diuron, hexazinone and tebuthiuron) by 2025. In 2017, the assessment methodology shifted to a risk-based profile, assessing concentrations of 22 pesticides (including non-PSII and PSII herbicides

and three insecticides) at end-of-catchment locations to estimate ecological risk in a Pesticide Risk Metric.

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

4.1.4 Significance of findings for policy, management and practice

The shift to a risk-based approach provides the capacity for determining where the greatest risk to aquatic ecosystems lie, despite some of the identified uncertainties in applying this information at land use level. While it provides greater insight into ecological risk at EOC, it removes some of the capacity of stakeholders to use this information to inform their activities at the paddock level.

The change in approach does allow predictive risk-based assessments to be made for the GBR lagoon that is the receiving environment for freshwater flows.

The recent findings have shown that trends can be variable year on year and longer-term trends are necessary to determine if real improvement in EOC pesticides is occurring.

4.1.5 Uncertainties and/or limitations of the evidence

Major uncertainties or limitations in the evidence identified in the review include:

- The shift to a risk-based (concentration) approach since 2016 has resulted in cessation of load reporting for end-of-catchment assessments (Warne et al., 2020b). This shift removes the more direct link between management practices and pesticide exports which can be useful information for understanding and managing contributions at a paddock scale.
- Changes in pesticide regulations, farming practices, increasing climate variability have also created challenges for pesticide management at the farm level.
- Continued reliance on non-tropical studies (e.g., of pesticide mobility, sorption, degradation) risks over- or under- estimating pesticide behaviours when applied to tropical and subtropical Queensland conditions.
- While application rates and timing are considered the major drivers of pesticide export at the local level, other factors including soil characteristics, soil sorption properties, and pesticide formulations can influence retention / export. However, these processes can be challenging to manage at the local level and often deliver confounding results.

4.2 Contextual variables influencing outcomes

Table 10. Summary of contextual variables for Question 5.2.

Contextual variables	Influence on question outcome or relationships
Climate change (or climate variability)	Climate variability as an additional contextual variable did not factor highly in the questions as rainfall frequency and intensity was a key factor in sub-question 3.
Application rate & application timing	The volumes of pesticide applied at the paddock level is considered a key factor in the amount that is potentially exported.
Timing of pesticide application	The timing of pesticide application is strongly linked with rainfall timing and intensity which influences runoff potential.
Soil characteristics	Soil characteristics and associated sorption capacity influences retention and migration of pesticides through the soil profile.
Pesticide formulations	Changes in pesticide formulations can influence retention capacity of pesticides, increasing or decreasing export.

4.3 Evidence appraisal

Relevance

Overall, the relevance of the body of evidence for sources of pesticides was considered to be High. Collectively, 64 of the 109 studies were considered to be of High overall relevance to the question with only 8 considered to be Low relevance. In contrast, the spatial relevance of the studies to the question was Moderate. Of the 109 studies, 43 covered multiple locations or a wide spatial context and were ranked High for spatial relevance, whereas 25 studies were focused on a single site or had limited spatial extent and were therefore rated Low. Similarly, temporal relevance was rated as Moderate as most studies were temporally limited with only 25 of the 109 studies covering an extensive time period (i.e., multiple years). This outcome is consistent with expectations. Those studies considered to be of lower relevance to the question were either focused on a single pesticide or had a strong modelling link which although providing some relevant conceptual information, typically had lower direct relevance to the question. Many studies had either a limited spatial or temporal focus resulting in them being considered of slightly lower relevance than studies with a whole of GBR focus. Experimental studies, which accounted for 29% of the evidence, tend to be more constrained both spatially and temporally due to resourcing limitations.

Consistency, Quantity and Diversity

In total, 109 studies were eligible for inclusion in the review. Two academic databases were searched along with additional Queensland Governments databases and an initial review of Google Scholar returns. In the Authors professional opinion, the combination of these searches resulted in the majority of peer reviewed published work being captured. All aspects of the question were covered.

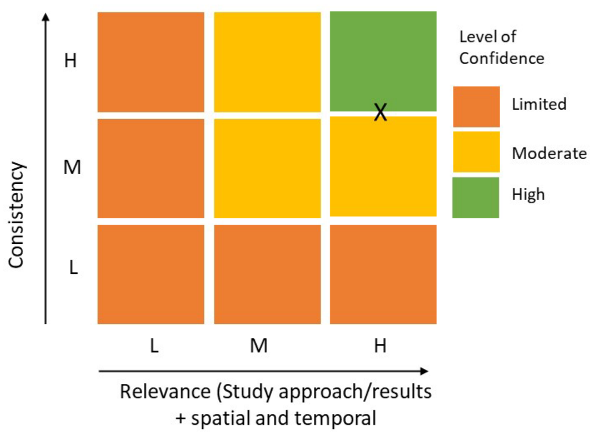
Collectively, monitoring and observational studies comprised 31% of the literature (including the GBRCLMP reporting). This was slightly lower than anticipated and just under half the studies were considered to cover the entire GBR catchment. Experimental studies comprised 29% of the studies included in the review while reviews comprised 23% of the literature. Reviews tended to collate studies from a range of sources so typically provided greater temporal and spatial extent than experimental studies, although some linkages within reviews could lack direct relevance while still providing a level of context. Reviews also provided an assessment of the consistency of findings between studies. Overall, reviews of pesticide contributions by source indicated sugarcane was a key source for many PSII herbicides and imidacloprid (e.g., Bainbridge et al., 2009; Bartley et al., 2017; Devlin et al., 2015; Nahar et al., 2023). Application rates and timing as a key driver of pesticide export was identified across a number of studies (e.g., Masters et al., 2013; Silburn et al., 2023). The remaining studies comprised a mix of modelling, design and management approaches.

Collectively the variation in study design approaches provided a broad evaluation of the issue. Increased monitoring of pesticide suites has improved the understanding of the types of pesticides in use. Shifts in reporting from a loads-based assessment (pre-2017) to a Pesticide Risk Metric reduces the capacity to directly compare pesticides at EOC pre- and post-2017. However, the new approach provides greater insight into the level of ecological protection afforded to aquatic communities at EOC.

Confidence

The confidence in the body of evidence used to address the question is Moderate-High (Table 11). In the evidence appraisal, the overall relevance of the studies to the question was considered High, while the consistency of approaches to the studies was Moderate-High. There was a level of variation among experimental studies in identified outcomes, which were justified based on fine scale contextual elements underpinning the experimental approaches.

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

<table>
<tr><th>Indicator</th><th>Rating</th><th>Overall measure of Confidence</th></tr>
<tr><td>Relevance (overall)</td><td>High</td><td rowspan="7">
</td></tr>
<tr><td>-To the Question</td><td>Moderate to High</td></tr>
<tr><td>-Spatial</td><td>Moderate</td></tr>
<tr><td>-Temporal</td><td>Moderate</td></tr>
<tr><td>Consistency</td><td>Moderate to High</td></tr>
<tr><td>Quantity</td><td>High
(109 studies)</td></tr>
<tr><td>Diversity</td><td>High
(31% observational, 29% experimental, 23% reviews and 17% other including modelling)</td></tr>
</table>

4.4 Indigenous engagement/participation within the body of evidence

Within the body of evidence, engagement with and / or participation by Indigenous organisations was very limited. Tsatsaros et al. (2021) is one of few studies to specifically identify Indigenous participation as a key element in the program.

4.5 Knowledge gaps

A summary of knowledge gaps for Question 5.2 is presented in Table 12.

Table 12. Summary of knowledge gaps for Question 5.2.

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
Pesticide persistence.	Estimate of potential residual pesticide contributions from soil and groundwater.	Better understanding of residual temporal risks.
Influence of soil characteristics on pesticide sorption characteristics.	Role of soil type and organic matter on pesticide mobility.	Improved pesticide management potential at on-farm level to minimise runoff
Contribution of particulate bound pesticides to off-site migration.	Discrimination between dissolved and particulate fractions to better characterise risk to aquatic and benthic inhabiting biota.	Better understanding of migration pathways and relative ecological risk across habitats.
Confounding effects of adjuvants on pesticide sorption and export characteristics.	Assessment of influence of adjuvants on active ingredient characteristics and influence on potential pesticide export.	Better understanding of effects of adjuvants on pesticide export processes.
Alternate pesticide properties, toxicities and behaviour.	Research into the properties, persistence and ecological toxicity of the newer emerging alternate pesticides.	Better understanding of the risks posed by these newer chemistries.
Pesticide movement, toxicity and persistence in groundwater.	Better understanding of the proportion of pesticides moving into aquatic ecosystems through groundwater paths. Also the potential risk that may apply to stygofauna communities.	Better understanding of the relative contributions, persistence and ecological toxicity of groundwater derived pesticide movements to GBR ecosystems.

5. Evidence Statement

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

Summary of findings relevant to policy or management

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

Supporting points

- Overall, there is no substantive evidence to indicate that the main land use contributions to pesticide concentrations in the Great Barrier Reef catchment area have significantly changed since the 2017 Scientific Consensus Statement.
- The 2009 to 2016 Great Barrier Reef Catchment Loads Monitoring Program focused on end-of-catchment loads with a target of 50% reduction in five key PSII herbicides (ametryn, atrazine, diuron, hexazinone and tebuthiuron) by 2025. In 2017, the assessment methodology shifted to a risk-based profile, assessing concentrations of 22 pesticides (including non-PSII and PSII herbicides and three insecticides) at end-of-catchment locations to estimate ecological risk in a Pesticide Risk Metric.
- Across all monitored basins between 2016 and 2020, the relative contribution of PSII herbicides to the overall pesticide risk increased from 47% to 57%, other herbicides increased from 32% to 35%, while insecticides decreased from 17% to 7%. These findings do not necessarily indicate a reduction in the use of insecticides, but their relative contribution to the overall pesticide risk is lower.
- Application rate and time between application and rainfall continue to be the biggest drivers of pesticide export from sugarcane. A range of studies have identified that the critical time period for pesticide runoff is 1-25 days after application. The longer the timeframe from application to runoff rainfall the lower the relative amount of pesticide exported.
- The first rainfall event of the wet season (typically described as the 'first flush' event) often delivers the greatest proportion of pesticides to the Great Barrier Reef. The proportion delivered is enhanced where short timeframes between application and rainfall occur. Pesticide contributions typically reduce with subsequent rainfall events. Similarly for irrigated areas, the greatest losses tend to be associated with the first irrigation event.

- Pesticide export profiles from irrigated sugarcane are similar to rainfall events, but irrigation can lead to higher ecological risk in receiving systems due to extended periods of exposure and limited flushing or dilution.
- The addition of adjuvants (substances or compounds added to pesticide formulations to improve their activity) is designed to reduce pesticide mobility offsite. However, some studies have shown these responses can be variable across soil types and climatic zones, leading to inconsistent effects on mobility.
- Variations in pesticide chemistry, use of alternative pesticides and associated adjuvants can influence export of pesticides off-site. Typically, pesticides with more polar chemistries (water-soluble) such as hexazinone and 2,4-D have lower sorption rates and are more vulnerable to dispersal, particularly under rainfall or irrigation events.
- Although most pesticide export to the Great Barrier Reef is via surface runoff, pesticide export via groundwater may be a contributor in some basins. While export via groundwater has been measured in a few studies in the Wet Tropics region and Lower Burdekin floodplain, the overall proportion of groundwater pesticide contributions is unknown. Groundwater contributions can also have significant lag effects from the timing of application, with pesticide export potentially continuing for years after application, leading to uncertainties in the understanding of pesticide migration.
- Pesticide concentrations in the Great Barrier Reef catchment area are typically reported as a dissolved concentration incorporating both the dissolved and particulate phases. Better understanding of the contribution of particle bound pesticides to off-site migration, and the drivers of transport, is important for characterising ecological risk to receiving ecosystems.
- There are fewer studies assessing the properties, persistence, delivery pathways and ecological toxicity of the newer emerging alternative pesticides such as imazapic and fluroxypyr.

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 approach to addressing Question 5.2

Theme 5: Pesticides – catchment to reef

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

Author team

Name	Organisation	Expertise	Role in addressing the Question	Sections/Topics involved
1. Shelley Templeman	TropWATER	Ecotoxicologist / Environmental Scientist	Lead author	All Sections
2. Sarah McDonald	TropWATER	Ecotoxicologist / Environmental Scientist	Contributor	Conceptual Model, Evidence Appraisal & Report Review