2022 Scientific Consensus Statement

Question 5.3 What are the most effective management practices for reducing pesticide risk 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?

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Cover image credit: Aaron Davis.

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

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

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

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

Two methods were developed for the 2022 SCS:

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

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

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

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

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

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

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

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

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

Guidance for using the synthesis of evidence

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

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

    - ***Key Findings:*** The **main body of the synthesis**. It includes a summary of the study characteristics (e.g., how many, when, where, how), a deep dive into the body of evidence covering key findings, trends or patterns, consistency of findings among studies, uncertainties and limitations of the evidence, significance of the findings to policy, practice and research, knowledge gaps, Indigenous engagement, conclusions and the evidence appraisal.
3. **Evidence Statement:** Provides a succinct, high-level overview of the main findings for the question with supporting points. The Evidence Statement for each Question was provided as input to the 2022 Scientific Consensus Statement Summary and Conclusions.

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

Peer Review and Quality Assurance

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

Contents

Acknowledgements

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Executive Summary

Question

Question 5.3 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?

Background

The decline of fresh and marine water quality associated with land-based runoff from adjacent agricultural catchments is a major cause of the poor state of many of the coastal ecosystems of Australia's Great Barrier Reef (GBR) World Heritage Area. Pesticides have been specifically identified as among the most important diffuse source contaminants from catchment areas of the GBR. High value freshwater, estuarine and inshore waters of the GBR are regularly exposed to pesticide runoff from agricultural and non-agricultural lands, particularly during wet season riverine flood events. Productivity (yield) loss from pest impacts is estimated to cost agricultural commodities in the GBR catchment area hundreds of millions of dollars annually, so pesticide use remains a key component of sustainable farming systems.

This review collates and synthesises information from published and peer reviewed literature about practices that reduce pesticide risks to GBR water quality. The focus was on studies from the GBR catchment area, however, studies from other areas of Queensland and Australia were also included where relevant. This question focuses on management practices relevant to six land uses, including grazing (representing ~72% of the catchment area of the GBR), sugarcane (~1%), irrigated and dryland cropping (~2.2 %), bananas and horticulture (<0.1 %), and non-agricultural (0.6%; urban residential, industrial, and commercial lands). It could be argued that conservation and forestry lands may also be included in non-agricultural lands however these were not examined from a management action perspective. Off-site treatments (where field runoff or groundwater/leachate is treated off-paddock) are excluded, including constructed wetlands, bioreactors and irrigation water recycle ponds for agricultural land uses. For non-agricultural land uses, off-site treatments such as wetlands and wastewater treatment were evaluated in addition to non-structural controls.

Methods

- A formal Rapid Review approach was used for the 2022 Scientific Consensus Statement (SCS) synthesis of evidence. Rapid reviews are a systematic review with a simplification or omission of some steps to accommodate the time and resources available[5]. For the SCS, this applies to the search effort, quality appraisal of evidence and the amount of data extracted. The process has well-defined steps enabling fit-for-purpose evidence to be searched, retrieved, assessed and synthesised into final products to inform policy. For this question, an Evidence Review method was used.
- Search locations included Web of Science and Scopus, as well as a smaller number of references found from manual searching.
- A total of 2,471 papers were identified from the initial search, and after final screening, 251 papers were found to be eligible and included in the synthesis. Of the 237 eligible studies for agricultural land uses, approximately 75% were based on on-ground studies or measurements at least in part within the GBR catchment area. These papers generally have higher levels of relevance to the SCS, but the findings are not always comprehensively applicable across the entire range of spatial scales and climate conditions found in the GBR. Additionally, a smaller

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

number of studies (mainly from cotton, grains and horticulture) conducted in Australia, but outside GBR catchments were considered. These were judged to have high relevance to the GBR on important issues for which there was no equivalent information from studies in the GBR. Several review papers were also found in the search which distilled relevant information from outside the GBR catchment area. For non-agricultural land uses, studies across Australia were included due to the lack of articles within the GBR on non-agricultural land uses. Some international studies, where directly relevant, were included.

Method limitations and caveats to using this Evidence Review

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

- Only studies written in English were included.
- Evidence searches were conducted using two academic databases (Scopus and Web of Science)
- Studies were predominantly from the Great Barrier Reef (GBR) and Australia.
- Studies were from 1990 onwards.
- Some studies of potential direct relevance (industry or government technical reports) were excluded because of lack of clarity around peer review status.

Key Findings

Summary of evidence to 2022

A growing body of research evidence continues to support several management practices as being demonstrably effective in reducing runoff losses, and subsequent ecosystem risk, of pesticides in the GBR catchment area. While additional insights have been gained and the information base strengthened, these practices have changed little since previous Scientific Consensus Statements. Specifically, long-term environmental risks of pesticides from agricultural land uses are reduced by:

1) Reducing the total amount of pesticide applied to a paddock or field, through lower application rates (within label recommendations), or through precision application practices such as banded/shielded spray applications and spot-spray technology.
2) Timing pesticide applications to minimise the risk of paddock runoff from rainfall or irrigation within several weeks of application.
3) Choosing products with physico-chemical properties (lower persistence, lower mobility and/or lower toxicity) that reduce environmental risks.
4) Reducing runoff and soil erosion by retaining cover, controlled traffic and irrigation management reduces the runoff risks of pesticides with greater soil sorption. Reductions associated with more soluble pesticides have recently emerged as more variable and inconsistent.

A relatively limited number of studies have been conducted (or specifically synthesised findings) across broad climatic zones or farming systems in different GBR regions, particularly with respect to comparison of specific water quality risks between practices. Nevertheless, broad findings with regard to key management practices thought to reduce risks (e.g., pesticide application rates, pesticide application timing in relation to runoff, and pesticide product selection) remain generally consistent across the GBR climatic regimes and farming systems. Factors relating to variability in soil properties (such as soil pesticide half-lives) rather than climate, appear to play significant roles in variable pesticide spatio-temporal behaviours across the GBR.

Assessment methods for cost-effectiveness of improved pesticide management across different agricultural land uses in the GBR catchment area has been inconsistent and requires an agreed approach to support future assessments. Economic returns remain critically dependent on region-specific variables including biophysical characteristics and enterprise structure, especially in relation to farm size and location. However, for sugarcane, progressing from traditional to industry standard herbicide management was reported to be generally profitable and provide return on investment across all farm sizes and sugarcane districts. The cost of changes in management practices can vary considerably.

Ground cover management and fallow management are the most expensive pesticide management changes costing $67,500 and $25,000 respectively for a large farm (250 ha). In contrast, pesticide application methods are cheaper with changes to nozzles and tracking legs costing ~$2,750 for a large farm. The variance in pesticide loads as a result of the practice changes drove the high variation in cost-effectiveness, with changes from 'traditional' to 'best practice' management modelled as a 55 g ha^{-1} yr^{-1} reduction in the Burdekin River Irrigation Area and 10 g ha^{-1} yr^{-1}in Mackay in the same year.

For non-agricultural lands, the key focus appears to largely rely on non-structural controls such as regulation and improved wastewater treatment processes. Urban stormwater does appear to be a contributor but there is limited evidence that treatment measures, other than non-structural approaches, are effective. It is noted that accumulation of micropollutants such as pesticides is occurring in some diffuse runoff treatment systems (e.g., wetlands) but whether this indicates effective treatment or simply just a potential fate pathway is unclear.

Recent findings 2016-2022

Since the 2017 SCS, new information has been gained on the water quality outcomes of agricultural management practices on farms. Much of the new research has essentially reinforced previous conclusions about the efficacy of many established practices for managing pesticide risks from agricultural lands. This provides increased confidence in the ongoing Water Quality Risk Frameworks used in the monitoring and evaluation of Reef Water Quality Protection Plan investments into water quality benefits of practice change.

Recognition of broader pesticide risk

There have been recent and notable modifications in Reef Plan targets under the current Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP) 2017–2022, shifting from the simpler 60% Photosystem II (PSII) herbicide load-based reduction measure, to achieving herbicide concentrations at river mouths that protect at least 99% of aquatic species. This change was designed to provide more ecologically meaningful herbicide monitoring and management in the GBR catchment area (acknowledging that PSIIs are not the only contributors to ecological risk). It also aligns with approaches used in National, State and marine GBR water quality guidelines (Australian & Queensland Government, 2018). Reef Plan pesticide focus has, accordingly, expanded substantially, now including a much broader range of 22 'priority' pesticides (a combination of herbicides and insecticides), extending considerably beyond the previous PSII priority herbicide suite (i.e., diuron, ametryn, atrazine, hexazinone, simazine, tebuthiuron).

There have been significant changes in recent paddock-scale studies relating to pesticide use and GBR water quality to better reflect these new targets. Several recent studies specifically assess changes in practice risk profiles across a broader range of herbicides, in addition to the more historic comparisons of load losses of PSII herbicides from paddocks. These recent benchmarking studies of paddock-scale management practice runoff trials have highlighted that several 'alternative' pre-emergent herbicides (e.g., metribuzin and metolachlor) present very similar ecosystem risk profiles to at least some of the previous priority PSII herbicides such as atrazine. Recent results from paddock studies also suggest that water quality can be significantly affected (sometimes negatively) by particular 'knockdown' herbicides in mixtures, an outcome not captured in previous research. The risk profiles of knockdown herbicides (often regarded as fundamental to reducing industry reliance on the environmentally problematic PSII residual herbicides) and herbicide mixtures, have been rarely considered in paddock or catchment-scale appraisals of water quality risk and the likely benefits of practice change by farmers. Use of more holistic water quality risk metrics, such as ms-PAF (multiple-substance potentially affected fraction; Traas et al., 2001), should be a prerequisite for future assessments of the ecological benefits of practice changes.

Integrated Pest Management

The broadening scope of the SCS, to include commodities such as horticulture, as well as some of the emergent challenges in many industries (pesticide resistance evolution, product registration changes and constraints) has highlighted Integrated Pest Management (IPM) as a key consideration for future GBR pesticide policy. IPM is an ecosystem-based strategy that encourages the reduction of synthetic pesticide use through a combination of techniques such as (but not limited to) biological control, habitat manipulation, modification of cultural farm practices, pest monitoring, and use of resistant crop varieties. Pesticides are used only after monitoring indicates they are needed according to established guidelines, and used in such a way that minimises risks to human health, beneficial and non-target organisms. While many elements of IPM (and specific practices identified in this review) have undoubted relevance to reducing pesticide risks, the specific long-term cost-benefits, practical considerations and clarity on what IPM should actually mean across different industries remains poorly quantified. Close collaboration and engagement with industries will be required to provide this additional information.

Increasing appreciation of variable water quality benefits from tillage-residue retention practices

There have also been notable recent shifts toward recognising that previously assumed water quality benefits from adoption of no till or reduced tillage farming systems compared to conventional tillage systems may be more variable and inconsistent than previously assumed. If tillage practices do not consistently reduce runoff of pesticides, other practices, such as selecting pesticides that are less toxic, more rapidly dissipated, more sorbed, and runoff less need to be considered.

Significance for policy, practice, and research

A number of key findings emerged from the review that are almost certain to have profound, and in some cases, already manifest implications for water quality and ecosystem risk across the GBR catchment area. These include:

- Rapid evolution of pesticide resistance is posing growing challenges across multiple industries. Managing herbicide and insecticide resistance, in fact, emerged as a dominant study focus from literature searches. Genetically modified crops in particular, have refashioned the pest management environment in many crops. While few studies had any direct consideration of specific water quality risks, the longer-term environmental impacts of pesticide resistance have major implications for managing GBR catchment area pesticide risks. Practices such as poor control of resistant pests necessitating greater pesticide use (‘follow-up’ or multiple pesticide applications), re-introduction of tillage and pre-emergent herbicides into glyphosate-based farming systems, different future pesticide formulations and modes of actions, grower and industry unfamiliarity with newer products and associated risk management, will all have implications for managing water quality risks. Evolution of pesticide resistance will potentially impact the future viability of entire farming systems approaches in some industries. Ensuring current practices recommended for improved water quality do not contribute to pesticide resistance is, therefore, a critical consideration for policy.
- Because of these current and future challenges, particularly surrounding pesticide resistance, product registration changes and emerging pests, many farmers will face new challenges that may alter how and when they use pesticides. Indeed, this Evidence Review highlights several significant GBR agricultural industries being forced to revisit integrated pest management (IPM) concepts. While a diverse range of IPM tactics were noted as being used by farmers, few industries in the GBR catchment area consistently or comprehensively use IPM. The underlying reasons for this lack of adoption are likely multifaceted, reflecting issues such as a continued desire for ‘simple’ or cheaper technological or chemical control solutions, short-term planning horizons and a failure by researchers to demonstrate and communicate the benefits of more integrated approaches.
- The need for additional pest control options is increasing industry and research interest in non-chemical pest control measures for integration within farming systems. Many elements of broader farm management (e.g., crop planting density, varietal selection, crop row spacing, habitat management) and area-wide management hold considerable promise for reducing pest pressure and reducing long-term pesticide applications but in most cases, actual comparative water quality benefits, and cost-effectiveness remain poorly quantified, or are yet to be rolled out at meaningful scales across commodities.

- The recent substantial expansion of the Reef Plan to include a much broader range of 22 ‘priority’ pesticides, and shifting from load-reduction based targets to new risk-based metrics has complicated assessment of practice change. A range of recent benchmarking studies of paddock-scale management practice runoff trials have highlighted that several ‘alternative’ pre-emergent herbicides (e.g., metribuzin, metolachlor) present similar ecosystem risk profiles to at least some of the priority PSII herbicides such as atrazine. Recent results from some paddock studies also suggest that water quality improvements associated with practice change can be affected significantly by the contribution of particular ‘knockdown’ herbicides included in mixtures, an outcome not captured in previous research. Achieving a better understanding of the comparative environmental risks posed by herbicide mixtures from different management practices should be a priority for future policy directives.
- On a similar note, data on many insecticides and fungicides used in GBR farming systems were lacking. Studies in other Australian horticultural catchments, for example, have documented widespread detection of fungicides in the aquatic environment, and fungicides have also been recorded in some recent GBR water quality monitoring programs. The data that are lacking includes half-lives, sorption, runoff potential and ecotoxicology under conditions relevant to the environments, farming systems and aquatic ecosystems of the GBR and its catchment area.

Key uncertainties and/or limitations

- Most available research focuses on herbicides, with insecticides, and particularly fungicides featuring rarely in any water quality-based assessments, particularly in terms of comparative management practice impacts on water quality.
- The risk profiles of knockdown herbicides (often regarded as fundamental to reducing industry reliance on the environmentally problematic PSII residual herbicides) have rarely been considered in paddock or catchment-scale appraisals of water quality risk and the likely benefits of practice change by sugarcane growers.
- Additive, synergistic or antagonistic effects between multiple residual-knockdown herbicide mixes on comparative management practice risk are poorly quantified at this point in time.
- The majority of water quality research focuses exclusively on pesticide surface water losses, with comparative losses to leachate and groundwater poorly described.
- The economic costs have been captured over multiple Water Quality Risk Frameworks making the comparison difficult and the low number of studies presents uncertainty to the findings.

Evidence appraisal

The overall relevance of the body of evidence to the question was Moderate. The relevance of each individual indicator was Moderate for relevance of the study approach and reporting of results to the question, Moderate for spatial relevance, and Moderate for temporal relevance. Of the 251 articles included in the review, 100 were given a ‘High’ score for overall relevance to the question. This was due to several factors described further below.

- The relevance of the study approach and reporting of study results was Moderate. Measurement and reporting of several of the identified practices in reducing pesticide risk is quite a mature science in the GBR scientific literature (application rates, runoff in relation to application, pesticide product choice). A number of commonly adopted study designs (paddock scale trials, rainfall simulations, dissipation trials) and reporting metrics (runoff loads, toxicity comparisons, half-lives) have been applied in the GBR context. Many aspects of the eligible literature had direct linkages to components of the conceptual model, but only indirectly related to water quality risk. Specific pesticide focus was particularly biased toward herbicides, with insecticides, and particular fungicides poorly represented across the literature.
- The relevance or generalisability of the spatial scale of studies was Moderate. Most of the eligible literature related directly to studies carried out in the GBR catchment area, or related specifically to commodities found at least in part, within the catchment area. Most studies were, however, limited to specific regions of the GBR, with few being replicated over broader regional scales, and the diversity of farming systems (even within a single commodity) found therein.

- Relevance or generalisability of the temporal scale of studies was Moderate. The temporal relevance of pesticide risk of a management practice to the environment tends to be limited to early runoff events following a pesticide application. Many studies were relevant to this paddock-scale spatio-temporal context. Longer term assessments of some broader pesticide management strategies relevant to the conceptual model (e.g., IPM, area-wide management, resistance management planning), and associated longer term risk reductions across both temporal and spatial scales were not as well quantified.

Essentially all studies found related to aspects of landscape, farm and paddock management strategies identified in the conceptual model. Most studies relating specifically to comparative water quality, however, related to farm management (cultural; tillage, residue retention), and particularly paddock scale practices (product choice, application method, application rates) found in the conceptual model. Management elements of the model, particularly at broader scales provides future research opportunities.

Consistency, Quantity and Diversity

While consistency for the overall body of evidence was Moderate, the consistency of findings varied within the sub-group analysis. For example, the consistency of study findings relating to the effectiveness of many specific paddock-scale practices in reducing pesticide risk was high, however, the consistency of study findings in reducing risks using many cultural and landscape-scale practices was lower. This was partially due to the specific lack of explicit water quality data available for many of these studies and concepts (e.g., IPM, area-wide management), although many of the relevant principles do relate to reducing longer-term risks through reduced pesticide usage over broader temporal and spatial scales. Consideration or management of pesticide resistance will also have longer term impacts on catchment water quality in the GBR, but are similarly poor with regard to water quality data.

It is considered that the quantity of the pool of evidence (n=251) used for this review is Moderate due to:

1) The authors experience with international pesticide literature.
2) Consideration of the inclusion/exclusion criteria used for the question.
3) The number of studies used by similar reviews or other syntheses.
4) The diverse nature of pesticide management and variable water quality evidence across many practices or strategies.

There were three different evidence types used in the review: 1) primary studies (experimental, observational or modelled), 2) secondary studies (reviews, Systematic Reviews or meta-analysis) or 3) mixed (involve a mixture of experimental, modelled and/or observational studies, and in some cases a review, with additional field observations, or new data). Almost half of screened studies (91) for agricultural land-uses were of a broad experimental nature, although the range of methodologies, scale, replication and use of a strict control or controlled manipulation of specific variables varied dramatically. Most experimental design studies (57) generally related to paddock-scale agronomic and/or water quality field studies, where broad paddock treatments were used as controls and variables, with interventions such as pesticide type or product, management practice (tillage, row spacing, planting density), pesticide application practices or pesticide control efficacy manipulated or monitored. Field trials involving rainfall simulation over relatively small areas/plots were also frequent (16 studies). Experiments involving more controlled conditions under a laboratory, glasshouse, or pot-trial type design were less prevalent. These typically involved research questions more amenable to control-replication such as comparison of spray-nozzle technology performance, or some aspects of pesticide physico-chemical behaviours such as pesticide dissipation. This diverse spectrum of experimental study types and scales underlines the challenges and expenses of conducting comparative, replicated, long-term agronomic and/or water quality research relating to pest control at commercially relevant farming scales.

A substantial proportion of studies (81 in total) were secondary studies (reviews, or reviews with an added observational element). Modelled studies involved a diverse range of topics. This included use or development of a range of paddock or subcatchment scale water quality models (often with underlying comparative management practice emphasis), modelling of different elements of genetic resistance to pesticides or pests, and socio-economic models of cost-benefits of farmers adopting a particular practice change.

In terms of specific study focus, fifty studies (less than a quarter) involved some direct element of quantification or consideration of the water quality implications of, or comparisons between, specific paddock-scale management practices. The nature of the specific practice, with associated quantification of water quality dynamics, however, varied widely. Water quality studies included comparisons between different pesticide product types and strategies, physico-chemical pesticide behaviours, pesticide application rates, application methods, and product efficacy. Integrated pest management concepts were the next most prevalent topic (29 studies). Remaining studies encompassed a broad range of agronomic, economic, pesticide resistance, pest control efficacy, precision agricultural and policy appraisal topics with linkages to this review's conceptual model. It is noteworthy that many studies, while relevant to improving water quality, and often mentioning it explicitly, often had little explicit quantification of comparative losses of pesticides associated with management practices. Nevertheless, they do relate to overarching management applications or considerations on the periphery of the conceptual model.

Additional Quality Assurance (Reliability)

A rapid internal validity assessment was made for all studies used in the synthesis to note any obvious potential bias and to identify studies most influential in drawing conclusions from the body of evidence. Of the 156 observational or experimental studies used to specifically appraise management practice pesticide risks, several were rated as having some risk of bias due to either the study design not accounting for all flow paths from the studied paddock (i.e., they only monitored surface water runoff), or having experimental designs that presented 'worst-case scenarios' of off-farm ecosystem risk from pesticide movement. Very few paddock scale studies monitored pesticide losses in leachate below the crop root zones (<5 studies). Those studies that did monitor groundwater losses typically identified groundwater concentrations and losses much lower than those documented in surface water runoff. It was determined, therefore, that these potential biases in terms of attention to specific loss pathways, were not significant enough to remove the studies from the synthesis.

Almost all rainfall simulation studies (15) provided a worst-case scenario in terms of resultant environmental impact, involving the application of significant, high intensity, simulated 'rainfall' within 2-3 days of pesticide application to a paddock (ca. 80 mm in an hour). Such events are, however, frequent enough in reality, likely occurring several times across each farming district in most years, and are the events that cause most soil and pesticide loss. While some rainfall simulation studies did monitor for several runoff events after application , many of the appraised rain simulation studies also typically only monitored one event after pesticide application, which provided a somewhat limited insight into longer term risks of a specific practice. Multiple longer term paddock studies did, however, identify that the majority (>80%) of annual pesticide load losses off-paddock typically occurred in the first 1-2 events. It was determined, therefore, that these potential biases were not significant enough to remove the studies from the synthesis.

Of the four modelled studies (water quality) identified from the literature and manual searches, all were rated as having a low risk of bias due to clear model validation and clarity of the assumptions used in the model. As the findings of these studies were also consistent with other field studies, all of these studies were considered in the synthesis.

The inclusion of many studies that addressed elements of broader Integrated Pest Management could also introduce potential biases to results. Environmental considerations and purported benefits or risk reductions in many IPM studies were often not specific to water quality risk of pesticides, and often considered other ecosystem components (e.g., terrestrial elements, soil health, resistance evolution). But while many of the water quality outcomes and cost-benefits of IPM remain poorly defined, many elements of IPM were theoretically relevant and sound with respect to many aspects or aspirations of the conceptual model (e.g., long-term or spatially broad overall reductions in total amounts of pesticide applied, use of alternative pest control techniques, lower risk chemical selection). It was therefore decided to include many of these papers that related to key aspects of the conceptual model in the review (while noting their inherent current limitations).

Overall it was determined that most studies (>95%) had a low risk of bias. The findings of those studies that were rated as having some potential risk of bias were generally consistent with the findings from the larger body of evidence hence the studies were retained in the synthesis.

The cost effectiveness of pesticide management and production implications were a small sub-set of the total database. The six papers that were reviewed were specific to the Water Quality Risk frameworks and were relevant to the catchments adjacent to the Great Barrier Reef. This meant that they all scored high in relevance to the questions and spatial relevance. The temporal relevance was varied with a mix of Water Quality Risk frameworks applied over time and therefore different costs considered. This resulted in a moderate score of two.

Confidence

The Confidence rating for the questions, based on the overall relevance rating and consistency was Moderate. As discussed above, while Consistency for the overall body of evidence was Moderate, consistency of findings varied within the sub-group analysis. As discussed above the Relevance rating for the body of evidence was determined to be Moderate. The Moderate confidence rating was also influenced by the authors’ views that a high number of eligible studies were used in the synthesis and that, with few exceptions, generally consistent findings resulted from observational, experimental modelled and secondary studies.

1. Background

In response to herbicide concentrations in the Great Barrier Reef (GBR) exceeding ecological guideline values, the Reef Water Quality Protection Plan 2009 ('Reef Plan') introduced targets to reduce end-of-catchment 'Photosystem II (PSII) priority' herbicide loads of diuron, atrazine, hexazinone and ametryn by 60% by 2018 (The State of Queensland, 2009). In the recent Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP) 2017–2022, herbicide load targets were changed to a pesticide concentration target based on a multiple species potentially affected fraction methodology (Australian & Queensland Government, 2018). The new concentration target aims to protect at least 99% of aquatic species at river mouths (Australian & Queensland Government, 2018), and complicates risk assessments through added consideration of mixtures of multiple pesticides and relative toxicity of different chemicals. It also broadens risk assessment from a historic herbicide focus (particularly in industries such as sugarcane, grazing and bananas) to a much broader suite of commodities and pesticides (herbicides, insecticides and fungicides).

When selecting pest control strategies, farmers also traditionally face a complex decision process (e.g., economic thresholds, product spectrum efficacy, compatibility with soil type and farming system, weather conditions, label restrictions, costs, pesticide compatibility, environmental risk.). It is the holistic consideration of all of these factors that will ultimately drive grower decision-making regarding practice change on-farm, and also consequent risk to water quality.

1.1 Question

Primary question	**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?

The health of GBR ecosystems is affected by contaminants discharged from agricultural lands and urban environments. Important amongst those contaminants are pesticides, a broad collection of herbicides, insecticides, fungicides and other biocides. Thus, it is important that agricultural lands are managed to minimise discharge of these contaminants. While these contaminants can be discharged from all land uses, the greatest discharges per hectare typically occur from cropped lands (sugarcane, horticulture, cotton, grains and banana, under both irrigated and dryland production) and urban environments.

The questions addressed in this Evidence Review focus on management practices that influence the amount of pesticides leaving a land use, and which can subsequently be transported from the field or urban area by runoff and/or leaching. The issue of off-site treatment of pesticides once they are discharged from a land use (e.g., using constructed wetlands, bioreactors and irrigation water recycle ponds) are not included in this question. It is dealt with under Question 4.7 (Waltham et al., this Scientific Consensus Statement (SCS)). Leaching as well as runoff is included, because pesticide contamination of groundwater resources is a component of risk. Leached pesticides can move through groundwater aquifers to creek and rivers, eventually discharging to GBR ecosystems – this is an important pathway for pesticides moving from fields to the GBR.

Given that farming is an economic enterprise, the cost effectiveness of the management actions relevant to the discharge of pesticides were also reviewed. Cost-effectiveness is defined through the costs of the practice and the resultant income (from crop yield), relative to the reduction in pollutant discharge.

For urban/non-agricultural land uses, two key contaminants streams for pesticides that were discussed in the literature have been considered, point sources related to wastewater discharges and diffuse runoff sources from urban stormwater surface runoff.

1.2 Conceptual diagrams

To provide a coherent framework for answering Question 5.3, two conceptual diagrams were developed to accommodate all the different biophysical, socio-economic and agronomic drivers for management decisions relating to pesticide use, and risk management from cropping versus non-agricultural land uses (Figure 1 and Figure 2). Decisions by farmers about pest control involve a spatio-temporal hierarchy of potential interventions and drivers from the scale of the broader landscape (beyond the farm boundary), economic-market and policy environment, down to decisions made at the scale of an individual paddock or conditions on a particular day. Decisions around chemical control (use of specific pesticides), in particular, can be complex, and for the purposes of this review are presented in detail in the agricultural conceptual model. For the purposes of this document, pesticide risk is defined by how the environment, particularly in downstream aquatic ecosystems, can be affected by a pesticide (the toxicity, concentration magnitude, spatial extent, frequency and duration of exposure to a pesticide or pesticides). Human health risk assessment, and the nature and probability of adverse health effects in humans who may be exposed to pesticides, is another important consideration for pesticide management, but not included in the scope of this review.

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	**Q4.7** What is the efficacy of natural/near natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in Great Barrier Reef catchments in improving water quality (nutrients, fine sediments and pesticides)? **Q4.8** What are the measured costs, and cost drivers associated with the use of natural/near natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in Great Barrier Reef catchments in improving water quality? **Q5.1** What is the spatial and temporal distribution of pesticides across Great Barrier Reef ecosystems, what evidence is there for pesticide risk and what are the (potential or observed) ecological impacts in these ecosystems? **Q5.2** What are the key factors that influence pesticide delivery from the Great Barrier Reef catchments, and where are these factors most significant?

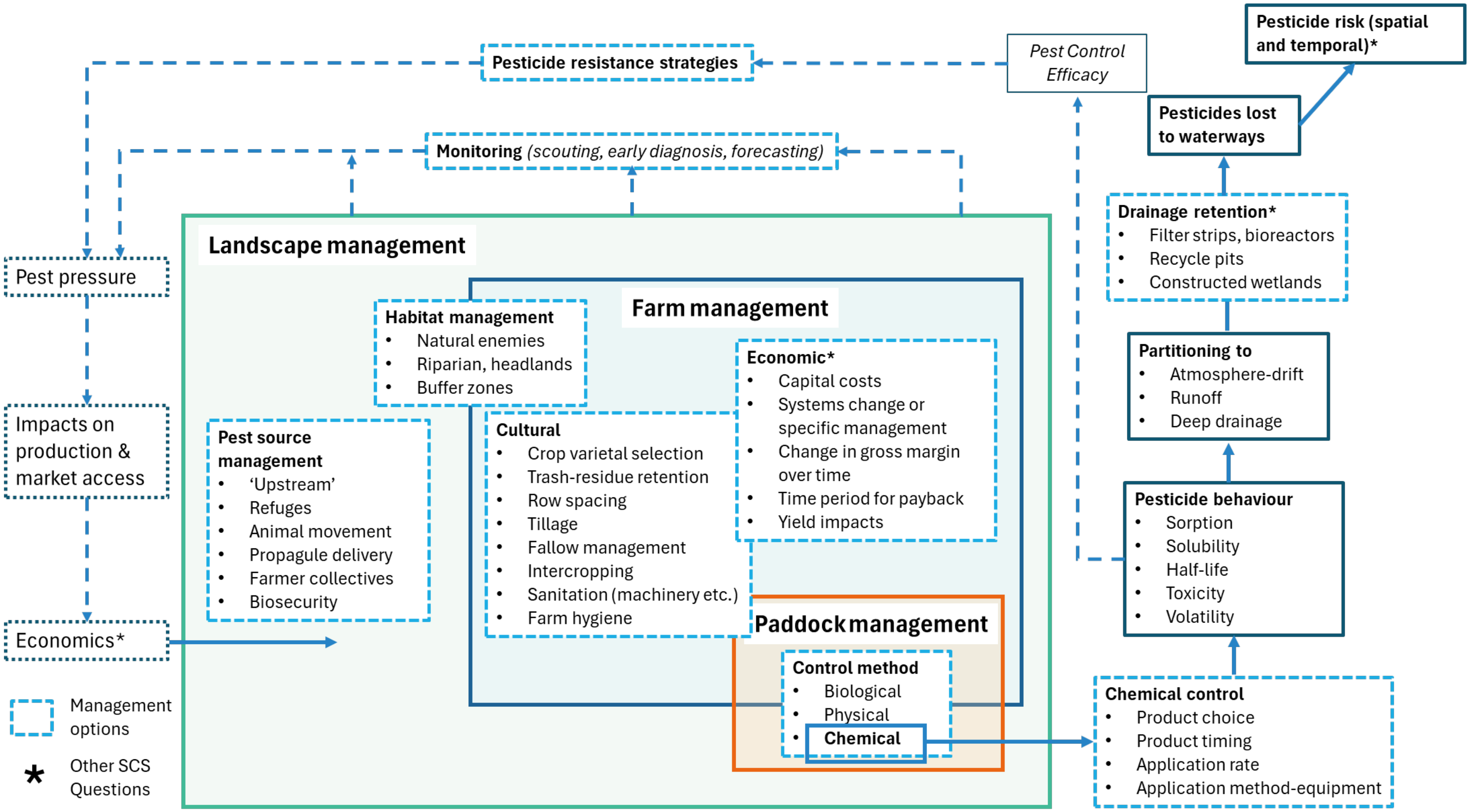
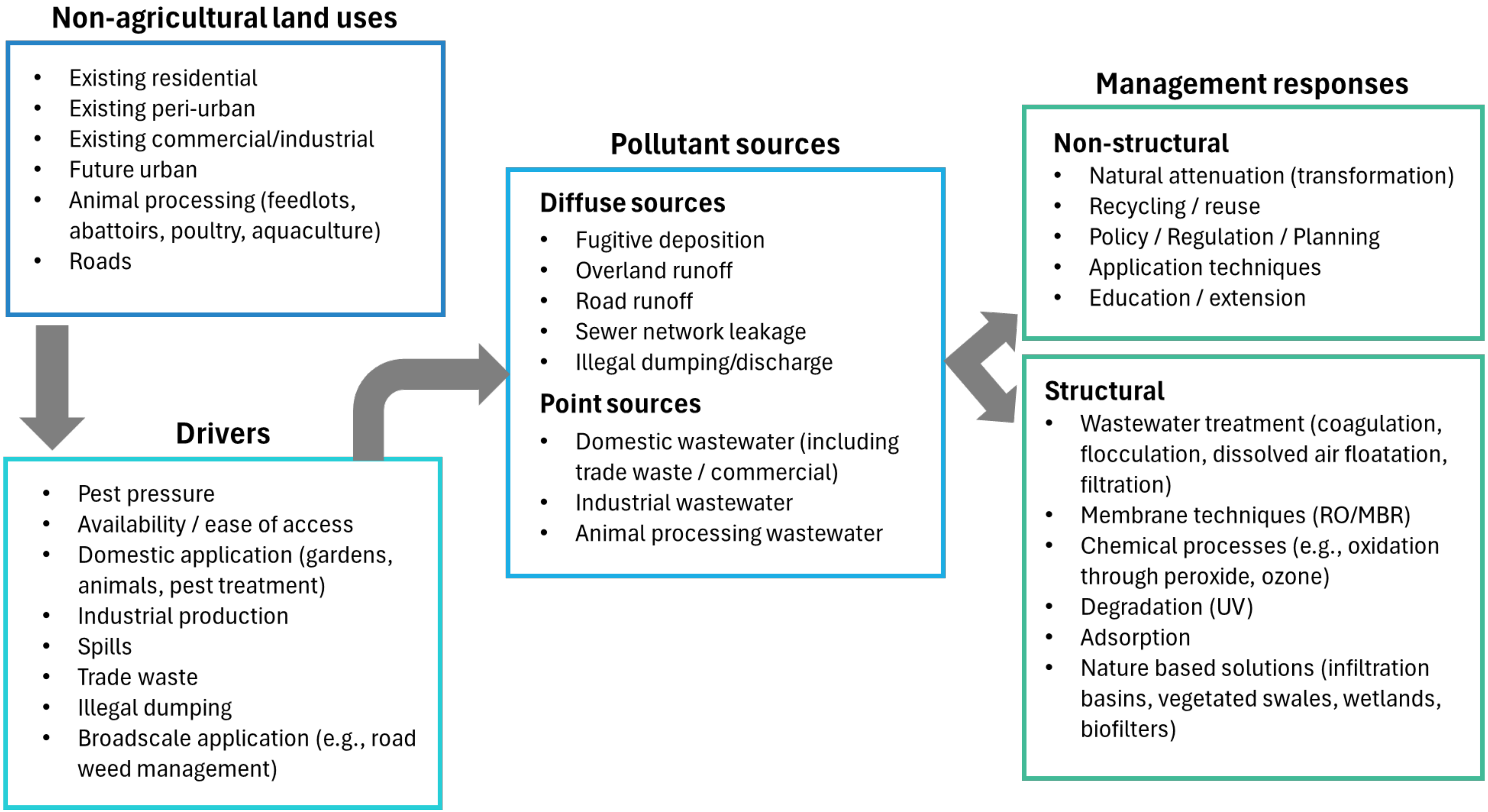


Figure 1. Conceptual framework for risk management and decision making around pesticide usage on cropping lands. Linkages to specific secondary questions or other questions of the SCS are also shown.



Non-agricultural land uses

- Existing residential
- Existing peri-urban
- Existing commercial/industrial
- Future urban
- Animal processing (feedlots, abattoirs, poultry, aquaculture)
- Roads

Drivers

- Pest pressure
- Availability / ease of access
- Domestic application (gardens, animals, pest treatment)
- Industrial production
- Spills
- Trade waste
- Illegal dumping
- Broadscale application (e.g., road weed management)

Pollutant sources

Diffuse sources

- Fugitive deposition
- Overland runoff
- Road runoff
- Sewer network leakage
- Illegal dumping/discharge

Point sources

- Domestic wastewater (including trade waste / commercial)
- Industrial wastewater
- Animal processing wastewater

Management responses

Non-structural

- Natural attenuation (transformation)
- Recycling / reuse
- Policy / Regulation / Planning
- Application techniques
- Education / extension

Structural

- Wastewater treatment (coagulation, flocculation, dissolved air floatation, filtration)
- Membrane techniques (RO/MBR)
- Chemical processes (e.g., oxidation through peroxide, ozone)
- Degradation (UV)
- Adsorption
- Nature based solutions (infiltration basins, vegetated swales, wetlands, biofilters)

Figure 2. Conceptual framework for pesticides on non-agricultural lands.

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 Review method was used.

2.1 Primary question elements and description

The primary question is: ***What are the most effective management practices for reducing pesticide risk from the GBR catchments? Do these practices vary spatially or in different climatic conditions? What are the production outcomes of these practices?***

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 question elements for Question 5.3.

Question S/PICO elements	Question term	Description
Subject/ Population	Pesticide losses (in catchments draining to the GBR)	The focus is on herbicides, insecticides, and fungicides. Losses are those resulting from transport of pesticides off the land surface, by moving with runoff or deep drainage water.
Subject qualifier	Pesticide losses in crop fields and urban landscapes	Cropped land use includes areas producing sugarcane, horticulture and bananas, both through irrigated and dryland production. Non-agricultural land uses include urban residential, industrial, commercial, mining and extractive industries and potentially military lands. It could be argued that conservation and forestry lands may also be included in non-agricultural

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

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

Question S/PICO elements	Question term	Description
		lands however these were not examined from a management action perspective.
Intervention, exposure & qualifiers	Management practices that reduce discharge pf pesticides (or risk to the GBR ecosystems)	Practices include all elements of pesticide management (see conceptual model) that reduce risk to GBR ecosystems. For non-agricultural land uses, this has included structural and non-structural actions such as vegetated treatment systems (swales, biofilters, wetlands), wastewater treatment systems and non-engineered approaches such as planning, policy, education, regulation, compliance and enforcement actions.
Comparator	Variability of the management practice effectiveness including challenges	Varying effectiveness of different management practices in reducing pesticide risks to GBR ecosystems. How the effectiveness of the interventions varies spatially or in different climatic conditions. Problems with/limits to implementing the interventions.
Outcome & outcome qualifiers	Reduced pesticide risk to the GBR	The evidence of the effective management practices in reducing risk (i.e., practices that have been shown to reduce ecological risk or negative outcomes). The costs, production outcomes and cost effectiveness of the interventions.

Table 2. Definitions for terms used in Question 5.3.

Definitions	
Climate conditions	The range of long-term temperature and rainfall distributions being found across the GBR catchment area, will be grouped broadly within NRM regions.
Economics - Cost effectiveness	Costs (capital, maintenance, opportunity cost) of implementing management practices compared with the effectiveness of an intervention at reducing pesticide losses.
Event Mean Concentration (EMC)	The total mass load of a contaminant (pesticide) parameter divided by the total runoff water volume discharged during an individual runoff event.
Fungicide	A pesticide used to kill fungi (plant-like organisms that do not make chlorophyll), such as yeasts, rusts and molds (and their spores).
GBR catchment	The 35 drainage basins that comprise the Great Barrier Reef cCatchment aArea, which drain directly into the Great Barrier Reef lagoon.
Herbicide	A pesticide that specifically kills or inhibits plant pests. Herbicides usually inhibit a specific biochemical pathway that only occurs in plants and thus are far more toxic to plants than other organisms.

Definitions	
Insecticide	A pesticide that specifically kills or inhibits insect pests. Insecticides usually inhibit a specific biochemical pathway that only occurs in insects and thus are far more toxic to insects and related arthropods than other organisms.
Knockdown herbicide	A non-selective herbicide which kills weeds through contact with green plant tissues (post-emergent application), and is nominally non-residual in the soil.
Multi-substance Potentially Affected Fraction (ms-PAF)	A statistical method allowing for the estimation of the effect of multiple pollutants on an ecosystem (originally described by Traas et al., 2001), and expressed as the percent of species affected or protected. The ms-PAF risk metric estimates the fraction of aquatic species affected by the temporal exposure to mixtures of pesticides during the principal exposure period (i.e., the course of a wet season).
Pesticide	Include chemicals used to control pest species including herbicides, insecticides, and fungicides.
Photosystem II (PSII) herbicide	PSII Herbicide: Herbicides that inhibit the photosynthetic process in plants by binding to specific sites within the photosystem II complex in plant chloroplasts, blocking electron transport and stopping CO_2 fixation, and production of energy needed for plant growth.
Residual or pre-emergent herbicides	Refers to application of the herbicide to the soil before the weeds have emerged (pre-emergent application), can remain active in the soil for an extended period of time (months) and can act on successive weed germinations.
Risk	Defined as Exposure x Consequences. There is a risk of harm to biota when measured concentrations of pesticides in aquatic systems exceed toxicity thresholds including Water Quality Guideline (WQG) values.
Spatial distribution	Includes entire GBR ecosystem (reef, seagrass meadow, freshwaters, groundwaters, wetlands). Comparisons of management practice effectiveness among Natural Resource Management (NRM) regions (possibly summary tables) and catchments.
Urban/non-agricultural	In this document, urban and non-agricultural land uses are considered together and are defined as those activities which may occur at a high level of intensity, with mixed application of pervious and impervious land surfaces and the generation of both diffuse and point sources of nutrients and other contaminants.

2.2 Search and eligibility

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

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

1. Results from the literature searches were screened against strict inclusion and exclusion criteria at the title and abstract review stage (initial screening). Literature that passed this initial screening step were then read in full to determine their eligibility for use in the synthesis of evidence.

2. Information was extracted from each of the eligible papers using a data extraction spreadsheet template. This included information that would enable the relevance (including spatial and temporal), consistency, quantity, and diversity of the studies to be assessed.

a) Search locations

Searches were performed in:

- Web of Science
- Scopus
- Personal databases (searched "by hand", including Queensland Government database and conference proceedings)

b) Search terms

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

Table 3. Search terms for S/PICO elements of Question 5.3.

Question element	Search terms
Subject/Population	Great Barrier Reef, GBR, Queensland pesticide(s), herbicide(s), insecticide(s), fungicide(s) *Non-agricultural* Urban, industrial, industry, commercial, roads, aquaculture
Exposure or Intervention	Management, tillage, reduction, rate, product *Non-agricultural* Management, action, policy, planning, treatment, measure, reuse, recycling, wetland
Comparator	Risk, sustainability, water quality, aquatic, runoff, deep drainage, loads, water quality
Outcome	Risk, sustainability, environment, water quality, aquatic, runoff, deep drainage, loads

c) Search strings

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

Table 4. Search strings used for electronic searches for Question 5.3.

Search strings
Agricultural pesticide risk management (Scopus and Web of Science) TITLE-ABS-KEY (((("Great Barrier Reef" OR gbr OR queensland) AND (pesticide OR herbicide OR insecticide OR fungicide) AND (effective* OR risk OR manage* OR environment OR sustainab* OR "no tillage" OR "water quality" OR aquatic OR runoff OR "deep drainage" OR "leachate" OR reduc* OR rate)))) AND (LIMIT-TO (PUBYEAR , 2023) OR LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2015) OR LIMIT-TO (PUBYEAR , 2014) OR LIMIT-TO (PUBYEAR , 2013) OR LIMIT-TO (PUBYEAR , 2012) OR LIMIT-TO (PUBYEAR , 2011) OR LIMIT-TO (PUBYEAR , 2010) OR LIMIT-TO (PUBYEAR , 2009) OR LIMIT-TO (PUBYEAR , 2008) OR LIMIT-TO (PUBYEAR , 2007) OR LIMIT-TO (PUBYEAR , 2006) OR LIMIT-TO (PUBYEAR , 2005) OR LIMIT-TO (PUBYEAR , 2004) OR LIMIT-TO (PUBYEAR , 2003) OR LIMIT-TO (PUBYEAR , 2002) OR LIMIT-TO (PUBYEAR , 2001) OR LIMIT-TO (PUBYEAR , 2000) OR LIMIT-TO (PUBYEAR , 1999) OR LIMIT-TO (PUBYEAR , 1998) OR LIMIT-TO (PUBYEAR , 1997) OR LIMIT-TO (PUBYEAR , 1996) OR LIMIT-TO (PUBYEAR , 1995) OR LIMIT-TO (PUBYEAR ,

Search strings
1994) OR LIMIT-TO (PUBYEAR , 1993) OR LIMIT-TO (PUBYEAR , 1992) OR LIMIT-TO (PUBYEAR , 1991) OR LIMIT-TO (PUBYEAR , 1990))
Economics (Scopus) pesticides AND cost AND great AND barrier AND reef
Non-agricultural pesticide risk management (Scopus) ((("urban" OR "industrial" OR "industry" OR "commercial" OR "road") AND ("runoff" OR "stormwater" OR "wastewater" OR "discharge" OR "water quality") AND ("pesticide" OR "herbicide" OR "insecticide" OR "fungicide") AND ("management" OR "action" OR "policy" OR "planning" OR "treatment" OR "measure") AND ("Queensland" OR "Australia" OR "Australian" OR "Great Barrier Reef") AND NOT ("crop" OR "farm")))

d) Inclusion and exclusion criteria

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

Table 5. Inclusion and exclusion criteria for Question 5.3 applied to the search returns.

Question element	Inclusion	Exclusion
Subject/ Population	**Pesticides:** Chemicals used to control pest species including herbicides, insecticides and fungicides.	Poisons and other biocides that control mammals, biological pesticides.
Exposure or Intervention	**Land uses:** Grazing, sugarcane, horticulture, banana (will be reviewed separately to horticulture), Irrigated & dryland cropping, and urban. **GBR ecosystems** include marine, estuarine and wetlands within the Great Barrier Reef Marine Park (GBRMP). **Non-agricultural land** practices included policy, planning, treatment, reuse, measure, and wetland.	Excluded from scope for specific discussion of management practices: • Conservation • Forestry • Mining • Military land • Commodities or crops outside of (or of minimal relevance) to the Great Barrier Reef catchment area
Comparator	All practices relevant to reducing long-term risks of pesticides to the environment. Spatial and temporal distribution include comparisons of management practices among NRM regions and catchments.	
Outcome	Ecosystem risks of losses of pesticides from a cropped field or urban environment, through runoff or deep drainage. Landholder economic measures of costs, cost-effectiveness and profitability of management practices for reducing pesticide losses.	Human health. Socio-economic aspects other than costs, benefits, cost-effectiveness and profitability studies (e.g., transition costs).
Language	English	Non-English language
Study type	Journal articles, reviews, reports	Non-peer reviewed by independent external reviewers and unpublished studies. Studies conducted before 1990.

3. Search Results

A total of 2,480 papers were identified from the initial search, and after final screening, 251 papers were found to be eligible and included in the synthesis. Of the 237 eligible studies for agricultural land uses, approximately 75% were based on on-ground studies or measurements at least in part within the GBR catchment area. These papers generally have higher levels of relevance to the SCS, but the findings are not always comprehensively applicable across the entire range of spatial scales and climate conditions found in the GBR. Additionally, a smaller number of studies (mainly from cotton, grains and horticulture) conducted in Australia, but outside GBR catchments were considered. These were judged to have high relevance to the GBR on important issues for which there was no equivalent information from studies in the GBR. In addition, several review papers were found in the search which distilled relevant information from outside the GBR catchment area. For non-agricultural land uses, studies across Australia were included due to the lack of articles within the GBR on non-agricultural land uses. Some international studies, where directly relevant, were also included (Table 6) (Figure 3). Three studies were unobtainable.

Table 6. Search results table, separated by A) Academic databases, B) Search engines (i.e., Google Scholar) and C) Manual searches.

Date (d/m/y)	Search strings	Sources	
A) Academic databases		Scopus	Web of Science
15/01/2023	*Agricultural pesticide management Search string 1: TITLE-ABS-KEY (((("Great Barrier Reef" OR gbr OR queensland) AND (pesticide OR herbicide OR insecticide OR fungicide) AND (effective* OR risk OR manage* OR environment OR sustainab* OR "no tillage" OR "water quality" OR aquatic OR runoff OR "deep drainage" OR "leachate" OR reduc* OR rate)))) AND (LIMIT-TO (PUBYEAR , 2023) OR LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2015) OR LIMIT-TO (PUBYEAR , 2014) OR LIMIT-TO (PUBYEAR , 2013) OR LIMIT-TO (PUBYEAR , 2012) OR LIMIT-TO (PUBYEAR , 2011) OR LIMIT-TO (PUBYEAR , 2010) OR LIMIT-TO (PUBYEAR , 2009) OR LIMIT-TO (PUBYEAR , 2008) OR LIMIT-TO (PUBYEAR , 2007) OR LIMIT-TO (PUBYEAR , 2006) OR LIMIT-TO (PUBYEAR , 2005) OR LIMIT-TO (PUBYEAR , 2004) OR LIMIT-TO (PUBYEAR , 2003) OR LIMIT-TO (PUBYEAR , 2002) OR LIMIT-TO (PUBYEAR , 2001) OR LIMIT-TO (PUBYEAR , 2000) OR LIMIT-TO (PUBYEAR , 1999) OR LIMIT-TO (PUBYEAR , 1998) OR LIMIT-TO (PUBYEAR , 1997) OR LIMIT-TO (PUBYEAR , 1996) OR LIMIT-TO (PUBYEAR , 1995) OR LIMIT-TO (PUBYEAR , 1994) OR LIMIT-TO (PUBYEAR , 1993) OR LIMIT-TO (PUBYEAR , 1992) OR LIMIT-TO (PUBYEAR , 1991) OR LIMIT-TO (PUBYEAR , 1990))*	*571* *(188 retained across both databases, following initial screening and removal of duplicates)*	*1,802* *(188 retained across both databases, following initial screening and removal of duplicates)*
	Economics search string 2: *pesticides AND cost AND great AND barrier AND reef*	*1 of 5*	*22 (8) of 985*

Date (d/m/y)	Search strings	Sources	
31/01/2023	*Non-agricultural* *((("urban" OR "industrial" OR "industry" OR "commercial" OR "road") AND ("runoff" OR "stormwater" OR "wastewater" OR "discharge" OR "water quality") AND ("pesticide" OR "herbicide" OR "insecticide" OR "fungicide") AND ("management" OR "action" OR "policy" OR "planning" OR "treatment" OR "measure") AND ("Queensland" OR "Australia" OR "Australian" OR "Great Barrier Reef") AND NOT ("crop" OR "farm")))*	*19 of 73 (initial screen)* *14 of 19 (secondary screen)*	
B) Search engines (e.g., Google Scholar)			
	n/a		
	Total items online searches	***211 (84 %)***	
C) Manual search			
Date	Source	Number of items added	
15/01/2023	*M. Silburn personal collection (predominantly Qld Government technical reports)*	*35*	
02/05/2023	*M. Star personal collection (predominantly Qld Government technical reports)*	*5*	
	Total items manual searches	***40 (16 %)***	

For this question, that had multiple land uses, with varying histories in specific water quality-based research, and several sub-questions, there were slight variations in the way each land use, or elements of assessing pesticide practice changes was assessed with respect to literature inclusion. This was dependent on the following conditions:

- Papers that provided measured, and specifically compared, water quality data associated with specific farming practices in GBR land uses, were preferenced, or given greater confidence-relevance ratings over other study types. Studies with replicated treatment water quality comparison were given the highest gradings for relevance and confidence to questions.
- There were, however, several exceptions. In land uses with minimal water quality data available (i.e., horticulture), studies relating to IPM concepts, or cultural practices, were included when they were published in peer reviewed journals, and/or had described some form of practice change relating to elements of the conceptual model.
- Given the movement of pesticides off-site is so consistently tied to pesticide application rate, studies describing practices that theoretically provide a decrease in application rate over a defined area, either in a single year, or over longer timeframes, with or without pesticide water quality data, were often included. This included rate reductions on a single paddock, or larger spatial scales (i.e., area wide management).
- Similarly, studies that provided data on practices that resulted in pest pressure reductions (i.e., cultural practices such as planting density, row spacing) were also included, with the assumption that decreases in pest pressure should also result in subsequent reductions in pesticide application rates. Many papers were vague about the actual long-term implications of practices that had resulted in significant reductions in pest pressure, specifically in relation to long-term reductions in overall pesticide usage.

- Information on the costs, cost-effectiveness and production outcomes of the practices were only collated if they were presented alongside changes in pesticide management.
- The results were presented with due consideration of the spatial variability and climatic conditions; but only for studies that had shown a change to pesticide risk following land management change.
- Studies that related to issues likely to have implications for management practice and water quality issues, or changes in practice relating to elements of the concept model were also included, but primarily for context, rather than specific water quality comparisons. This included papers highlighting changes to pesticide application and tillage practices and IPM issues around industry responses to emerging pesticide resistance management. These studies were given lesser weighting than specific water quality comparisons, but included for context, and longer-term importance.
- Studies relating largely to comparative pesticide efficacy (i.e., weed control) were also given lesser weighting, but were included if they provided some context to broader water quality issues.

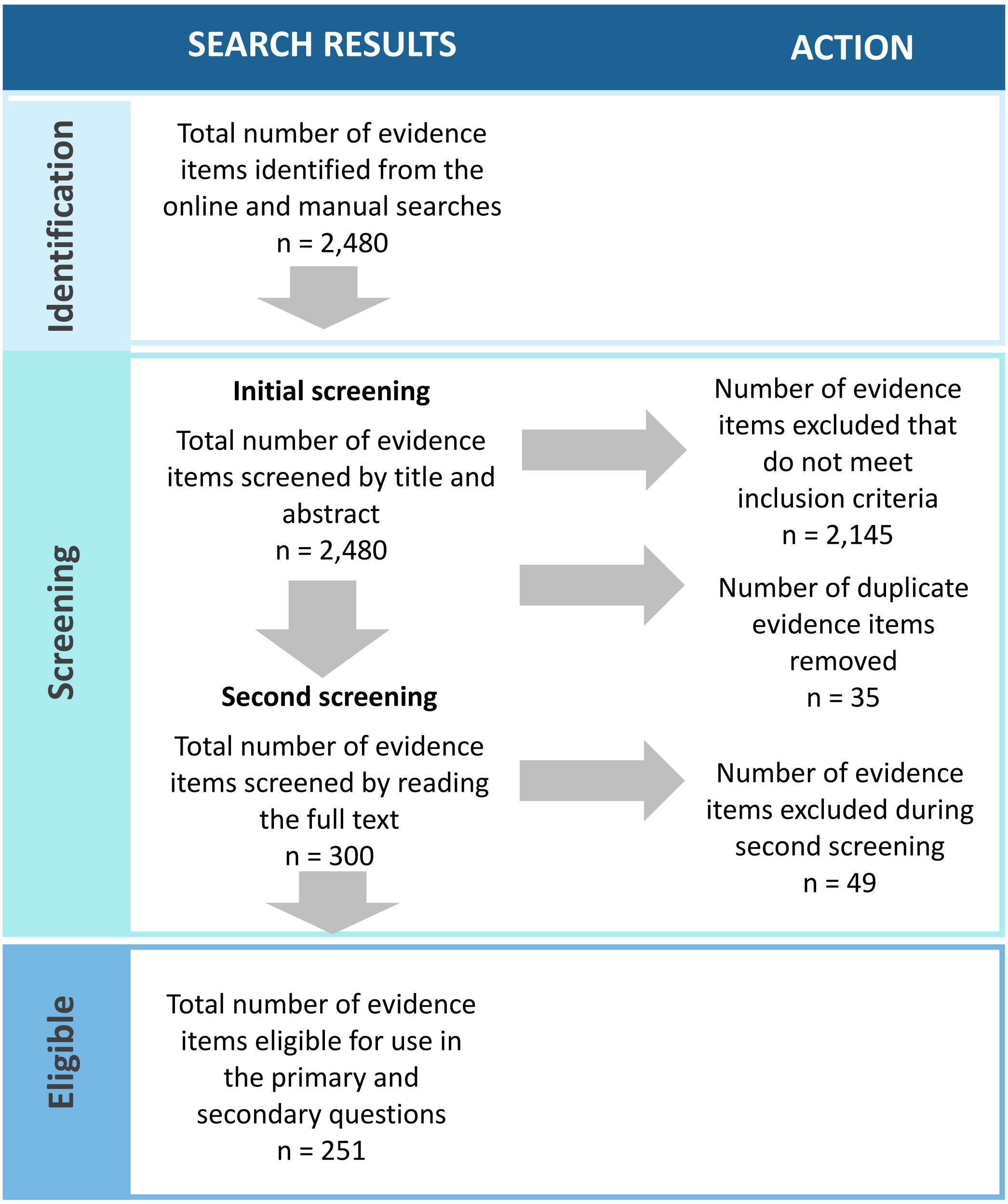

Figure 3. Flow chart of results of screening and assessing all search results for Question 5.3.

4. Key Findings

4.1 Narrative synthesis

4.1.0 Summary of study characteristics

A total of 251 eligible studies were found for Question 5.3 following the literature search screening. The main study characteristics in terms of agricultural commodity (235 studies) are summarised in Table 7. Over 70% of the eligible studies are from locations and specific land uses found at least, in part, within the GBR catchment area, with sugarcane, grains and cotton dominating research effort. Weed control dominated the literature, with 105 studies related specifically to herbicide usage, 21 relating to insecticides, 18 with general pest management, and 12 studies for fungicides or rust control.

Table 7. Summary of the primary agricultural industries and pesticide characteristics evaluated.

Primary land use or commodity							
Bananas	Cotton	Grains	Grazing	Horticulture	Sugarcane	Multiple commodities	No specific commodity
3	25	35	11	17	60	17	28
Pest management target-topic							
Biocides	Fungicides-Rust control	General pest management	Herbi-cides	Herbicides-Insecticides	Insecti-cides	Nematicides	General water quality
1	12	25	115	15	28	2	9

Studies found were classified as primary studies (experimental or observational), secondary studies (reviews, Systematic Reviews or meta-analysis), modelled or mixed (e.g., involved a mixture of experimental, modelled and/or observational studies and reviews). Almost half of the screened studies (91) were of a broad experimental nature, although the range of methodologies, scale, replication and use of a strict control or controlled manipulation of specific variables varied dramatically (Figure 4). Most experimental design studies (57) generally related to paddock-scale agronomic and/or water quality field studies, where broad paddock treatments were used as controls and variables, with interventions such as pesticide type or product, management practice (tillage, row spacing, planting density), pesticide application practices or pesticide control efficacy manipulated or monitored. Field trials involving rainfall simulation over relatively small areas/plots were also frequent (16 studies). Experiments involving more controlled conditions under a laboratory, glasshouse, or pot-trial type design were less prevalent. These typically involved research questions more amenable to control-replication such as a comparison of spray-nozzle technology performance, or some aspects of pesticide physico-chemical behaviours such as pesticide dissipation (Dang et al., 2016; Shaw et al., 2013a). This diverse spectrum of experimental study types and scales underlines the challenges and expenses of conducting comparative, replicated, long-term agronomic and/or water quality research relating to pest control at commercially relevant farming scales.

A substantial proportion of studies (81 in total) were secondary studies (reviews, or reviews with an added observational element). Modelled studies involved a diverse range of topics. This included use or development of a range of paddock or subcatchment scale, water quality models (often with underlying comparative management practice emphasis), modelling of different elements of genetic resistance to pesticides or pests, and socio-economic models of cost-benefits of farmers adopting a particular practice change.

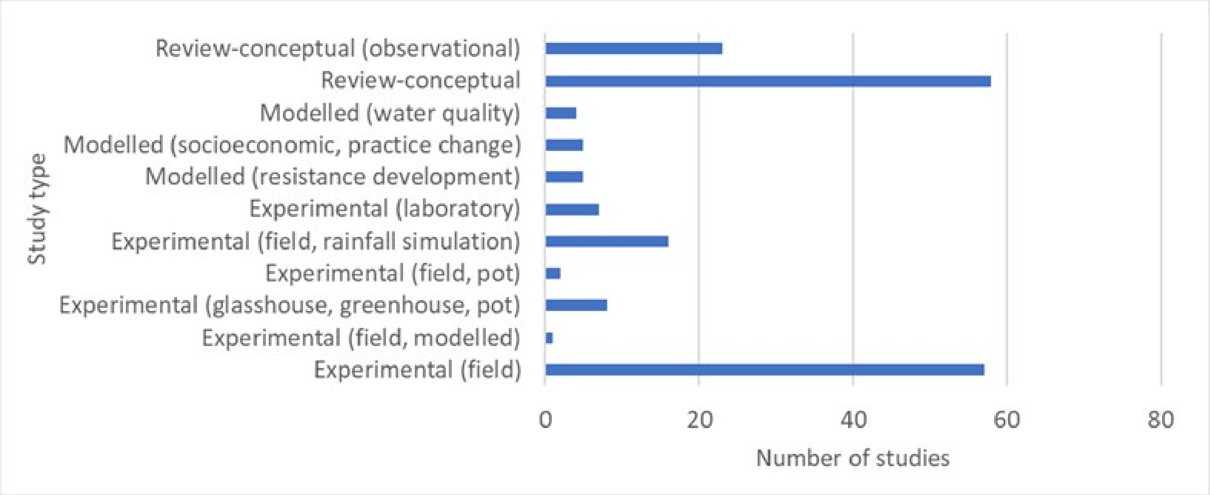

Figure 4. Range of study types from literature review screening and study extraction for agricultural land uses.

In terms of specific study focus, 50 studies involved some direct element of quantification or consideration of the water quality implications of, or comparisons between, specific paddock-scale management practices (Figure 5). The nature of the specific practice, with associated quantification of water quality dynamics, however, varied widely. Water quality studies included comparisons between different pesticide product types and strategies, physico-chemical pesticide behaviours, pesticide application rates, application methods, and product efficacy. Integrated pest management concepts were the next most prevalent topic (29 studies). Remaining studies encompassed a broad range of agronomic, economic, pesticide resistance, pest control efficacy, precision agriculture and policy appraisal topics with linkages to this review's conceptual model. It is noteworthy that many studies, while relevant to improving water quality, and often mentioning it explicitly, often had little explicit quantification of comparative losses of pesticides associated with management practices. Nevertheless, they do relate to overarching management applications or considerations on the periphery of the conceptual models outlined in Figure 1 and Figure 2.

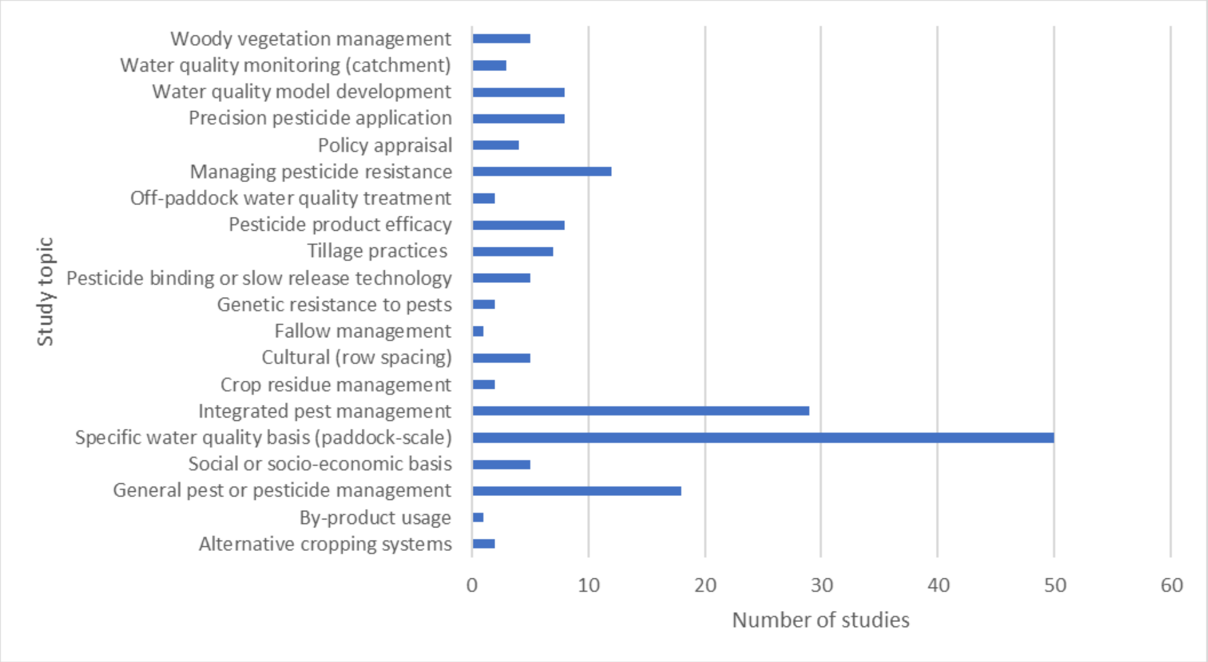

Figure 5. Range of pest management study focus topics from literature review screening.

4.1.1 Summary of evidence to 2022

What are the most effective management practices for reducing pesticide risk from the GBR catchments?

4.1.1.1 Management of pesticides in agricultural lands

Most studies specifically addressing the risks of pesticides to water quality focused on aspects at the scale of farm management (cultural decisions around crop residue management, tillage and fallow management), and control method decisions at a paddock scale, predominantly around chemical control (pesticide choice, application rates and methods). Table 8 shows specific farm and paddock management practices that were effective in reducing runoff losses, or ecosystem risk of pesticides in Great Barrier Reef catchments.

Table 8. Effectiveness of management practices in reducing pesticide risks (studies since 2017 SCS in bold).

Management practice	Risk reduction effectiveness	Relevant studies
Tillage and residue management: reducing runoff and soil erosion through retaining cover, controlled traffic, increased crop frequency and irrigation water management.	On average, 15% reduction in runoff with wide-row spacing (controlled traffic) in sugarcane in Mackay Whitsunday region (Rohde et al., 2013). Predominantly effective in reducing pesticide losses in runoff of compounds that are sorbed to sediment, due to its effectiveness in controlling erosion. Results for more soluble herbicides more variable and inconsistent.	Cowie et al., 2012a; 2012b; Masters et al., 2013; Nachimuthu et al., 2016; Rohde et al., 2013; **Silburn, 2020**; Silburn et al., 2002; 2013.
Application rates: Reducing the amount of pesticide applied, through precision application practices such as banded/shielded/spot spray applications, or applications below maximum label rates.	Pesticide runoff load reductions from paddocks are typically directly proportional to rate reductions in rainfall scenarios (i.e., 50% reduction in area applied or product applied results in 50% reduction in load loss). Reductions can be disproportionately greater (up to 90%) in furrow irrigated management systems.	**Davis & Neelamraju, 2019**; Davis & Pradolin, 2016; **Fillols et al., 2020**; Masters et al., 2013; Melland et al., 2016; Nachimuthu et al., 2016; Oliver et al., 2014; Silburn & Kennedy, 2007; Silburn et al., 2013; **2023**.
Application timing: timing pesticide applications to avoid risk of runoff from rainfall or irrigation within several weeks of the application.	Variable (magnitude dependent on duration of runoff delay and persistence characteristics of specific pesticides). >90% load and EMC reductions for a 1 versus 21-day runoff delay for ametryn and atrazine cf. ~50% reductions for diuron and hexazinone.	Armour et al., 2012; 2013; **2022**, Davis et al., 2013; Masters et al., 2013; Murphy et al., 2013; Nachimuthu et al., 2013; 2016; Rohde et al., 2013; Thornton & Elledge, 2016.
Product choice: choosing products with shorter persistence, greater sorption, lower mobility and lower toxicity.	Depends on specific product.	Cowie et al., 2012; Davis et al., 2014; **Davis & Neelamraju, 2019; Fillols et al., 2020**; Lewis et al., 2013; Melland et al., 2016; Shaw et al., 2011; Silburn et al., 2013; **2023**.
Product placement:	50% reductions in pesticide runoff EMC for imidacloprid application at 100 mm (label recommendations) versus 50 mm depth.	**Fillols & Davis, 2020**

It is also worth noting several potential avenues for reducing pesticide losses by using binding adjuvants (Fillols & Davis, 2020; 2021a), or incorporating weed detection automation into spray technologies are in the early stages of testing in the GBR (Calvert et al., 2021), but have not matured enough for definitive demonstrations of utility.

4.1.1.1.1 Integrated Pest Management

A notable outcome of this review is the preponderance of studies (ca. 25%) relating specifically to, or capturing at least, significant elements of Integrated Pest Management (IPM) concepts. A critical step in reducing the amounts of pesticides applied (and lost to the environment) is effective, strategic pest control over the longer term. The approach is termed 'integrated pest management' and involves the careful integration of multiple pest control techniques, combining biological, chemical, physical and crop specific (cultural) management strategies and practices to grow healthy crops and minimise the use and risks of pesticides to human health and the environment. IPM also relates to managing issues such as pesticide resistance development. Previous Scientific Consensus Statements have explicitly recognised the value of IPM (Eberhard et al., 2017) in the context of integrated weed management. This emphasised weed management over many crop cycles to reduce the weed seed burden over time, using suppression of weeds through high levels of crop residues and crop competition and diligent weed control during fallow phases to avoid regeneration of the weed seed bank (Armour et al., 2022).

Given the diversity and scope of studies emerging from this review, the evolution and application of these concepts are certain to have profound implications for reducing future pesticide risk to GBR ecosystems. Unfortunately, the comparative water quality effects of many, if not most, of these strategies and practices at the scale of individual paddocks, farms, or farming areas is essentially non-existent. However, for many agricultural sectors in the GBR catchment area, collective IPM concepts, without specific water quality research, constitute the only recommendations for reducing pesticide risks to aquatic receiving environments. Throughout this review the term IPM is used to refer to the integration of several tactics to manage pests, rather than a sole reliance on synthetic pesticides, and typically capture some element of the conceptual model outlined in Figure 1. Many elements of IPM do, however, also relate directly to the specific practices identified as delivering reduced pesticide water quality risks to aquatic ecosystems identified above in Table 8 (e.g., reductions in pesticide application rates, selection of more selective or lower risk pesticides, precision application technologies, use of non-pesticidal control measures). It should thus be possible to calculate the water quality benefit of most of these practices in more targeted studies and modelling exercises but that is outside the scope of this review.

Integrated Pest Management in the GBR catchments

Some IPM tactics noted as being used by GBR farmers in periodic reviews could include, but are not restricted to, the use of selective pesticides or biopesticides, good farm hygiene practices, control of weed hosts and regular crop monitoring, cultural controls such as destruction of weed host plants, conservation of natural enemies, identification of economic thresholds to trigger pesticide strategies, host plant resistance, and regular crop sampling to monitor pest and beneficial organism activity (Heisswolf & Kay, 2007; Macfadyen et al., 2019). It also relates to 'area-wide management' (AWM) strategies based on using an understanding of a pest's ecology, biology and host range, to manage its abundance and impact across a defined region (Brier et al., 2008).

IPM in several north east Australia grain, cotton and horticultural crops (soybeans, strawberries) has benefited considerably through the increased adoption of new, more selective insecticides and biopesticides, and the identification of pest–crop scenarios where spraying is unnecessary and pest pressure is reduced through conservation of natural enemies (Brier et al., 2008; Waite, 2006). Despite a desire to adopt IPM, and many non-chemical management practices being recorded across sectors, multiple studies note the unpredictable nature of pest outbreaks and small profit margins that have contributed to a high reliance on chemical applications (often prophylactic) as the sole method for pest control in many crops (Allsopp, 2021; Macfadyen et al., 2019; Osten et al., 2007). Few GBR catchment area industries consistently or comprehensively use IPM. The underlying reasons for this lack of adoption are multifaceted and likely reflect a continued desire for 'simple' technological solutions, short-term planning horizons and a failure by researchers to demonstrate and communicate the benefits of more integrated approaches. In part, future research approaches can address these questions using transdisciplinary frameworks that enable co-development of pest control technology and IPM systems, socio-economic approaches to better understand farmer decision-making, and a wider framing of pest management challenges and solutions, including through public–private collaborations (Neve et al., 2018).

Indeed, several significant GBR agricultural industries (grains, cotton, horticulture) are being forced to revisit IPM in light of new challenges altering how and when they use pesticides. For example, the development of pesticide resistance in some of the more widespread pest species will reduce the efficacy of certain insecticides and herbicides, and growers may be forced to use newer, more expensive products (Macfadyen et al., 2019), or newer chemicals with less environmental persistence and field efficacy (Huwer et al., 2015). The entry of new pests (i.e., cotton mealybug) and growing pesticide resistance in the spectrum of key cotton pests in Australia is providing fresh impetus for developing sustainable, cost-effective and integrated pest management (IPM) compatible population control options in Bollgard®-based production systems (Hopkinson et al., 2020; Wilson et al., 2013, 2018). In Australian cotton production systems, the severity of pest insect infestations is thought to be linked to the use of broad-spectrum insecticides to control key sucking pests such as mirids (*Creontiades* spp.) and aphids, mediated through deleterious effects of the insecticides on beneficial arthropod communities (Hopkinson et al., 2020; Wilson et al., 2013).

Fruit-spotting bugs *Amblypelta nitida* Stål and *Amblypelta lutescens lutescens* (Distant) (Hemiptera: Coreidae) are major native pests in subtropical and tropical horticultural crops in Australia and a key pest in avocado and mangoes. The mainstay of fruit-spotting bug chemical control in virtually all crops mentioned had been endosulfan, which had its Australian registration withdrawn by the Australian Pesticides and Veterinary Medicines Authority (APVMA) in October 2010, removing it as an option for horticultural producers (Huwer et al., 2015). There are few effective replacements for endosulfan, all of which are broad-spectrum, more expensive and potentially more disruptive to natural enemies. Reduction in the use of broad-spectrum insecticides is fundamental to the advancement of IPM, but in crops such as mangoes this has resulted in damage caused by fruit-spotting bugs becoming a significant issue, with research into alternative control techniques a high priority (Domeniak & Ekman, 2013; Huwer et al., 2015).

4.1.1.1.2 Managing resistance

Managing herbicide and insecticide resistance emerged as a dominant study focus from the systematic literature searches. While few studies had any direct consideration of specific water quality risks, the longer-term environmental impacts of pesticide resistance will almost certainly have major implications for managing future GBR catchment pesticide risks. Emergent issues already include poor pest control necessitating greater pesticide use (follow-up sprays following an initial failure), new herbicide rotations, double knockdown (use of a different second herbicide treatment to kill any survivors), changing herbicide application rates and methods, different future pesticide formulations and modes of actions[8], grower and industry unfamiliarity with newer products and associated risk management (Height et al., 2022). Ensuring current practices recommended for improved water quality do not contribute to pesticide resistance is also a critical consideration for policy. The estimated cost of additional herbicide treatments and the integration of extra weed management strategies to control herbicide-resistant weeds have already been estimated to cost

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[8] Grains Research & Development Corporation: https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2020/02/new-chemistry-whats-new,-whats-coming-and-how-to-keep-them-for-longer

AUD $187 million per year (Mobli & Chauhan, 2020). Evolution of pesticide resistance will also potentially impact the future viability of entire farming systems approaches in some industries. Indeed, this makes pesticide resistance a key consideration, with profound and far-reaching implications for future policy in the GBR catchment area.

Genetically modified crops, in particular, have refashioned the weed management environment in many crops, leading to much greater dependency on glyphosate for weed control. Weed management practices in cotton systems were historically based on frequent cultivation, residual herbicides, and some post-emergent herbicides. The ability to use glyphosate as a knockdown before planting, in shielded sprayers, and now over-the-top in glyphosate-tolerant cotton, has produced a significant reduction in the use of residual herbicides and cultivation. Such overreliance on glyphosate has, however, led to the evolution of 43 glyphosate-resistant weed populations globally, with at least 16 species reported from Australia, and several other weeds presenting as very strong candidates for increased resistance in glyphosate-based farming systems relevant to major GBR crops (Chauhan, 2023; Chauhan et al., 2022; Werth et al., 2011; 2013; Widderick et al., 2013).

One response to slow glyphosate resistance is the integration of multiple herbicide-resistant genes (trait stacking) into crop plants which would allow over the top application of herbicides that are otherwise fatal to crops is (i.e., ‘triple-stacking’ dicamba, glyphosate and glufosinate-resistant traits in cotton). Recent research, however, suggests that where there is already a substantial background of existing resistance to one or more of these herbicides, substantial extra management beyond what a glyphosate/glufosinate/dicamba resistance stack provides will be required (Thornby et al., 2018). Genetically resistant weeds, in combination with challenges in controlling volunteer glyphosate-tolerant crop plants are now decreasing the value of the GM crops and forcing growers to spend more time, effort, and investment in their management. Weed management strategies need to be diversified and integrated with non-chemical methods and alternative herbicides not only to achieve efficient control, but to reduce the rate of evolution of resistant weeds. In future, research is needed to improve integrated weed management through development and use of more diverse systems involving competitive and multiple herbicide-tolerant (HT) crops, robust resistance management systems, organic herbicides, bioherbicides, RNAi technology and robotics (Iqbal et al., 2019a; 2019b; Thornby et al., 2018).

The addition (i.e., re-introduction) of sequential applications of pre-emergent modes of action plus cultivation (strategic tillage) to farming systems are increasingly recommended to effectively control glyphosate-resistant grasses and extend viability of glyphosate-based weed control into the future (Thornby et al., 2013; 2018; Widderick et al., 2013). It has been explicitly recognised that for currently glyphosate-resistant cotton cropping to remain profitable in Australian farming systems in the long-term, farmers must adapt to the high probability that they will have to deal with summer weeds that are no longer susceptible to glyphosate (Thornby et al., 2018).

4.1.1.1.3 Cultural controls (e.g., row-spacing, crop competition)

Cultural control for pest management is a broad concept, encompassing practices that manipulate the broader crop production system across a farm to reduce pest establishment, reproduction, dispersal, competitiveness and/or survival (minimising the need or scale of subsequent chemical or physical control of an established pest presence). It includes practices such as paddock-field layout and orientation, fallow management, crop rotation, timing of planting, harvesting and field operations, resistant crop varieties, crop planting density, seed or plant quality, and management of adjacent environments. Weed resistance, limited new modes of action herbicides, growing costs and concerns over environmental issues associated with frequent herbicide use and tillage has prompted increased interest in alternative, non-chemical weed management options. Much of the recent literature since the 2017 SCS addresses several aspects or strategies for cultural control of pests.

Row spacing and planting density

Cultural techniques of weed management, in which crops themselves are better able to compete with weeds (including narrow row-spacing, higher crop planting density, changing crop row orientation relative to sunlight direction, and choosing early and vigorously growing crop species and cultivars) are gaining popularity as a more important component of integrated weed management strategies (Iqbal et al., 2022; van der Meulen & Chauhan, 2017). The use of narrower row-spacing or increased planting densities, in particular, are some of the most promising approaches to weed suppression for cost-effectiveness, water-efficiency, environmental footprint, weed control and maintenance of and, in some cases, provision of greater yields in many crops (Iqbal et al., 2022; Mobli et al., 2020b). While these options already have a long-standing history and development in Australian cropping systems and are proven in their ability to reduce weed biomass and fecundity in crops relevant to the GBR catchment area including cotton, sorghum, maize, rice , wheat, soybean and mungbean (Iqbal et al., 2022; Mhlanga et al., 2016; van der Meulen & Chauhan, 2017), the research has frequently been focused locally and not extrapolated more broadly throughout the broader Australian production region. Crop competition can potentially be a sustainable weed management option in reducing the reliance on herbicides, combating future herbicide-resistant weed populations, and is broadly advocated for future integrated weed management plans (Bajwa et al., 2017; Iqbal et al., 2022; van der Meulen & Chauhan, 2017).

Crop residue management

Crop residue management in the form of green-cane trash blanketing (GCTB) in sugarcane has a long and established history as an efficient practice to manage weeds in sugarcane production. However, information gaps remain on the optimal thickness of a green-cane trash blanket for weed control or the optimal timing of the herbicide applications in this situation. Poggio et al. (2014) showed that, in comparison to bare soil, trash at all levels reduced weed coverage and contributed to additional yield and profitability. In particular, increasing the level of trash led to improved management of broadleaf weeds and grasses, and strategies involving early application of pre-emergent herbicides were more efficient. Waters (2001) measured sediment, pesticide, and nutrient runoff for irrigated conventional cotton compared to cotton planted into a wheat cover crop in Australia. Wheat-cotton rotation reduced soil erosion by 70% and endosulfan insecticide concentrations in runoff by 40%. In addition, three less insecticide sprays were needed for the wheat-cotton rotation crops.

Use of crop residues for weed control in other commodities is not as evolved or clear cut. Nachimuthu et al. (2016) found that using knockdown herbicides (that are non-selective and kill all plants) and an inter-row soybean mulch instead of residual herbicides, resulted in adequate weed control in the plant cane crop and a complete absence of residual herbicides detected in runoff. The same strategy in the first ratoon crop resulted in poor weed control and additional herbicide applications were necessary at a later stage of the crop. The authors considered that the trash layer in the ratoon crop was not thick enough for long enough to provide weed control, but it did cause interactions between the herbicide and the trash that had negative effects on weed control. Recent crop residue retention pot trials in sorghum and wheat demonstrated the high potential of using crop residues in eco-friendly weed management strategies, such as harvest weed seed control tactics, but results are yet to be extended to commercially relevant scales (Mobli & Chauhan, 2020).

Fallow management

To break the cycle of continuous cultivation of grass crops (sugarcane and sweetcorn), leguminous rotation breaks (cowpea and soybean) are commonly used. They were introduced to determine their effects on soil properties and sugarcane yields in Florida Histosols. Soybean suffered from initial weed pressure, as did sweetcorn, whereas cowpea had an excellent smothering effect on weeds with quick ground coverage (Vuyyuru et al., 2019).

4.1.1.1.4 Tillage

Tillage is defined here in a broad sense, including disturbance of the soil and crop residues, wheel traffic and sowing opportunities. In tropical and subtropical, semi-arid cropping areas in Australia, tillage systems have evolved from intensively tilled bare fallow systems, with high soil losses, to reduced and no tillage systems (Freebairn & Wockner, 1986 & other review papers; Thomas et al., 2007). In recent years, the use of controlled traffic (typically wider row spacings) has also increased (Tullberg, 2010). These conservation tillage systems are successful in reducing water erosion of soil (Freebairn & Wockner, 1986) and sediment-bound chemicals (Silburn et al., 2002). Previous GBR research, and Scientific Consensus Statements (Eberhard et al., 2017; and references therein) have emphasised tillage management's effectiveness in reducing pesticide losses. These reductions were associated with the degree to which the treatment reduced runoff. Recent literature is, however, being more circumspect and offering more clarity in language around tillage benefits in managing pesticide risk, particularly in dealing with more soluble (less sediment bound) pesticides.

Perhaps one of the most notable recent changes since the 2017 SCS is a shift toward recognising that previously assumed water quality benefits from adoption of no till or reduced tillage farming systems (NRT) compared to conventional tillage (CT) systems may be more variable and inconsistent than previously assumed (see Silburn, 2020). A key long-standing theoretical assumption of NRT farming systems and stubble retention is that pesticides are intercepted on surface cover. Sorption of pesticides on crop residues can vary between pesticides, crop residues, and ages of residues, but most pesticides can be washed off by rainfall. Limited data indicates half-lives may be greater on crop residues than in soil, but both more rapid and slower dissipation has been found. Equally, dissipation in the soil has been found to be slower, equal, or faster in NRT compared to CT. Sorption to NRT soils is often greater due to greater organic carbon, but in practice the difference can be minor. Thus, recent reviews and meta-analyses indicate many aspects of pesticide behaviour in NRT systems are variable, inconsistent, or inconsequential (see Silburn, 2020 for references). Fawcett et al. (1994) reviewed pesticide runoff (mainly soluble herbicides) from NT systems and found runoff was typically lower with NRT, but only considered six natural rainfall studies. A more recent review (Elias et al., 2018), which examined 34 studies, found pesticide loads were greater for NRT than 'plow till' (CT) for two pesticides, lower for another, and not different for the remainder (17 pesticides). Similarly, concentrations were greater in runoff from NT for four herbicides and were not different for all others. However, NRT (retaining cover) is typically effective in reducing pesticide losses in runoff of compounds that are sorbed to sediment, due to its effectiveness in controlling erosion.

While adoption of NRT has progressed globally, and particularly in north-eastern Australia (Thomas et al., 2007), there are concerns regarding long-term sustainability of these systems, through build-up of herbicide-resistant weed populations, increased incidence of soil and stubble-borne diseases and stratification of nutrients and organic carbon in the topsoil (Dang et al., 2015a; 2015b). There is growing interest in the use of an occasional strategic tillage (ST) to combat both biotic and abiotic constraints in NT systems (Dang et al., 2015a; 2015b; Kurstjens, 2007). The results show that generally, there were no significant differences in crop productivity and soil health between tillage implements and tillage frequencies between ST and NT. The study suggests that ST can be a viable strategy to manage constraints of NT systems, with few short-term soil and environmental costs and some benefits such as short-term farm productivity and profitability and reduced reliance on herbicides (Dang et al., 2015a; 2015b; 2018).

The recent development of commercially available camera-based weed detection systems for targeted tillage for fallow weed control hold considerable promise for the introduction of site-specific, non-chemical weed control for particular scenarios in conservation cropping systems (i.e., fallow fields with low weed densities), providing very high weed control efficacies and associated low levels of soil disturbance (Walsh et al., 2020).

4.1.1.1.5 Habitat Management

Habitat management is an ecologically based approach to suppress pest densities, and a form of conservation biological control, using properties of non-crop vegetation to improve the impact of natural enemies or to directly affect pest behaviour (Rizvi et al., 2022; Wyckhuys et al., 2022). Common habitat management tactics include provision of non-crop vegetation (field borders or secondary intercropping with flowering plants to provide food resources or shelter to pest predators), use of trap crops to divert pests from high-value crops (a population sink) or controlling host plants that encourage pests (Lindsay et al., 2019; Rizvi et al., 2022). Research in this approach has escalated dramatically this century, extending to uptake in some crops, but adoption in Australia has been lower than overseas (Rizvi et al., 2022). The need of the Australian vegetable sector to reduce reliance on insecticides has seen recent habitat management platform development by researchers and farmer-led studies to help identify opportunities and recommendations for habitat management approaches in Australian vegetable production systems, including several crops (sweetcorn and capsicum, various legumes) of direct significance to the GBR catchment area (Rizvi et al., 2022).

Several precedents exist with relevance to key crops in the GBR context for habitat management. In recent years, macadamia growers have been encouraged to adopt wider spacing and/or pruning techniques to increase light into their orchards for improved tree health and nut production. Use of more florally diverse, weedy, flowering mid-row ground-cover vegetation (‘light’ orchards) harboured a significantly higher abundance of beneficial invertebrates than denser canopies. This significantly decreased abundance of a major pest, the macadamia lace bug, *Ulonemia concava* Drake (Hemiptera: Tingidae), and had significantly lower levels of damage to nuts (Huwer et al., 2015). Transgenic cotton that produces toxic proteins from the bacterium, *Bacillus thuringiensis* (Bt) is now widely used to help control *Helicoverpa* spp. (Lepidoptera: Noctuidae) damage in Bollgard II® cotton (Wilson et al., 2013). As part of a pre-emptive resistance management plan for Bollgard II® cotton, it is mandatory for cotton growers to plant 10% of farm area under a structured refuge crop (crop that does not contain or will not be sprayed with products that contain the Bt proteins present in Bollgard II® cotton) to produce large numbers of Bt-susceptible moths and so help to reduce the risk of resistance developing (Wilson et al., 2013).

4.1.1.1.6 Area-wide management, pest monitoring and economic thresholds

Area-wide management (AWM) contrasts with more traditional field-by-field pest management by controlling the total population of a pest species within a much broader, delimited geographic area (Lloyd et al., 2010). AWM is increasingly accepted especially for mobile pests where management at a larger scale is more effective and less environmentally detrimental than an uncoordinated field-by-field, curative approach, which often relies on repeated use of insecticides on individual fields. Several successful GBR precedents exist for AWM and implementation of broad-scale risk assessment programs to enable strategic application of pesticides and to encourage growers to embrace more proactive approaches towards pest management, although the longevity and continued impact of these initiatives is variable. For example, following severe damage in the 1990s, AWM programs have been implemented to mitigate damage to sugarcane caused by the greyback canegrub, *Dermolepida albohirtum* (Allsopp, 2010; 2021; Sallam & Lowe, 2012). Implementation of a broad-based approach to canegrub management in the Mulgrave sugarcane growing region of Far North Queensland saw the risk of potential greyback infestation on selected fields assessed using grub monitoring, and predictive models used to advise farmers whether to treat these fields according to the predicted level of risk. Data showed a significant reduction in grub numbers where growers applied a chemical treatment. Where growers were advised to refrain from treatment, grub numbers were still well below economic levels. However, despite the success of this project and demonstrated importance of research-based extension, and the undoubted rationale behind an integrated approach, the subsequent availability of cheaper imidacloprid formulations masked the benefits of the system, and growers have since regressed to reliance on that one insecticide to manage the pests (Allsopp, 2021).

Area-wide management of Queensland fruit flies (*Bactrocera tryoni* (Froggatt)) in the Central Burnett district of Queensland similarly represented the first attempt to implement a large-scale AWM program against native fruit fly species in an area with moderate to high endemic populations in Australia (Lloyd et al., 2010). The application of control measures from 2003 to 2007 resulted in overall suppression of fruit fly populations across the entire district. The program evaluation survey showed 96% of growers experienced improved fruit fly control under AWM; no additional insecticide sprays were required to protect highly susceptible varieties (e.g., late season Murcott mandarins); extension of the Murcott season into October without fruit fly problems; and improved fruit fly control in table grape farms. Results demonstrated remarkable improvement in fruit fly control and economic benefit to the Central Burnett horticulture with commercial growers continuing the AWM program as a long-term, industry funded activity, to provide an additional layer of phytosanitary security for market access of fruit commodities from this district. Similarly, an AWM strategy was initiated for central Queensland cotton farming to limit the rate of in-crop *Helicoverpa* spp. recruitment and exchange between cropping systems, using a trap cropping programme, concentrating the pest into small areas for mechanical destruction (slashing and cultivation) (Grundy et al., 2004). The subsequent emergence of transgenic Bollgard II® cotton rendered these approaches at least temporarily obsolete (Wilson et al., 2013).

Due to the increasing emergence of herbicide-resistant weeds, researchers have begun to recognise that management of herbicide-resistant weeds also represents a collective action problem that requires cross-property collaboration (i.e., area-wide management). Recent findings indicate that even high-efficacy herbicide management strategies practiced at the farm scale are insufficient to slow resistance evolution, whereas when best practices were aggregated at large spatial scales, resistance evolution was hindered; conversely, when poor management practices were aggregated, resistance was exacerbated, spreading to neighbouring properties and undermining their efforts (Evans et al., 2018). These findings highlight the importance of landscape-scale cooperative management for confronting common-pool-resource resistance problems in weeds and other analogous systems (Evans et al., 2018). Area-wide resistance management strategies align closely with those for controlling pests: clearly defining the boundaries of the area in which herbicide-resistant weeds will be managed; having land managers within that area agreeing to a shared goal; providing support to land managers who have fewer resources for managing herbicide-resistant weeds; and building strong working relationships among land managers (Height et al., 2022).

4.1.1.1.7 Trends or patterns in outcomes or effects including consistencies or heterogeneity within and between study findings

One of the noteworthy points to emerge from this Evidence Review is the often underappreciated tensions between different management practices or sustainability targets. An overly reductive focus on one practice or water quality issue can lead to contrasting impacts, or 'push-pull' trade-offs between different practices and environmental challenges facing farmers and pesticide decision making (Table 9).

Table 9. Some example trade-offs between management practices relating to reducing pesticide risk.

Practice	Potential trade-offs or perverse outcomes (ecosystem disservices)
Adoption of minimum tillage, conservation agriculture (sediment, greenhouse gas emissions)	• Increased reliance on, and losses, of herbicides for weed control (Davis et al., 2014; Owens et al., 2017a; 2017b; Tullberg, 2010). • Continual pressure by non-selective herbicides, such as glyphosate, paraquat and diquat leading to herbicide resistance and weed species composition shifts (Kurstjens, 2007; Peltzer et al., 2009). • Increased incidence of soil and stubble-borne diseases and stratification of nutrients and organic carbon in the topsoil (Dang et al., 2015b). • Decreased yields, reduced competition with weeds, and problems with crop rotations. • Increased water infiltration below the crop root zone, increasing the risk of salinity or groundwater contamination (Silburn et al., 2007a; 2021).
Transgenic crops	• Rapid evolution of higher than expected levels of resistance in pest species. • Reduced insecticide sprays against previous primary target species allowing some secondary pests (formerly coincidentally controlled by broad spectrum sprays) to increase to damaging levels (Wilson et al., 2013). Lack of knowledge and experience with these pests creates uncertainty and encourages insecticide use by farmers.
Use of trap crops in IPM	• Water requirements of a 'non-productive' crop during periods of water scarcity (Wilson et al., 2013).
Strategic tillage	• Higher risks of runoff and associated loss of nutrients and sediment during intense rainfall after strategic tillage (Dang et al., 2018; Melland et al., 2016).
Habitat management (host species)	• Native and non-native species and riparian zones as pest hosts (sources) (Huwer et al., 2015; Lindsay et al., 2019).

4.1.1.2 Spatial variation

Does effectiveness of these practices in reducing pesticide risks to water quality vary spatially or in different climatic conditions?

A relatively limited number of studies have been conducted (or specifically synthesised findings) across broad climatic zones or farming systems in different GBR regions, particularly with respect to comparison of specific water quality risks between practices. Nevertheless, broad findings with regard to key management practices thought to reduce risks (Table 1; e.g., pesticide application rates, pesticide application timing in relation to runoff, pesticide product selection) remain generally consistent.

- Collective results across multiple wet tropical, dry tropical, and temperate GBR regions showed diminishing risks of pesticide losses from paddocks with increasing duration of time between application and first runoff. Regardless of climate, multiple studies demonstrated that under certain conditions (i.e., heavy rainfall shortly after application), very high surface runoff losses of herbicides (>10% of active ingredient (a.i.) applied) are possible, and the key periods of greatest risk occur when rainfall-runoff occurs within 2-3 weeks of pesticide application to paddocks (Armour et al., 2013; 2022; Fillols et al., 2020; Masters et al., 2013; Rohde et al., 2012; 2013). Indeed, rainfall received, and timing of runoff-producing rainfall, can have a greater effect on pesticide losses than other aspects of management such as tillage system, an outcome paralleling global experiences (Silburn, 2020). Reduction in runoff loads after the first 2-3 weeks following application arises because pesticide residues degrade in soil or are lost from the soil surface via other processes such as leaching, volatilisation, microbial or photodegradation.
- Risk reductions associated with application rate are also generally consistent across regions and climatic zones, for reduced application rates of an individual pesticide ('low rates' versus 'high rates' of the same pesticide), and different application rates for different herbicides (pesticides applied at lower rates to paddocks). Pesticides applied at lower rates to paddocks (<150 g.a.i ha^{-1}; imazapic, isoxaflutole) often exhibit lower absolute load losses than pesticides applied at higher rates (>1,000 g.a.i ha^{-1}; diuron, atrazine, metolachlor, metribuzin) (Fillols et al., 2020; Silburn et al., 2023), although losses as a proportion of amount applied may not differ from some pesticides applied at higher rates. Reduced runoff losses by reducing pesticide application rates to paddocks are generally directly proportional across multiple studies, for multiple herbicides in multiple regions (Davis & Pradolin, 2017; Fillols et al., 2020; Masters et al., 2013; Melland et al., 2016). In one of the more spatially comprehensive studies, the relative reduction in runoff losses with reduction in pesticide load in soil and trash (pesticides sprayed onto 0, 20, 40, 50, 70, or 100% of the area of runoff plots) were very consistent across different GBR regions and soil types (Melland et al., 2016; Silburn et al., 2023; Figure 6). Although absolute losses of pesticides vary significantly across different GBR regions and soil types, the relative reduction in runoff loss that is delivered by a given reduction in pesticide load in soil and trash is very consistent across different GBR regions and soil types.

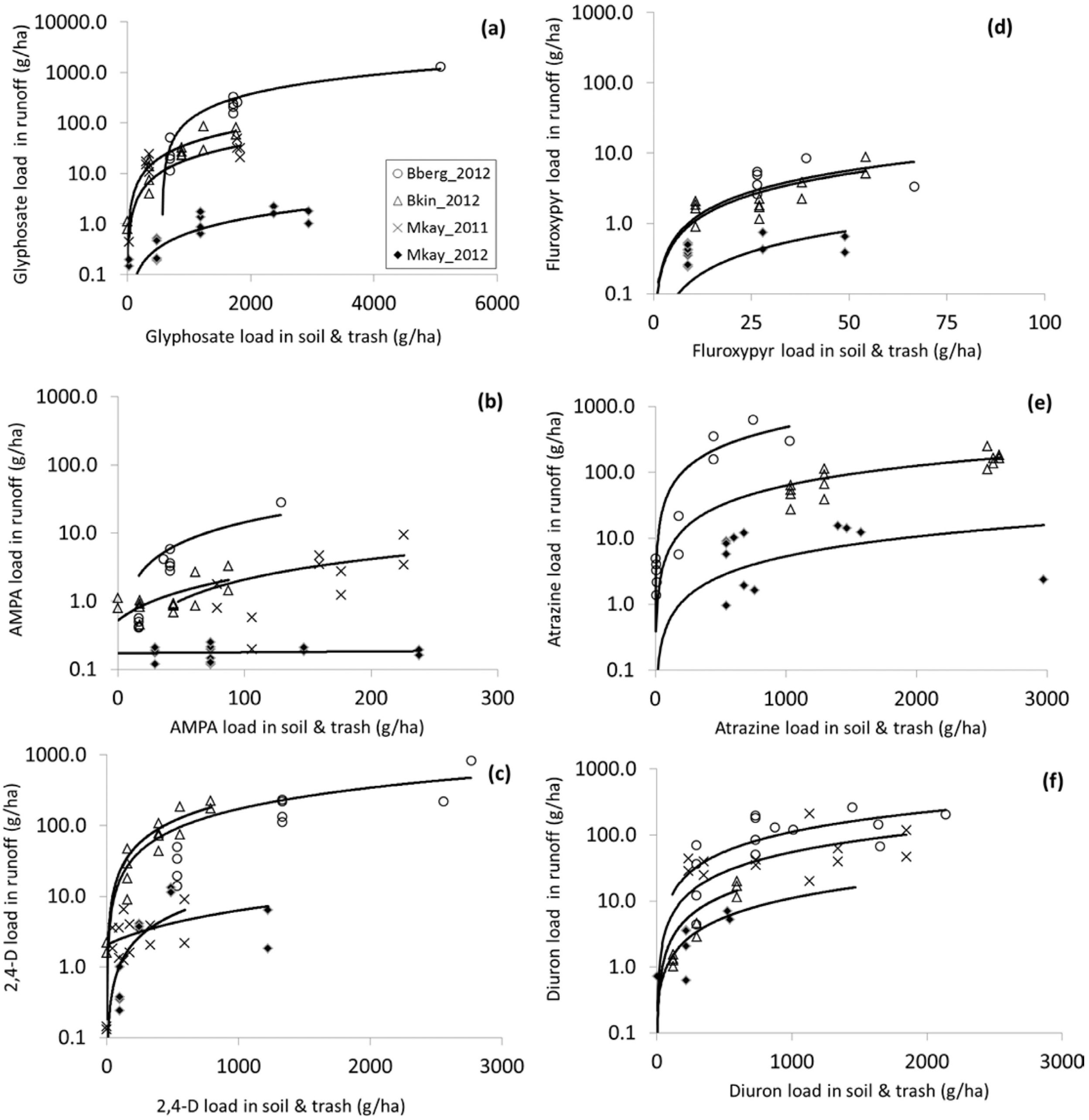

Figure 6. Loads of herbicide active ingredient (g.a.i ha^{-1}) in the dissolved phase of plot runoff and in soil and trash for (a) glyphosate, (b) AMPA, (c) 2,4-D, (d) fluroxypyr, I atrazine, and (f) diuron, showing linear lines of best fit. Note the y-axis log scale range for glyphosate runoff loads (a) is larger than for the other herbicides. (Source: Melland et al., 2016).

- Product choice, and the selection of different, lower risk pesticides has also produced consistently lower risk across different GBR regions. Several studies have used diuron as a benchmark for aquatic ecosystem risk, developing subsequent risk metrics from replicated rainfall simulation studies. These combine toxicity equivalents and load-concentration losses of herbicides in similar management scenarios (70-80 mm rainfall in an hour, within 2-3 days of paddock application). Relative ranking of different herbicides, both to diuron, and each other, emerged as broadly consistent across regions and farming systems (Table 10). Indeed, variations in herbicide loads lost (and associated risks) in surface runoff largely reflect the variability in runoff volumes across the treatment plots, rather than any marked differences in relative loss behaviour of herbicides between sites (i.e., relative load loss patterns were generally consistent between sites). Environmental risk profiles for a range of herbicides in runoff (relative to diuron) have, accordingly, been broadly similar across multiple studies and regions.

Table 10. Comparative risk profiles (compared to diuron) for multiple herbicides across multiple GBR region rainfall simulation studies (Fillols et al., 2020; Silburn et al., 2023). TEF is the toxic equivalency factor.

	TEF (cf. to diuron)	Tully	Aloomba	Mackay (trash)	Bundaberg (trash)	Burdekin (bare)	Mackay (bare)
'Older', residual, pre-emergent herbicides							
Diuron	1	1	1	1	1	1	1
Diuron-hexazinone	1	1.25	1.11	1.19	1.4		
Ametryn	0.64	1.01	0.434			1.265	1.49
Atrazine	0.036	0.105	0.058		0.254	0.109	0.03
'Alternative' residuals							
Metolachlor	0.047	0.085	0.036			0.103	0.018
Imazapic	0.23	0.026	0.013		0.052	0.55	0.01
Isoxaflutole	0.32	0.063	0.022		0.039	0.218	0.053
Metribuzin	0.23	0.364	0.126		0.476	0.494	0.26
Knockdown/contact herbicides							
2,4-D	0.0002	0.0006	0.0002		0.00047	0.0057	0.00016
Fluroxypyr	0.002	0.0002	0.0002		0.00006	0.001	0.00015
Glyphosate	0.002	0.0002	0.0015	0.003	0.0069	0.0066	0.00025

- Factors relating to soil variability, rather than climate may play significant roles in pesticide spatio-temporal behaviour. Studies of pesticide dissipation across a range of common GBR soil types found half-lives varied by less than a factor of 2 between soils for the herbicide's atrazine, 2,4-D and isoxaflutole, whereas half-lives for diuron varied by a factor of 14 (Shaw et al., 2013a). Total organic carbon was a significant explanatory variable for predicting degradation rates for many of the herbicides in this study. Further analysis of the data is required to investigate the relationship between measured half-lives and soil properties to extend prediction of spatial variability in herbicide degradation for all soils in the GBR catchment area.
- Shaw et al. (2013a) measured the half-lives of 14 herbicides commonly applied in sugarcane and grains on sugarcane residue over a period of 100 days in a glasshouse (which controlled temperature and soil moisture but would have limited photodegradation). Half-lives for all herbicides on sugarcane residues were slower than had been previously reported, which may be because of herbicide washoff from crop residues conducted in field studies and to limited photodegradation in the glasshouse. Degradation rates on sugarcane trash were found to range from 19–117 days, with no detectable degradation observed for diuron or tebuthiuron. The shortest half-life was 19 days for pendimethalin, six herbicides had half-lives of 30–45 days, and six had half-lives of 59–117 days. The half-lives were greater than half-lives measured in nine cropping soils in the same study, except for pendimethalin and paraquat which were less in sugarcane residues. These longer half-lives on sugarcane residues, and the wash-off from crop residues discussed previously, mean applying herbicides to crop residues should not reduce their efficacy (except where initial losses are higher than in soil), but would potentially increase their runoff risk.

4.1.1.3 What are the costs of the practices, and cost-effectiveness of these practices, and do these vary spatially or in different climatic conditions?

The number of available studies to address this question was relatively low, and predominantly limited to a small number of commodities, such as sugarcane. Management practices in GBR catchments have been grouped according to water quality outcomes. Farm management practice frameworks have also changed over time. Initial iterations broadly described a continuum of practices which were categorised based on their likely impact on pollutant loss and land resource condition (Drewry et al., 2008), with categories ranging from D – superseded or unacceptable, through to common medium risk practices (C), low risk (B - best management) and lowest risk (A – aspirational best practice). These frameworks were refined to focus more explicitly on the subset of farm practices with most influence on off-farm water quality, with management practice frameworks based on water quality risk developed in 2014 (Australian & Queensland Government, 2014) and further revised into Water Quality Risk Frameworks in 2016[9]. Farm management practices were aligned with risk states, from highest to lowest risk.

Poggio et al. (2014) explored the cost of managing PSII herbicides across the mill districts of Tully, Burdekin River Irrigation Area (BRIA), Burdekin Delta, and Mackay. A large number of combinations of different farm sizes were modelled with How Leaky across a number of practices and soil types. Poggio et al. (2014) specifically looked at pesticides (nutrient and sediment management practices were not considered) and explored the costs across the key principles of rate management, fallow management, herbicide selection, strategic use, application method, application timing, record keeping and planning and tillage management. Within these principles, different management actions were assessed in alignment with the ABCD management practice frameworks from 2013 (described above).

Capital costs ranged from $1,870 for implementation of capital expenditure pertaining to application method which involved the purchase of octopus bars, tracking legs, air inducted nozzles, triplet inducted nozzle heads and connections on a 50 ha farm through to $67,500 for a zonal ripper and rotary hoe for a 250 ha farm changing tillage management (Table 11). The analysis found efficiencies in farm machinery costs particularly for larger farms was a key driver of the economic outcomes.

Table 11. Economic assessment of pesticide management practice change shifts for different farm sizes shifting through the different management classifications (summarised from Poggio et al., 2014). For management practices, D – superseded or unacceptable practice or high risk, C – common or medium risk practices, B – best management or low risk and A – aspirational best practice or lowest risk.

Farm size	Application rate management C&B to A	Application methods C to M	Application method C to A	Application method B to A	Fallow manage-ment C to B	Ground cover manage-ment C to B
Small (50 ha)	$5,437	$1,870	$6,138	$5,647	$25,000	$12,500
Medium (150 ha)	$5,437	$1,870	$6,138	$5,647	$25,000	$19,500
Large (250 ha)	$5,437	$2,750	$8,331	$7,649	$25,000	$67,500
Equipment description:	Rate controller: Teejet 844 console and harness; flow meter; electronic regulating valves; GPS integration.	Octopus bars; tracking legs; air-inducted nozzles; triplet air-inducted nozzle heads and connections.	Hoods for sprayer; spray bar; adjustable size; spray tanks; electric pump; all appropriate connections; air-inducted nozzles; triplet nozzle heads and connections.	Hoods for sprayer; spray bar; adjustable size; spray tanks; electric pump; all appropriate connection.	Zero Till Legume planter.	Zonal ripper - rotary hoe.

It was found that progressing from C- to B-Class herbicide management was expected to be profitable and provide the highest return on investment across all farm sizes and sugarcane districts. Given that the capital expense was the same across all farm sizes, the larger the farm size the increased positive economic outcomes and the shorter the payback period. In Poggio et al. (2014) moving from C- to B-Class herbicide management in Tully resulted in a reduction of up to 14 g ha^{-1} yr^{-1} (~41%) in PSII-

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[9] Water Quality Risk Frameworks: https://www.reefplan.qld.gov.au/tracking-progress/paddock-to-reef/management-practices

equivalent herbicide (PSII-HEq) losses, depending on fallow and tillage practices. Relative reductions across other sugarcane districts are shown to be up to 10 g ha^{-1} yr^{-1} (~52%) in Mackay; up to 26 g ha^{-1} yr^{-1} (~52%) in the Burdekin Delta; and up to 55 g ha^{-1} yr^{-1} (~48%) in the BRIA.

Moving from C- to A-Class herbicide management was also found to be profitable in many cases; however, the payback period for 50 ha farms varied across districts. Corresponding modelling showed water quality benefits in the reduction of PSII-HEq losses by up to 29 g ha^{-1} yr^{-1} (~83%) in Tully; up to 15 g ha^{-1} yr^{-1} (~76%) in Mackay; up to 49 g ha^{-1} yr^{-1} (~98%) in the Burdekin Delta; and up to 109 g ha^{-1} yr^{-1} (~97%) in the BRIA.

Moving from B- to A-Class herbicide management is expected to come at an economic cost for 50 ha farms. This is predominantly due to the amount of capital expenditure required relative to farming area. On the other hand, it was expected to be profitable for 150 ha and 250 ha farms. Moving from B- to A-Class herbicide management showed significant improvements to water quality: a reduction of up to 15 g ha^{-1} yr^{-1} (~72%) in PSII-HEq losses for Tully; up to 5 g ha^{-1} yr^{-1} (~50%) in Mackay; up to 23 g ha^{-1} yr^{-1} (~95%) in the Burdekin Delta; and up to 55 g ha^{-1} yr^{-1} (~94%) in the BRIA.

Collier et al. (2015), Harvey et al. (2016) and Smith et al. (2014) reviewed the herbicide economic findings of Poggio et al. (2014). Smith explored the work in conjunction with nutrient and adoption data providing further research opportunities. Collier et al. (2015) and Harvey et al. (2016) both noted that the results were found to be critically dependent on regional-specific variables including biophysical characteristics and enterprise structure, especially in relation to farm size and location. The reliance of Collier et al. (2015), Harvey et al. (2016) and Smith et al. (2014) on the findings of Poggio et al. (2014) highlights the limited economic analysis that has occurred in assessing the economic implications of pesticides.

4.1.1.4 What are the production outcomes of these practices?

Studies on specific impacts of pesticide practice change on crop production (crop yield) were sparse across the results obtained in the literature search, and available results tended to concentrate on broader implications of pest impacts. For example, Fillols et al. (2020) noted yield loss from weed competition is estimated to cost the Australian sugar industry $70 M annually, with herbicidal control strategies costing the industry an additional $14 M annually, with herbicides themselves also causing yield declines through phytotoxic effects on crops. Fillols et al. (2020) quantified and compared the efficacy, economic costs and environmental risk profiles of a range of established, emerging, and recently registered pre-emergent herbicides across field trials in the Wet Tropics region of North Queensland. Several herbicides were effective on certain weed species, but lacked broad spectrum control. Better efficacy results from products with multiple active ingredients (i.e., imazapic-hexazinone) demonstrated the benefits of using mixtures of active ingredients to widen the spectrum of weed control efficacy. This variable efficacy suggests likely follow-on impacts from management practice decisions, but such outcomes were largely unexplored in the available literature. Clarification of yield impacts associated with different pesticide management strategies, or effects of pesticides themselves (phytotoxicity in crops) is a likely information gap.

Harvey et al. (2016) completed a review of all farm management practices across sediments, nutrients and pesticides in sugarcane and reviewed seven papers regarding pesticides. Five were focused on the Mackay Whitsunday region and one in the Wet Tropics. The Mackay trials predominantly focused on herbicide management in conjunction with Green Cane Trash Blanketing (GCTB). These trials found that a thicker trash blanketing suppressed weeds and a pre-emergent strategy was more profitable due to overall herbicide costs. The Fillols (2013) trial focused on herbicide application methods: pre-emergent at leaf stage (broadcast and banded spray); knockdown at stooling stage (direct spray with droppers, shield blanket spray, precision spray (Weedseeker™ Shield Sprayer) and knockdown at out of hand stage (shield blanket, precision spray (Weedseeker™ Shield Sprayer). The trial found that post-emergent strategies using the Weedseeker® shielded sprayer in November and December were very efficient in managing the emerged weeds however, herbicide savings for the spot-sprayed treatments using the Weedseeker® were not as large as expected because the weed infestation in the trial was light and uniform in coverage, not in patches.

Harvey et al. (2016) noted that the results found no difference in yield between the herbicide treatments tested. Partial net benefit economic analysis found trial one to be the most costly (marginal return just below \$3,000 ha^{-1}), trials two and three were cost equivalent (marginal return approx. \$3,200 ha^{-1} and \$3,275 ha^{-1}) and trial four and trial five were the cheapest (marginal return \$3,225 ha^{-1} and \$3,200 ha^{-1}) as they did not use pre-emergents and the precision sprayer used less herbicide. However, there was no statistical difference in marginal return between herbicide treatments and control treatments (marginal return of control treatment just below \$3,000 ha^{-1}), as yield gains offset herbicide costs. It must be noted that this trial was completed in 2013 and therefore the herbicide costs will now be different.

Harvey et al. (2016) also reviewed a trial in Mackay, reported in Bally et al. (2013), where the costs of the treatments were presented for trials done in 2011 and 2012. In 2011 and 2012 the most cost-effective trial was no pre-emergence then Weedseeker™ Shield Sprayer with glyphosate + selective knockdown over the row when needed. Harvey et al. (2016) reported that the most expensive trial in 2011 was the broadcast application of a pre-emergent herbicide just after harvest followed by directed knockdown if needed and in 2012 the most expensive was the banded pre-emergence, Weedseeker™ Shield Sprayer. There was no difference in yield between the herbicide treatments and treated plots yielded 11.8 t ha^{-1} more than untreated plots. Harvey et al. (2016) noted that a water quality analysis was also included, finding that runoff concentrations for all herbicides were directly proportional to the percentage of spray coverage and total load of herbicide on the soil and trash. Knockdowns ran off less than or equal to residuals and new residuals ran off less than older ones.

Harvey et al. (2016) also reviewed Thompson (2013) who explored Dual Herbicide Sprayer compared to a standard Irvine Sprayer. Thompson (2013) evaluated a 120-ha farm in the Herbert finding that the investment was highly sensitive to yield changes, with the investment becoming economically unviable if ratoon yields declined more than 10%. The sensitivity of farm size was also explored finding that if the dual Herbicide Sprayer was used over 200 ha yr^{-1} and it cost \$1,000 to modify the Irvin boom, then the grower could recoup their investment within 0.4 years. A break-even analysis found that the Dual Herbicide Sprayer needed to be used over at least 28 ha y^{-1} for the investment to payoff within 10 years. Moreover, property using the Dual Herbicide Sprayer across 40 ha or more will have less than a five-year payback period if their investment in the Dual Herbicide Sprayer is \$2,000 or less.

Alluvium (2019) applied the 2018 Water Quality Risk Framework for management practices to estimate the costs of pesticide management at a paddock scale and these were subsequently extrapolated to the subcatchment scale. The costs were assessed as low, medium and high to demonstrate the range of costs that could be associated with implementing changes based on the landholders starting point and existing machinery (the low cost was \$29,600 and the high cost was \$100,000). The 2018 Water Quality Risk Framework focused more on soil testing and agronomy advice in the transition from Low risk (B) to Very Low risk Innovative (A) practices and therefore the costs are more focused on services, mapping and testing. The costs were aligned to the specific management changes, not a whole of farm management system (Table 12). Similarly Star et al. (2018) extrapolated the findings from Rolfe and Windle (2018) who evaluated a past investment program to assess costs. This was based on the 2009 ABCD Management Practice framework, and highlighted that the costs varied based on the management practices that were different between frameworks and are therefore not comparable.

Table 12. Descriptions and costs of pesticide management changes in Sugarcane based on the 2018 Water Quality Risk management framework and subsequent cost ranges (adapted from Alluvium (2019).

Moderate risk to low risk	Low risk to innovative
Minimal use of residual herbicides. High clearance (out of hand) dual herbicide sprayer implemented with variable rate controller. Example range of costs from a minimum: Purchase variable rate chemical controller ($5,000) Upgrade spray boom for variable rate ($24,600) Maximum costs: Purchase second-hand JD high clearance tractor & rig 1.8 m space, 2 tanks, rate controllers & boom ($100,000) Prices include air inducted nozzles and Irvin legs, which have been costed separately to highlight partial shifts.	Soil test (1 every 2.5 ha @ $15 per test) and EC mapping to indicate soil boundaries. Purchase of SMS for mapping and risk assessment ($910).
	Expert agronomy advice and electronic record keeping of spraying events (1 hr for every 10 ha at $85 per hour).
Irvin legs are adopted. Tracking leg s- $1,542.00. Price includes 4 legs, Dropper pod, parallelogram, tracking head all pins & hose to nozzle platform.	Shielded sprayer used for inter-row applications, knockdown herbicides replace residuals where possible (minimum cost for 7 shields to modify existing - $3,500. Maximum cost of second-hand 7 row shielded sprayer - $54,000.
Air inducted nozzles used to reduce drift. Nozzles – Teejet AIXR 110- $11.00 per nozzle. Nozzles – Teejet XR 110 - $9.80 per nozzle.	Risk assessment undertaken before spraying.
Risk assessment undertaken before spraying and better timing of herbicide applications.	Seasonal rainfall outlooks analysed for spraying strategies.

4.1.1.5 Management of pesticides non-agricultural lands

Pesticide contributions to receiving waters from non-agricultural sources are largely derived from contributions through wastewater discharge and diffuse sources from stormwater runoff. Control of these has focused on non-structural approaches, specifically regulatory controls limiting the use of problem compounds, and improved wastewater management. Of the 14 studies reviewed, 4 considered the role of non-structural approaches, with the remainder focused on structural measures, largely around wastewater treatment. Given this, we have summarised the studies into only non-structural and structural measures and have not further disaggregated them by potential contaminant source.

4.1.1.5.1 Non-structural measures

The natural attenuation of a range of organic compounds (including some pesticides) that may be contributed to Lake Wivenhoe through an indirect potable reuse scheme was examined by Hawker et al. (2011). A total of 247 compounds were considered in their modelling analysis, 15 of which were detected in recycled wastewater including pesticides talapon and triclopyr. Transformation in the water column was found to be the primary removal mechanism as it was noted that all of the 15 detected compounds had relatively short half-lives in the water column, but persisted once they reacted in the sediment compartment. Model results showed considerable attenuation in Lake Wivenhoe due to both biotic and abiotic transformation processes in the water with photodegradation dominating the transformation of triclopyr.

Khan (2010) reviewed monitoring approaches to recycled water schemes across the world, including the Western Corridor Water Recycling Scheme in southeast Queensland. They proposed using a chemical risk assessment process, toxicity testing and the use of indicator chemicals and surrogates to all assist in evaluating treatment performance. It was also noted in that work that pesticides may enter municipal wastewater systems by a variety of means including stormwater influx and illegal direct disposal to sewage systems and the use of chemical risk assessments and risk management practices can enhance the provision of a safe indirect potable reuse system.

The effects of non-structural controls in terms of the reductions of organochlorine (OC) pesticides and polycyclic aromatic hydrocarbons (PAHs) were examined by Mueller et al. (2011) through the use of semipermeable membrane passive samplers deployed in 1997/1998 and 2001/2002 in the Brisbane River, in Queensland. This showed that while spatial patterns of pesticides were similar between both time periods, accumulation of OC pesticides reduced significantly e.g., DDE reduced from 0.084 to 0.015 ng L^{-1} and dieldrin from 3.9 to 1.4 ng L^{-1}. Dieldrin was only withdrawn in the decade prior to sampling (late 1980s) whereas other organochlorine pesticides were progressively deregistered in the early 1980s and it would appear that regulation may be a contributing factor to the reductions observed.

In a study by Marshall et al. (2016), sediment cores from 99 stormwater treatment wetlands across Melbourne were sampled to determine pesticide accumulation. These cores showed widespread accumulation and suggested that regulatory controls were not adequate to control them in urban environments. It was also noted in that study that bifenthrin appeared to be a potential insecticide of concern from urban areas. Marshall et al. (2016) noted that “trace organic compounds are common in urban stormwater wetlands. A screening assessment suggests bifenthrin presents the greatest ecological risk, although pyrimethanil, diuron and the personal care products DEET and triclosan were also common. Associations between land use and demographics indicated bifenthrin was specifically associated with urban catchments of low housing and population density.” Their conclusions attributed the frequent detection of insecticides in their study to weak regulation.

Non-structural measures do appear to have some ability to lead to reductions in pesticide concentrations more generally in non-agricultural areas, but natural attenuation also shows some removal in the water column, with persistence in the sediments likely if they accumulate there. The use of reuse water from treated municipal wastewater effluent also shows that some assessment of chemical risk is required to ensure that micropollutants such as pesticides are not contained in the reuse stream. While regulatory controls have some benefit for reductions through withdrawing of problem compounds, it would appear that they are still prevalent in urban stormwater.

4.1.1.5.2 Structural measures

Wastewater treatment mechanisms are primarily designed to reduce organic matter, nutrient concentrations and particulate matter in the waste stream, with disinfection processes often employed to ensure pathogens do not cause issues with downstream uses and waterway values when discharged. These processes can also be effective at removing other contaminants such as metals, organic compounds and micropollutants. For example, Cardenas et al. (2016) examined the removal efficiency of micropollutants (which included pesticides) by a 3-stage wastewater treatment plant in southeast Queensland. Whilst focusing largely on pharmaceuticals, pesticides were also detected in the influent and showed that the wastewater treatment plant (WWTP) process can lead to significant reductions in some micropollutants. For the pesticides 2,4-D and MCPA, 2,4-D appeared to have an approximately 50% removal whereas there appeared to be no removal of MCPA.

Similarly, Drewes et al. (2010) assessed process performance of an advanced WWTP in St Marys, NSW for removing organic micropollutants using indicator chemicals and surrogates. Removal of the pesticide atrazine was considered, but also many pharmaceuticals. No removal efficiencies were determined but the method of detection was demonstrated, and reverse osmosis removal appeared to be the primary treatment mechanism.

Reuse of wastewater requires the treated effluent from conventional WWTPs to be further treated to standards that reflect the end use of the recycled water. This may include further disinfection and other treatments such as reverse osmosis and membrane filtration. Souza et al. (2013) considered the practicality of using UV and peroxide to treat secondary wastewater effluent for reuse, including removal of micropollutants such as atrazine. While this work was completed in Barcelona, Spain, the authors referred to Queensland Water Recycling Guidelines for water quality and treatment criteria. This study showed that if the exposure time for disinfection by ozone and ultraviolet exposure was increased from 5 min to 35 min, complete removal of atrazine was achieved. In another study by

Macova et al. (2010), the use of bioassays to evaluate toxicity of organic micropollutants was examined through the wastewater effluent treatment process to produce recycled water in South Caboolture, Queensland. The Advanced WWTP processed treated effluent from an existing treatment plant using coagulation, flocculation, Dissolved Air Filtration, sand filtration and ozonation. They stated that micropollutant burden was reduced significantly but no specific reductions for pesticides were provided. Trinh et al. (2012) also considered the performance of advanced treatment processes through evaluating the treatment potential of membrane bioreactors in wastewater treatment to also target 48 trace organic chemicals, including the pesticides atrazine and linuron. Most compounds, including the pesticides, were removed at >90%, though some other micropollutant removals ranged from 24-68%. The outflow concentrations from the bioreactor were 1-6 orders of magnitude lower than the requirements of the Australian Guidelines for water recycling.

Proprietary treatment processes have also been evaluated in an experimental study by Fergusson et al. (2015) in Australia where they used ozofractionation to study the treatment of pesticides and heavy metals in wastewater. The wastewater samples were collected from a stormwater holding tank at a pesticide manufacturer. All post-treatment concentrations for organic contaminants were below the limit of detection, with removal rates quoted as 100%. In another study evaluating a proprietary treatment product, Shattar et al. (2019) investigated the use of a montmorillonite-derived absorbent for treatment of pesticides, trialled on 2,4-D and metolachlor, which showed great promise for treating pesticides in wastewater or agricultural applications.

From these studies, it would appear that the removal of pesticides from wastewater discharges is possible using existing and advanced treatment processes with a number of techniques showing considerable promise. The reuse of effluent may also result in reductions of pesticides and other organic micropollutants if it is further treated prior to reuse.

Urban stormwater may contain diffuse sources of pesticides through wash off from lawns, gardens, animal washing, spills and illegal dumping. The treatment performance of structural measures used to improve urban stormwater quality has not been extensively evaluated in the literature, with only one study with partial relevance identified. Birch et al. (2005) looked at removal efficiencies for a range of contaminants for a stormwater infiltration basin in Annandale, NSW using a weighted average concentration method for determining removal efficiency of micropollutants. While they intended to evaluate pesticide removal, this was not able to be determined because of concentrations less than the detection limit for the pesticides monitored.

Diffuse sources of pesticides may also be reduced through changes in application practices, with O'Brien et al. (2022) conducting experiments on the use of stem implantation of pesticide containing capsules for the control of Chinese elm (*Celtis sinensis*) in Grandchester, Queensland. Compared to conventional techniques of basal bark spraying, stem injection and cut-stump applications, this technique was expected to significantly minimise the possibility of exposure of the environment or operators to synthetic compounds, though again, no removal rates were provided.

These studies demonstrate that removal of pesticides using structural measures for diffuse sources is currently uncertain, with minimal Australian studies considering removal of pesticides and other micropollutants.

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

Since the 2017 SCS, new information has been gained on the water quality outcomes of agricultural management practices on farms. Much of the new research has essentially reinforced previous conclusions about the efficacy of many established practices for managing pesticide risks from agricultural lands (Table 2). This provides increased confidence in the ongoing Water Quality Risk Frameworks used in the monitoring and evaluation of Reef 2050 Water Quality Improvement Plan investments into water quality benefits of practice change (Australian & Queensland Government, 2018). There have, however, been several issues or findings emerging since the previous SCS that warrant particular consideration which are summarised below.

Recognition of broader pesticide risk

There have been recent and notable modifications in Reef Plan targets under the current (Reef 2050 WQIP 2017–2022, shifting from the simpler 60% PSII load-based reduction measure, to achieving herbicide concentrations at river mouths that protect at least 99% of aquatic species. This change was designed to provide more ecologically meaningful herbicide monitoring and management in the GBR catchment (acknowledging that PSIIs are not the only contributors to ecological risk). It also aligns with approaches used in National, State and marine GBR water quality guidelines (Australian & Queensland Government, 2018). The Reef Plan pesticide focus has, accordingly, expanded substantially, now including a much broader range of 22 'priority' pesticides (a combination of herbicides and insecticides), extending considerably beyond the previous PSII priority herbicide suite (i.e., diuron, ametryn, atrazine, hexazinone, simazine, tebuthiuron).

There have been significant changes in recent paddock-scale studies relating to pesticide use and GBR water quality to better reflect these new targets. Several recent studies specifically assess changes in practice risk profiles across a broader range of herbicides, in addition to the more historic comparisons of load losses of PSII herbicides from paddocks (Davis et al., 2014; Fillols et al., 2020; Silburn et al., 2023). These recent benchmarking studies of paddock-scale management practice runoff trials have highlighted that several 'alternative' pre-emergent herbicides (e.g., metribuzin, metolachlor) present very similar ecosystem risk profiles to at least some of the previous priority PSII herbicides such as atrazine (Fillols et al., 2020; Silburn et al., 2023). Recent results from paddock studies also suggest that water quality can be significantly improved by using particular 'knockdown' herbicides in mixtures (Davis & Neelamraju, 2019), an outcome not captured in previous research. The risk profiles of knockdown herbicides (often regarded as fundamental to reducing industry reliance on the environmentally problematic PSII residual herbicides) and herbicide mixtures, have been rarely considered in paddock or catchment-scale appraisals of water quality risk and the likely benefits of practice change by farmer. Use of more holistic risk metrics, such as ms-PAF (Davis & Neelamraju, 2019), should be a prerequisite for future assessments of the ecological benefits of practice changes.

Renewed significance of Integrated Pest Management concepts

The broadening scope of the SCS, to include commodities such as horticulture, as well as some of the emergent challenges in many industries (pesticide resistance evolution, product registration changes and constraints) has highlighted IPM as a key consideration for future GBR pesticide policy. While many elements of IPM (and specific practices identified in this review) have undoubted relevance to reducing pesticide risks, the specific long-term cost-benefits, practical considerations and clarity on what IPM should actually mean across different industries remains poorly quantified. Close collaboration and engagement with industries will be required to provide this additional information.

Increasing appreciation of variable water quality benefits from tillage-residue retention practices

There have also been notable recent shifts toward recognition that previously assumed water quality benefits from adoption of no till or reduced tillage farming systems (NRT) compared to conventional tillage (CT) systems may be more variable and inconsistent than previously assumed. If tillage practices do not consistently reduce runoff of pesticides, other practices, such as selecting pesticides that are less toxic, more rapidly dissipated, more sorbed, and runoff less need to be considered (Jayaraman et al., 2021; Silburn, 2020).

Cost effectiveness of pesticide management

There has been very limited work completed on the economic implications of pesticide management. However, the available findings indicate that there are varied economic implications based on farm size, regionally specific biophysical conditions and subsequent pesticide management. Generally, it has been found that progressing from traditional to industry herbicide management was expected to be profitable and provide return on investment across all farm sizes and sugarcane districts.

4.1.3 Key conclusions

A growing body of research evidence continues to support several management practices as being demonstrably effective in reducing runoff losses, and subsequent ecosystem risk, of pesticides from agricultural lands in Great Barrier Reef catchments. While additional insights have been gained, and the information base strengthened, these practices have changed little since previous Scientific Consensus Statements. Specifically, long-term environmental risks of pesticides are reduced by:

1) Reducing the total amount of pesticide applied to a paddock or field, through lower application rates (within label recommendations), or through precision application practices such as banded/shielded spray applications and spot spray technology.
2) Timing pesticide applications to minimise the risk of paddock runoff from rainfall or irrigation within several weeks of application.
3) Choosing products with physico-chemical properties (lower persistence, lower mobility and lower toxicity) that reduce environmental risks.
4) Reducing runoff and soil erosion by retaining cover, controlled traffic, and irrigation management reduces the runoff risks of pesticides with greater soil sorption. Reductions associated with more soluble pesticides has recently emerged as more variable and inconsistent.

For non-agricultural lands, the key focus appears to largely rely on non-structural controls such as regulation and improved wastewater treatment processes. Urban stormwater does appear to be a contributor but there is limited evidence that treatment measures, other than non-structural approaches, are effective. It is noted that accumulation of micropollutants such as pesticides is occurring in some diffuse runoff treatment systems (e.g., wetlands) but whether this indicates effective treatment or simply just a potential fate pathway is unclear.

A number of other key findings also emerged from the review that are almost certain to have profound, and in some cases, already manifest implications for water quality and ecosystem risk across the GBR catchment area. These include:

- Rapid evolution of pesticide resistance is posing growing challenges across multiple industries. Managing herbicide and insecticide resistance, in fact, emerged as a dominant study focus from literature searches. Genetically modified crops, in particular, have refashioned the pest management environment in many crops. While few studies had any direct consideration of specific water quality risks, the longer-term environmental impacts of pesticide resistance have major implications for managing GBR catchment pesticide risks. Practices such as poor control of resistant pests necessitating greater pesticide use (‘follow-up’ or multiple applications), re-introduction of tillage and pre-emergent herbicides into glyphosate-based farming systems, different future pesticide formulations and modes of actions, grower and industry unfamiliarity with newer products and associated risk management will all have implications for managing water quality risks. Evolution of pesticide resistance will potentially impact the future viability of entire farming systems approaches in some industries. Ensuring current practices recommended for improved water quality do not contribute to pesticide resistance is, therefore, a critical consideration for policy.
- Because of these current and future challenges, particularly surrounding pesticide resistance, product registration changes, and emerging pests, many farmers will face new challenges that may alter how and when they use pesticides. Indeed, this review highlights several significant GBR agricultural industries being forced to revisit integrated pest management (IPM) concepts. While a diverse range of IPM tactics were noted as being used by farmers, few industries in the GBR catchment area consistently or comprehensively use IPM. The underlying reasons for this lack of adoption are likely multifaceted, reflecting issues such as a continued desire for ‘simple’ or cheaper technological or chemical control solutions, short-term planning horizons and a failure by researchers to demonstrate and communicate the benefits of more integrated approaches.

- The need for additional pest control options is increasing industry and research interest in non-chemical pest control measures for integration within farming systems. Many elements of broader farm management (e.g., crop planting density, varietal selection, crop row spacing, habitat management) and area-wide management hold considerable promise for reducing pest pressure and reducing long-term pesticide applications. But in most cases, actual comparative water quality benefits, and cost-effectiveness remain poorly quantified, or are yet to be rolled out at meaningful scales across commodities.
- Overall, collective findings on practices that reduce the risk of pesticide losses in runoff from farming land uses (application rates, product choice, timing of application, application methods) have remained relatively consistent through time. Given the consistent relationships documented for reduced risks associated with pesticide application rates, and product choice (there are often pronounced differences in relative toxicity between products), practices that focus on these aspects of management should be a priority. Good practices are generally complementary, although examples do exist where tensions can exist between some practices that address different elements of farming sustainability (Table 9).
- The effectiveness of these practices also remained relatively consistent across the climatic regimes and farming systems of the GBR catchment area.
- The emergence of issues such as significant pesticide resistance across multiple industries is likely to impose (and in some cases has already resulted in) considerable future changes in how farmers use pesticides, and other alternative pest control measures.
- A range of potential non-chemical pesticide control measures (IPM, cultural controls) hold considerable potential for reducing reliance on chemical control measures, but most are yet to be trialled at broad industry scales.
- The cost-effectiveness of improved pesticide management across the diversity of GBR catchment area agricultural commodities has been inconsistent. In industries such as sugarcane, it has been found that progressing from traditional to industry herbicide management was expected to generally be profitable and provide return on investment across all farm sizes and sugarcane districts. Economic returns, however, remain critically dependent on regional-specific variables including biophysical characteristics and enterprise structure, especially in relation to farm size and location.
- Non-agricultural lands, largely rely on non-structural controls such as regulation and improved wastewater treatment processes. Urban stormwater does appear to be a contributor but there is limited evidence that treatment measures, other than non-structural approaches, are effective. It is noted that accumulation of micropollutants such as pesticides is occurring in some diffuse runoff treatment systems (e.g., wetlands) but whether this indicates effective treatment or a potential fate pathway is unclear.

4.1.4 Significance of findings for policy, management and practice

Since the 2017 SCS, much of the new information gained on pesticide water quality outcomes of agricultural management practices on farms has been reinforced, and supported previous policy frameworks. Several considerations for policy have, however, emerged from this review that warrant attention:

- Ensuring current or future practices recommended for improved water quality do not contribute to pesticide resistance is a critical consideration for policy. A recurrent theme from reviewed literature is that the evolution of pesticide resistance will potentially impact the future viability of entire farming systems approaches in some industries (Chauhan et al., 2022; 2023; Iqbal et al., 2019a; 2019b; Thornby et al., 2018). Several major industries are already adapting with revised practices, including recommendations for re-introduction of tillage for weed control, increased herbicide applications, or re-introduction of pre-emergent herbicides. These changes will have significant, but largely unquantified impacts on water quality. This makes acknowledging pesticide resistance a key consideration, with profound and far-reaching implications for future policy in the GBR catchment area. Communication or directives about incorporation of ‘knockdown’ herbicides in reduced pesticide risk frameworks need to be

carefully considered at several different levels. The emergent resistance challenges in glyphosate-based farming systems, particularly in cotton and grains, is likely to result in significant future shifts in pesticide management strategies in the near term. While other major industries such as sugarcane use a broader range of herbicides and modes of actions that reduce risk of rapid weed resistance, anecdotal accounts do already exist of potentially resistant weeds in some sugarcane growing areas, suggesting the issue should not be overlooked.
- The recent substantial expansion of the Reef Plan pesticide focus to include a much broader range of 22 'priority' pesticides, and shifting from load-reduction based targets to new risk-based metrics has complicated the assessment of practice change. A range of recent benchmarking studies of paddock-scale management practice runoff trials have highlighted that several 'alternative' pre-emergent herbicides (e.g., metribuzin, metolachlor) present similar ecosystem risk profiles to at least some of the priority PSII herbicides such as atrazine (Fillols et al., 2020; Silburn et al., 2023). Recent results from some paddock studies also suggest that water quality improvements associated with practice change can be affected significantly by the contribution of particular 'knockdown' herbicides included in mixtures (Davis & Neelamraju, 2019), an outcome not captured in previous research. A better understanding of the comparative environmental risks posed by herbicide mixtures from different management practices should be a priority for future policy directives.
- On a similar note, data on many insecticides and fungicides used in GBR farming systems was particularly lacking. Studies in other Australian horticultural catchments, for example, have documented widespread detection of fungicides in the aquatic environment (Wightwick et al., 2012), and fungicides have also been found in some recent GBR water quality monitoring programs (unpublished data). The data that are lacking includes half-lives, sorption, runoff potential and toxicology.

4.1.5 Uncertainties and/or limitations of the evidence

- Much of the data from the studies included in this review were reported using quantitative measures including statistical measures that made reporting on descriptive statistics across studies difficult in a narrative synthesis format.
- Evidence searches were conducted using two academic databases (Scopus and Web of Science) given the resource constraints of the review.
- Evidence searches were conducted from the period 1990 – 2022 so significant findings before this time period may not be included.
- Most available research focuses on herbicides, with insecticides, and particularly fungicides featuring rarely in any water quality-based assessments, particularly in terms of comparative management practice impacts on water quality.
- The risk profiles of knockdown herbicides (often regarded as fundamental to reducing industry reliance on the environmentally problematic PSII residual herbicides) have rarely been considered in paddock or catchment-scale appraisals of water quality risk and the likely benefits of practice change by sugarcane growers.
- Additive, synergistic or antagonistic effects between multiple residual-knockdown herbicide mixes on comparative management practice risk are poorly quantified at this point in time.
- The majority of water quality research focuses exclusively on pesticide surface water losses, with comparative losses to leachate and groundwater poorly described.
- The economic costs have been captured over multiple Water Quality Risk frameworks making the comparison difficult and the low number of studies adds uncertainty to the findings.

4.2 Contextual variables influencing outcomes

As discussed in Section 4.1 there are a large number of variables that influence the effectiveness and efficiency of management practices in reducing pesticide risks. Table 13 below describes contextual variables documented within the studies used. These variables relate to components of the conceptual model shown in Figure 1. As shown, some of these contextual factors relate to properties of soils and climate, and others to specific management practices such as product choice and cultural practices on-farm.

Table 13. Summary of contextual variables for Question 5.3.

Contextual variables	Influence on question outcome or relationships as per conceptual model
Rainfall-irrigation runoff timing	Herbicide runoff is generally dominated by a small number of runoff events, usually shortly after herbicide application. This is a typical finding for runoff of pesticides with half-lives (DT50 values) of 20-25 days or less. Rapid half-lives lead to reduced runoff losses (Fillols et al., 2020; Silburn et al., 2023). Indeed, Shipitalo and Owens (2003) found that the rainfall received, and timing of runoff-producing rainfall, had a greater effect on runoff losses of atrazine and metabolites, deethylatrazine (DEA) and deisopropylatrazine (DIA) than did tillage system. Dang et al. (2016), who studied the behaviour of six herbicides (atrazine, ametryn, diuron, hexazinone, tebuthiuron, and S-metolachlor) also observed that the rate of washoff (from sugarcane crop residues) declined with increasing time after application; however, 70% still washed off.
Crop residue management	Shaw et al. (2013a) measured the half-lives of 14 herbicides commonly applied in sugarcane and grains on sugarcane residue over a period of 100 days in a glasshouse. Half-lives for all herbicides on sugarcane residues were slower than had previously been reported. These longer half-lives on sugarcane residues, and the washoff discussed previously, mean applying herbicides to crop residues should not reduce their efficacy (except where initial losses are higher than in soil), but would potentially increase their runoff risk. Crop residues, in the form of cover, also reduce sediment losses and thus runoff losses of more sorbed pesticides. They are less or not effective in reducing runoff losses of poorly sorbed pesticides.
Soil characteristics	Half-lives varied by less than a factor of 2 between soils for the herbicide's atrazine, 2,4-D and isoxaflutole whereas half-lives for diuron varied by a factor of 14 (Shaw et al., 2013a). Total organic carbon was a significant explanatory variable for predicting degradation rates for many of the herbicides in this study. Further analysis of the data is required to investigate the relationship between measured half-lives and soil properties to extend prediction of spatial variability in herbicide degradation for all soils in the GBR catchment.
Pesticide application rate	Application of less herbicide on the paddock typically translated to a proportional reduction in runoff losses. Band spraying has also consistently been found to be effective in reducing runoff concentrations and loads (Davis & Pradolin, 2016; Masters et al., 2013; Melland et al., 2016; Oliver et al., 2014; Silburn et al., 2013), by about the proportion that the spray rate is reduced. Band spraying was also highly effective in reducing herbicide runoff for furrow irrigation where tailwater flow is isolated from the sprayed hills (Davis & Pradolin, 2016; Lewis et al., 2013; Silburn et al., 2013).
Pesticide physico-chemical factors	There is considerable variation in toxicity of various pesticides, their application amounts, dissipation rate and in their sorption and runoff potential. In some cases this provides land managers with a degree of choice with regard to pesticide selection, toward pesticides that have lower risks of both runoff and off-site environmental water quality risk.

4.3 Evidence appraisal

Relevance

The overall relevance of the body of evidence to the question was Moderate. The relevance of each individual indicator was Moderate for the relevance of the study approach and reporting of results to the question, Moderate for spatial relevance, and Moderate for temporal relevance. Of the 251 articles included in this review, 100 were given a 'High' score for overall relevance to the question. This was due to several factors described further below.

- The relevance of the study approach and study results was Moderate. Measurement and reporting of several of the identified practices in reducing pesticide risk is quite a mature science in the GBR scientific literature (application rates, runoff in relation to application, pesticide product choice). A number of commonly adopted study designs (paddock scale trials, rainfall simulations, dissipation trials) and reporting metrics (runoff loads, toxicity comparisons, half-lives) have been applied in the GBR context. Many aspects of the eligible literature had direct linkages to components of the conceptual model, but only indirectly related to water quality risk. Specific pesticide focus was particularly biased toward herbicides, with insecticides, and particular fungicides poorly represented across the literature.
- The relevance or generalisability of the spatial scale of studies was Moderate. Most of the eligible literature related directly to studies carried out in the GBRC catchment area, or related specifically to commodities found at least in part, within the catchment area Most studies were, however, limited to specific regions of the GBR, with few being replicated over broader regional scales, and the diversity of farming systems (even within a single commodity) found therein.
- Relevance or generalisability of the temporal scale of studies was Moderate. The temporal relevance of pesticide risk of a management practice to the environment tends to be limited to early runoff events following a pesticide application. Many studies were relevant to this paddock-scale spatio-temporal context. Longer term assessments of some broader pesticide management strategies relevant to the conceptual model (e.g., IPM, area-wide management, resistance management planning), and associated longer term risk reductions across both temporal and spatial scales were not as well quantified.

Essentially all studies related to aspects of landscape, farm and paddock management strategies identified in the conceptual model. Most studies relating specifically to comparative water quality, however, related to farm management (cultural; tillage, residue retention), and particularly paddock scale practices (product choice, application method, application rates) found in the conceptual model. Management elements of the model, particularly at broader scales provides future research opportunities.

Consistency, Quantity and Diversity

While consistency for the overall body of evidence was Moderate, consistency of findings varied within the sub-group analysis. For example, the consistency of study findings relating to the effectiveness of many specific paddock-scale practices in reducing pesticide risk was high, however, the consistency of study findings in reducing risks using many cultural and landscape-scale practices was lower. This was partially due to the specific lack of explicit water quality data available for many of these studies and concepts (e.g., IPM, area-wide management), although many of the relevant principles do relate to reducing longer-term risks through reduced pesticide usage over broader temporal and spatial scales. Consideration or management of pesticide resistance will also have longer term impacts on catchment water quality in the GBR, but are similarly poor with specific regard to water quality data.

It is considered that the quantity of the pool of evidence (n=251) used for this review is Moderate due to:

1) The authors experience with international pesticide literature.
2) Consideration of the inclusion/exclusion criteria used for the question.
3) The number of studies used by similar reviews or other syntheses.

4) The diverse nature of pesticide management had variable water quality evidence across many practices or strategies.

There were three different evidence types used in the review: 1) primary studies (experimental, observational or modelled), 2) secondary studies (reviews, Systematic Reviews or meta-analysis) or 3) mixed (involve a mixture of experimental, modelled and/or observational studies). Almost half of the eligible studies (91) were of a broad experimental nature, although the range of methodologies, scale, replication and use of a strict control or controlled manipulation of specific variables varied dramatically (Figure 4). Most experimental design studies (57) generally related to paddock-scale agronomic and/or water quality field studies, where broad paddock treatments were used as a controls and variables, with interventions such as pesticide type or product, management practice (tillage, row spacing, planting density), pesticide application practices or pesticide control efficacy manipulated or monitored. Field trials involving rainfall simulation over relatively small areas/plots were also frequent (16 studies). Experiments involving more controlled conditions under a laboratory, glasshouse, or pot-trial type design were less prevalent. These typically involved research questions more amenable to control-replication such as comparison of spray-nozzle technology performance, or some aspects of pesticide physico-chemical behaviours such as pesticide dissipation (Dang et al., 2016; Shaw et al., 2013a). This diverse spectrum of experimental study types and scales underlines the challenges and expenses of conducting comparative, replicated, long-term agronomic and/or water quality research relating to pest control at commercially relevant farming scales.

A substantial proportion of studies (81 in total) were secondary studies (reviews, or reviews with an added observational element). Modelled studies involved a diverse range of topics. This included use or development of a range of paddock or subcatchment scale water quality models (often with underlying comparative management practice emphasis), modelling of different elements of genetic resistance to pesticides or pests, and socio-economic models of cost-benefits of farmers adopting a particular practice change.

In terms of specific study focus, fifty studies involved some direct element of quantification or consideration of the water quality implications of, or comparisons between, specific paddock-scale management practices (Figure 5). The nature of the specific practice, with associated quantification of water quality dynamics, however, varied widely. Water quality studies included comparisons between different pesticide product types and strategies, physico-chemical pesticide behaviours, pesticide application rates, application methods, and product efficacy. Integrated pest management concepts were the next most prevalent topic (29 studies). Remaining studies encompassed a broad range of agronomic, economic, pesticide resistance, pest control efficacy, precision agriculture and policy appraisal topics with linkages to this review's conceptual model. It is noteworthy that many studies, while relevant to improving water quality, and often mentioning it explicitly, often had little explicit quantification of comparative losses of pesticides associated with management practices. Nevertheless, they do relate to overarching management applications or considerations on the periphery of the conceptual model outlined in Figure 1.

Additional Quality Assurance (Reliability)

A rapid internal validity assessment was made to all studies used in the synthesis to note any obvious potential bias and to identify studies most influential in drawing conclusions from the body of evidence. Of the 156 observational or experimental studies used to specifically appraise management practice pesticide risks, several were rated as having some risk of bias due to either the study design not accounting for all flow paths from the studied paddock (i.e., they only monitored surface water runoff), or having experimental designs that present 'worst-case scenarios' of off-farm ecosystem risk from pesticide movement. Very few paddock scale studies monitored pesticide losses in leachate below the crop root zones (<5 studies). Those studies that did, however, monitor groundwater losses typically identified groundwater concentrations and losses much lower than those documented in surface water runoff. It was determined, therefore, that these potential biases in terms of attention to specific loss pathways, were not significant enough to remove the studies from the synthesis.

Almost all rainfall simulation studies (15) provide a worst-case scenario in terms of resultant environmental impact, involving the application of significant, high intensity, simulated 'rainfall' within 2-3 days of pesticide application to a paddock (ca. 80 mm in an hour). Such events are, however, frequent enough in reality, likely occurring several times across each farming district in most years, and are the events that cause most soil and pesticide losses. While some rainfall simulation studies did monitor for several runoff events after application (Masters et al., 2013; Silburn et al., 2013) many of the appraised rain simulation studies also typically only monitored one event after pesticide application, which provides a somewhat limited insight into longer term risks of a specific practice. Multiple longer term paddock studies did, however, identify that the majority (>80%) of annual pesticide load losses off-paddock typically occurred in the first 1-2 events. It was determined, therefore, that these potential biases were not significant enough to remove the studies from the synthesis.

Of the four modelled studies (water quality) identified from the literature and manual searches, all were rated as having a low risk of bias due to clear model validation and clarity of the assumptions used in the model. As the findings of these studies were also consistent with other field studies, all of these studies were considered in the synthesis.

The inclusion of many studies that address elements of broader Integrated Pest Management could also introduce potential biases to results. Environmental considerations and purported benefits or risk reductions in many IPM studies were often not specific to water quality risk of pesticides, and often considered other ecosystem components (e.g., terrestrial elements, soil health, resistance evolution). While many of the water quality outcomes and cost-benefits of IPM remain poorly defined, many elements of IPM are theoretically relevant and sound with respect to many aspects or aspirations of the conceptual model (Figure 1; long-term or spatially broad overall reductions in total amounts of pesticide applied, use of alternative pest control techniques, lower risk chemical selection). It was therefore decided to include many of these papers that related to key aspects of the conceptual model in the review (while noting their inherent current limitations).

Overall it was determined that most studies (>95%) had a low risk of bias. The findings of those studies that were rated as having some potential risk of bias were generally consistent with the findings from the larger body of evidence and hence the studies were retained in the synthesis.

The cost effectiveness of pesticide management and production implications were a small subset of the total database. The six papers that were reviewed were specific to the Water Quality Risk frameworks and were relevant to the catchments adjacent to the Great Barrier Reef. This meant that they all scored high in relevance to the questions and spatial relevance. The temporal relevance was varied with a mix of Water Quality Risk frameworks applied over time and therefore different costs considered. This resulted in a moderate score of two.

Confidence

The Confidence rating for the question, based on the overall relevance rating and consistency was Moderate as shown in Table 14 below.

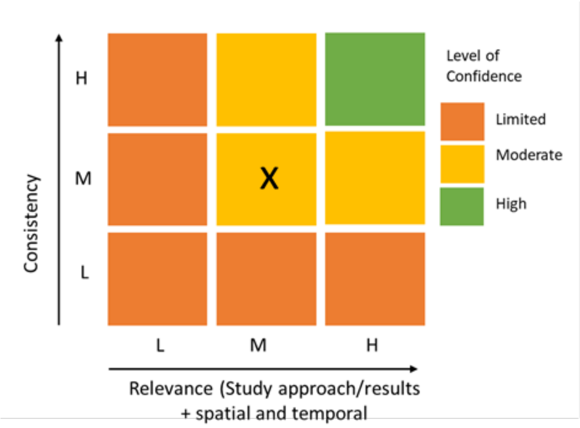
As discussed above, while Consistency for the overall body of evidence was Moderate, consistency of findings varied within the sub-group analysis. In relatively well-studied commodities such as sugarcane, consistency and confidence in findings and farming practices that would improve herbicide water quality would be high. Many of these studies had a specific water quality quantification emphasis, were conducted across multiple GBR regions, were replicated (at least in some cases), and generally produced consistent results for improved water quality for several management practices. While the principles that emerged from these well-studied commodities would likely translate well to other crop types and farming systems (e.g., bananas, horticulture), the lack of specific available water quality, and economic data, precludes a higher overall confidence rating. Similarly, while herbicide-based studies are relatively prevalent, studies on insecticides and particularly fungicides are lacking across all commodities. Similarly, the broad definition of IPM concepts across different commodities, and a lack of explicit quantification of practices and associated data for flow-on water quality benefits limits the confidence rating to moderate. As discussed above, the Relevance rating for the body of evidence was therefore determined to be Moderate.

The Moderate Confidence rating was also influenced by the authors' views that a high number of eligible studies were used in the synthesis and that, with few exceptions, generally consistent findings resulted from observational, experimental modelled and secondary studies.

The cost-effectiveness of improved pesticide management across the diversity of GBR catchment area agricultural commodities has been inconsistent, which affects the overall Confidence. In industries such as sugarcane, it has been found that progressing from traditional to industry herbicide management was expected to generally be profitable and provide return on investment across all farm sizes and sugarcane districts. Economic returns, however, remain critically dependent on regional-specific variables including biophysical characteristics and enterprise structure, especially in relation to farm size and location.

There was one key study assessing the cost-effectiveness comprehensively (Poggio et al., 2014) and other studies had then drawn on these findings. Although this study had a high degree of confidence in findings and methods, the other studies had a relatively low number of data points and no primary data resulting in a score of 1 for both quantity and diversity.

Table 14. Summary of results for the evidence appraisal of the whole body of evidence used in addressing Question 5.3. The overall measure of Confidence (i.e., Limited, Moderate and High) is represented by a matrix encompassing overall relevance and consistency.

Indicator	Rating	Overall measure of Confidence
Relevance (overall)	Moderate (but varied across different components of conceptual model)	
-To the Question	Moderate	
-Spatial (if relevant)	Moderate	
-Temporal (if relevant)	Moderate	
Consistency	Moderate	
Quantity	High (251 studies)	
Diversity	High (36% experimental, 32% secondary-observational, 32% mixed studies)	

4.4 Indigenous engagement/participation within the body of evidence

In the review of evidence items, no items specifically identified Indigenous engagement (at least to the authors' knowledge).

4.5 Knowledge gaps

While the body of evidence had a Moderate Confidence rating, the assessment of study types specifically relevant to the GBR identified a low number of field observational studies specifically measuring pesticide water quality of a range of components of the conceptual model. Aspects of specific management of pesticides (particularly herbicides) at a paddock scale was very well represented. Consideration of many other elements of broader pesticide management at a farm (cultural practices), and broader landscape scale (e.g., habitat management, area-wide management) was relatively limited.

Table 15. Summary of knowledge gaps for Question 5.3.

Gap in knowledge (based on what is presented in Section 4.1)	Possible research or M&E question to be addressed	Potential outcome or Impact for management if addressed
How adapting to pesticide resistance evolution will affect management practice behaviours across different industries.	Better quantification or description (and possibly modelling) of likely industry practice changes to combat resistance evolution (changed herbicide applications, re-introduction of tillage etc.).	Better understanding or predictive capacity relating to impacts of pest resistance on GBR catchment water quality.
Implications of Integrated Pest Management strategies to longer term and broader scale pesticide risk reductions.	How does IPM relate to pesticide risk in different commodities?	Definition of the specific water quality outcomes associated with adoption of IPM strategies. Enhancing IPM strategies to deliver pesticide risk reductions.
Most studies were of a short-term nature (less than 12 months). Long terms effectiveness studies are needed.	Long-term sustainability of some farming systems (glyphosate-based)?	Longer-term planning and management options may be developed.
Much available water quality research is limited to surface water runoff risks. Loss to, and dissipation to, groundwater resources is poorly known.	Groundwater pesticide dynamics.	More holistic understanding of management practices and their interaction with ecosystem risks (i.e., practices that may modify (increase or decrease) drainage water infiltration to groundwaters).
Water quality management of fungicide risks is very poorly described. Studies in SE Australian horticultural catchments documented widespread detection of fungicides in aquatic environment (although below risk thresholds) (Wightwick et al., 2012).	Further research is required to adequately assess the risk of fungicides in aquatic environments.	Better understanding of fungicide losses and risk, and their management.
How to integrate the shift from load-based targets at edge-of-field to more holistic integrated risk assessment of risk and mixture toxicity when comparing specific management practices.	Adaption of risk-based approaches such as ms-PAF to paddock scale comparisons of water quality data between treatments.	Aligning paddock-scale water quality data more appropriately to end-of-catchment targets and risk appraisals.
Economic implications for sugarcane, grain, horticulture, banana growers and graziers adopting pesticide management changes.	What are the economic impacts across the different GBR catchments at an individual practice and across the farming system of changing pesticide management practices?	Improved understanding for program design and adoption.

Gap in knowledge (based on what is presented in Section 4.1)	Possible research or M&E question to be addressed	Potential outcome or Impact for management if addressed
Contribution of point source pesticide losses (e.g., spills during transfer into sprayers, filling of sprayers, leaky nozzles during transfer between paddocks, sprayer and tank washdown) to the total loadings of pesticides to surface waters from agriculture. International experiences suggest such sources have been found to contribute significantly to total loading of pesticides into surface waters (Kreuger et al., 1998; Mason et al., 1999).	Appraisal of losses arising from pesticide handling activities in GBR farming contexts (e.g., spills during transfer into sprayers, filling of sprayers, leaky nozzles during transfer between paddocks, sprayer and tank washdown activities).	Identification of a significant and possibly much more manageable intervention point for reducing pesticide load losses from agricultural catchments.
A current lack of hydrodynamic models to explicitly appraise dilution processes from paddocks to downstream receiving ecosystems and how paddock concentrations from management actions reflect ecosystem risk.	Development of models to specifically address dilution processes in paddock surface water and groundwater loss pathways.	Better quantification of specific water quality risk comparisons between different management practices.

5. Evidence Statement

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

Summary of findings relevant to policy or management action

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

Supporting points

- A range of non-chemical pesticide control measures (integrated pest management, cultural controls that modify the pest's growing environment) hold considerable potential for reducing reliance on chemical control measures, but most are yet to be trialled with respect to long-term pesticide use reductions, efficacy and economic outcomes. Much of the new research (since 2016) has essentially reinforced previous conclusions about the efficacy of many established practices for managing pesticide risks from agricultural lands. Key issues and emerging findings since 2016 include greater recognition of pesticide risk in management frameworks, allowing management practices to be better targeted to manage specific risks, renewed focus on Integrated Pest Management concepts and increasing acknowledgement of variable water quality benefits from tillage-crop residue retention practices.
- The more recent research emphasis on comparative ecosystem risk profiles of a broader range of pesticides has identified that several 'alternative' pre-emergent herbicides (metribuzin, metolachlor etc.) present similar ecosystem risk profiles to at least some of the priority PSII herbicides such as atrazine.
- Data required to assess the management effectiveness of many insecticides and fungicides used in Great Barrier Reef farming systems is particularly lacking, including usage patterns, current presence in the environment, half-lives, sorption, runoff potential and ecotoxicology under conditions relevant to the Great Barrier Reef catchment and its aquatic ecosystems.
- Recent results from paddock studies suggest that water quality improvements associated with management practice change can be affected significantly by the contribution of particular 'knockdown' herbicides included in mixtures, an outcome not captured in previous research. Better understanding of the comparative environmental risks posed by herbicide mixtures from different management practices, for multiple land uses, is important for future policy directives.

- Most studies that assessed the effectiveness of management practices focused exclusively on the assessment of the losses of pesticides from surface water pathways, with limited measurement of losses to groundwater.
- In the assessment of cost-effectiveness of pesticide management in agricultural industries, economic returns remain critically dependent on region-specific variables including biophysical characteristics and enterprise structure, especially in relation to farm size and location. However, for sugarcane, progressing from traditional to industry standard herbicide management was reported to be generally profitable and provide return on investment across all farm sizes and sugarcane districts.
- A limited number of studies have compared specific water quality risks among practices across broad climatic zones or farming systems. Broad findings were generally consistent across both. Factors relating to variability in soil properties such as soil pesticide half-lives, rather than climate, appear to play significant roles in the spatiotemporal behaviour of pesticides.
- Few studies have examined how pesticide practice change can influence crop production (crop yield), and available results tended to focus on broader implications of pesticide impacts. Assessment of pest management in conjunction with nutrient management would also provide further insights for changes in yields and productivity outcomes.
- The recent move to incorporate and benchmark the relative ecosystem risks of different paddock scale herbicide practices is an improvement from simple load-based comparisons, but these are still largely based on comparisons between individual pesticides. The lack of frameworks and risk-based metrics that accommodate paddock scale data including pesticide mixtures, and subsequent downstream aquatic ecosystem risk, has posed challenges for the assessment of pesticide management practice change.
- In urban areas, there is limited evidence that stormwater treatment measures such as wetlands and infiltration basins are effective. In wastewater treatment, the existing tertiary treatment measures (e.g., membrane bioreactors, reverse osmosis) can be effective for pesticide removal in some cases.
- Accumulation of micropollutants such as pesticides is occurring in some diffuse runoff treatment systems (e.g., wetlands) but whether this accumulation indicates effective treatment or a potential fate pathway is unclear.
- Assessment of the chemical risk of wastewater re-use where tertiary treatment is not occurring is needed as there is a potential for pesticides to be transferred to the end use environments of the recycled water.

6. References

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

Body of Evidence

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Appendix 1: 2022 Scientific Consensus Statement author contributions to Question 5.3

Theme 5: Pesticides – catchment to reef

Question 5.3 What are the most effective management practices for reducing pesticide risk from the Great Barrier Reef catchments, and do these vary spatially or in different climatic conditions?

Author team

Name	Organisation	Expertise	Role in addressing the Question	Sections/Topics involved
1. Aaron Davis	TropWATER, JCU	Pesticide risk management, on-farm management practices	Lead Author	All Sections
2. Mark Silburn	Reef Science, Landscape Sciences Department of Environment and Science	On-farm management practices, paddock water quality	Contributor	Searches and data extraction (agricultural land uses), agricultural pesticide management conceptual model development Document review, narrative synthesis and final version of overall report
3. Tony Weber	Alluvium Consulting	Urban water quality and pesticide management	Contributor (urban pesticide management)	Urban Conceptual model, urban pesticide management section within the narrative synthesis and final revision of overall report
4. Megan Star	Star Economics, Central Queensland University	Economic analysis of pesticide management practice change	Contributor (agricultural economics)	Economics of farming practice change, agricultural pesticide management conceptual model development