2022 Scientific Consensus Statement

Question 4.9 What role do natural/near-natural wetlands play in the provision of ecosystem services and how is the service of water quality treatment compatible or at odds with other services (e.g., habitat, carbon sequestration)?

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Explanatory Notes for readers of the 2022 SCS Syntheses of Evidence

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

What is the Scientific Consensus Statement?

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

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

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

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

Method used to address the 2022 SCS Questions

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

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

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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.

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Acknowledgements

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Executive Summary

Question

Question 4.9 What role do natural/near-natural wetlands play in the provision of ecosystem services and how is the service of water quality treatment compatible or at odds with other services (e.g., habitat, carbon sequestration)?

Background

The Ramsar Convention defines wetlands as 'areas of marsh, fen, peatland, or water, whether natural or artificial, permanent, or temporary, with water that is static or flowing, fresh, brackish, or salt, including areas of marine water the depth of which at low tide does not exceed six meters'. Wetlands, including those that hold water temporarily or permanently, provide many benefits and services to society and the environment including ecosystem services such as improved water quality, biodiversity, and habitat; cultural services such as aesthetics and recreation; economic services including food, water, and resource provisioning; as well as climate change mitigation possibilities. However, urban and industrial expansion and the growing demand for food production and clean water provisioning have resulted in substantial land use changes within catchments and major modifications to coastal wetlands including those on floodplains. These changes have contributed to the degradation and even the loss of wetland habitats, and the ecosystem services they provide. Furthermore, in attempting to maximise the benefits and services provided by wetlands following restoration or conservation, there can be trade-offs among ecosystem services that require careful consideration. Therefore, when designing wetland management, restoration, and maintenance programs for the provision of specific ecosystem services or goals, it is essential to understand the interactions, wetland components and processes, co-benefits, and trade-offs when embarking on a program or project. This review collates and summarises published evidence regarding the ecosystem services provided by natural and near-natural wetlands, and how the service of water quality treatment is compatible or at odds with other services (e.g., habitat, carbon sequestration).

Methods

- A formal Rapid Review approach was used for the 2022 Scientific Consensus Statement (SCS) synthesis of evidence. Rapid reviews are a systematic review with a simplification or omission of some steps to accommodate the time and resources available[5]. For the SCS, this applies to the search effort, quality appraisal of evidence and the amount of data extracted. The process has well-defined steps enabling fit-for-purpose evidence to be searched, retrieved, assessed and synthesised into final products to inform policy. For this question, an Evidence Summary method was used.
- Search locations included Web of Science and Scopus, in addition to a review of the grey literature websites including Queensland Government (Wetland*Info*, the Department of Environment and Science), the Australian Government's Department of Climate Change, Energy, the Environment and Water, and Pandora.
- The main source of evidence: Peer-reviewed publications from tropical and subtropical climates globally.
- From the initial keyword search, Scopus returned 658 results (661 before duplicates were removed), Web of Science returned 24 results (51 before duplicates with Scopus outputs were removed) and Google Scholar returned ~17,500, therefore only the first 200 records were used. After initial screening by title, 262 potentially relevant items were identified through online searches for peer reviewed and published literature. After further screening by scanning the full text for relevance, 108 sources from the search results contained relevant information for the synthesis. A further 10 peer reviewed papers were added from other searches conducted for

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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

Question 4.7 and seven peer reviewed papers from the author’s library. A total of 125 sources were used as the body of evidence for this synthesis

Method limitations and caveats to using this Evidence Summary

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

- Only studies written in English from 1990 to 2022 were included.
- The Evidence Summary focused on studies in tropical and subtropical locations from overseas, as well as studies from the Great Barrier Reef (GBR). Any studies from temperate locations were excluded from this synthesis.
- Subtidal and subterranean wetlands were excluded from this review.
- The definition of wetlands and the scope of this review were set in collaboration with the SCS Coordination Team, policy representatives and the authors.
- Constructed and treatment wetlands were excluded from this review unless compared with the function and services of natural/near-natural/restored wetlands.
- Studies evaluating ecosystem service provision based solely on human perception and valuation were excluded from this review.

Key Findings

Summary of evidence to 2022

The key points from the Evidence Summary are:

- Natural and near-natural wetlands in the GBR catchment include lacustrine (e.g., lakes), palustrine (e.g., vegetated swamps, billabongs), estuarine, and riverine wetlands. These wetlands support many ecosystem services including regulating services such as improved water quality and carbon sequestration, supporting services such as nutrient cycling and habitat provision, cultural services such as aesthetics and recreation, and provisioning services including food, water and other resources.
- This synthesis identified a small number of research studies in the GBR catchment area compared to studies on natural and near-natural wetland from overseas, with most studies from the USA (35%), China (11%), South America (11%), and Australia (10%). Most studies have focused on estuarine settings (32%), 22% on riverine systems, 12% on palustrine/lacustrine, 17% investigated a combination of habitats, whilst 17% were from unidentified settings.
- In tropical/subtropical wetlands, stressors that compromise wetland water quality can impact the ecosystem services wetlands provide. For instance, connectivity and hydrology have an important role in protecting water quality and other wetland ecosystem services; disruption to connectivity or hydrology can change water chemistry with flow on effects to aquatic organisms (e.g., fish kills).
- In GBR coastal and floodplain areas where historical wetland losses are high, the capacity of the remaining wetlands to process the volume of pollutants they receive is likely to be reduced. Therefore, restoration efforts and engineering interventions may be required to increase the water quality improvement efficiency, and the associated delivery of associated ecosystem services, for the wetlands remaining within the GBR catchment area.
- Trade-offs between water quality improvement and other services in natural and near-natural wetlands can include instances where hydrology or connectivity are affected. For example, seasonal wetland flooding has been found to result in greater connectivity among wetlands, micro-habitat creation, enhanced nutrient dynamics and carbon storage, flood protection, freshwater provision, and improved local water quality, but may lead to less favourable conditions for agricultural production.
- While wetlands can be restored to enhance water quality conditions, the maintenance following restoration works or intervention activities is critical. Without a long-term maintenance plan and a mechanism to fund these works, restoration sites have a high chance of returning to a degraded state. Mitigating risks to wetlands presents the greatest opportunity

to enhance and protect the range of wetland ecosystem services provided within the GBR catchment.

- Mangroves, saltmarshes, and other floodplain native vegetation communities provide coastal protection, sequester carbon, and process nutrients that help to improve water quality. However, a limited number of studies have indicated that natural and near-natural wetlands have a wide-ranging capacity for both pollutant export and retention. While the international literature shows that the ecosystem services provided by wetlands are considerable, more research is needed to quantify these ecosystem services (e.g., environmental, economic, and social value) within the GBR catchment area.
- The Queensland Government has developed a values-based framework to guide the restoration, rehabilitation, and protection of coastal wetlands. This framework focuses on the components and processes in wetlands that maximise restoration success and ecosystem services for beneficiaries (user groups such as tourism, fishing, recreational and cultural). A whole-of-system approach is required so that the interconnected components and processes of the wetland systems, and landscape more broadly, are examined and understood, and management approaches are aligned with restoration goals.
- Ongoing monitoring and evaluation of restored, natural, and near-natural wetlands in the GBR catchment area is required to better understand the potential impacts of restoration actions on wetland values, water quality, and other ecosystem services. The Queensland Government is currently developing frameworks designed to provide managers with a tool to consistently examine and evaluate restoration projects in Queensland.
- Inclusion of all beneficiaries in a co-design process early in the project cycle (design, implementation, and maintenance) is important for defining and achieving ecosystem service goals. The potential implications of future climate change projections, such as sea level rise and more severe weather events (e.g., cyclones), for wetland treatment and restoration projects must also be considered.
- There is a need for policies and planning to achieve long-term protection and conservation of the remaining natural and near-natural wetlands in the GBR catchment area.

Recent findings 2016-2022

Since 2016, studies investigating the ecosystem services provided by natural, near-natural and restored wetlands in the GBR catchments have included: water treatment efficacy and nutrient cycling in natural and near-natural wetlands and fish biodiversity and water quality in restored wetlands. These studies have followed a values-based approach (a framework developed by the Queensland Government) focusing on understanding and evaluating the components, processes, and threats to then provide solutions for wetland protection or restoration. This approach is important and has shown that more desirable outcomes are possible for the beneficiaries (user groups or sectors), which has the added advantage of reducing pervasive and maintenance-intensive outcomes. This approach must also consider long-term funding arrangements for maintenance, without which, there is a high likelihood that the restoration site will return to a degraded state.

Significance for policy, practice, and research

While this review collates and summarises published evidence regarding the ecosystem services provided by natural and near-natural wetlands, it has also examined how the service of water quality treatment is compatible or at odds with other services (e.g., habitat and carbon sequestration etc.). Based on the details and information provided here, greater effort is necessary to protect and restore the services provided by wetlands in the GBR. While there is considerable research and management interest, appropriate policies and plans are necessary to deliver on the goal of protection and conservation. This focus and recognition are outlined in the United Nations Decade on Ecosystem Restoration (2021 to 2030), which calls for the halt of further habitat loss and improvement of the world's ecosystems – including natural and near-natural wetlands.

Wetlands in the GBR catchment area are unique and hold incredible value. However, with the expansion of coastal agriculture and development and the subsequent loss of wetlands, these same wetlands are under pressure to continue to provide ecosystem services into the future. In GBR coastal and floodplain areas where wetland losses have been high, the capacity of the remaining wetlands to process the volume of contaminants they receive is likely to be reduced. Therefore, restoration efforts and engineering interventions may be required to increase the water quality improvement efficiency, and the associated delivery of associated ecosystem services, for the remaining wetlands within the GBR catchment area.

To improve our understanding of the components and processes of wetlands, there is a growing investment of time (staff) and resources (funding for studies), and an increased effort to align the goods and services that wetlands provide with government policies, such as the Department of Environment and Heritage Protection's (DEHP) revision of the Wetlands in the Great Barrier Reef Catchments Management Strategy 2016-2021, and the Department of Climate Change, Energy, the Environment and Water's (DCCEEW) Reef 2050 Long Term Sustainability Plan. In addition, a GBR Wetlands Network has been established, consisting of members from Natural Resource Management (NRM) groups, government, industry, universities, the broader community, and Indigenous groups, as well as a community of practice groups (e.g., Treatment Wetlands). These human resources are critical in the sharing of knowledge, data, and training of practitioners. These groups and human resources require ongoing support to continue their forward operation and planning so that the values and services provided by wetlands continue into the future.

Examining the restoration approaches used since 2016 has been important given the government's emerging interest in developing environmental markets. These markets are used to initiate, incentivise, and fund restoration for a range of ecosystem services. Studies have also mapped and estimated the potential economic return for landholders to transition from farming to wetlands for water treatment or ecosystem services (e.g., blue carbon or biodiversity). However, with the rapid development of environmental markets, this review highlights the need for a values-based approach – to consider trade-offs, avoid perverse outcomes, and that monitoring and evaluation programs are in place to capture the learnings and successes. The potential implications of future climate change projections, such as sea level rise and more severe weather events (e.g., cyclones), require careful consideration when designing restoration projects and activities in the GBR. This also highlights the need for a co-design process early in the project cycle where all stakeholders and beneficiaries are involved in setting the ecosystem service goals.

Key uncertainties and/or limitations

A summary of the key uncertainties and/or limitations in the evidence base is presented below:

- There is no ongoing assessment or monitoring and evaluation of natural and near-natural wetlands in the GBR prior to, or following, the completion of a restoration project or activity. This is challenging as the success of restoration activities (i.e., achieving and sustaining restoration goals) might not be fully known or understood, to help inform future projects (lessons learned). Long-term monitoring of water quality conditions is supported in the GBR, as part of the Marine Monitoring Program where water quality samples are routinely collected and reported via various reporting outlets; a comparable level of monitoring is needed for coastal wetlands.
- The number of research studies on ecosystem services in natural and near-natural wetlands (using the definition that has been applied in this review) is small in the GBR catchment area compared to the quantity of studies completed overseas.
- Processes that facilitate more co-design and inclusion of a range of stakeholders in the development and implementation of restoration projects so that the goals reflect all beneficiaries are needed. This will also address some of the uncertainties that exist around assessing the full impacts of restoration projects on wetland values and ecosystem services.
- There is a high level of uncertainty in the understanding of the efficacy of natural and near-natural wetlands in the GBR. This could be addressed through the development of a water quality model that links pollutant removal efficacy back to the ecosystem services agreed to by the beneficiaries. Several studies are available, but more investment is required when

considering the potential role wetlands have in improving water quality (based on overseas examples).
- More detailed studies overcoming these limitations (e.g., sampling in a single wet/dry season) are needed to reduce the substantial variation observed in how effective wetlands are in removing contaminants.

Evidence appraisal

Overall, the relevance in the body of evidence was rated as Moderate (6/9), with 34% of the studies included (43 of 125) having High relevance to the question, 52% Moderate (65 of 125), and 14% (17 of 125) rated as Low. However, only 25% (32 of 125) and 16% (20 of 125) were rated as highly spatially and temporally generalisable to the question, respectively. These studies are diverse in their approaches, data sources and authorship, featuring a mixture of primary and secondary data collection, as well as several conceptual, theoretical and review studies. Observational, modelling, and review studies were the most featured within the body of evidence, comprising 72% of the studies used. There is also a High degree of consistency among studies, with the body of evidence identifying 19 provisioning ecosystem services listed on 60 occasions, 13 cultural services listed on 26 occasions, 24 supporting services listed on 128 occasions and 25 regulating services listed on 203 occasions. Of the 53 ecosystem services provided by wetlands, as identified in the body of evidence, carbon sequestration, water quality, biodiversity, and nutrient cycling were the most commonly reported (Appendix 2).

1. Background

Coastal wetlands exist across the land and sea and include estuaries, rivers, and creeks, as well as floodplains and seasonal flowing (dry for parts of the year) channels and low-lying areas (Queensland Museum, 2022). They have highly variable physical, hydrological, and biological components that are vital for the many services they provide (Dubuc et al., 2019; Findlay & Fischer, 2013; Sheaves et al., 2016; Wolanski et al., 1980). The coastal seascape exists as a mixed set of habitats, including vegetated areas (e.g., seagrass, mangroves, saltmarshes) and unvegetated areas(e.g., sandy beaches and mudflats) (Pittman et al., 2011).

Globally, 100% of wetlands are estimated as likely or highly likely to suffer from habitat loss and fragmentation exacerbated by climate change, compared to rainforest ecosystems at 45.3% (Powers & Jetz, 2019). By far, coastal industrialisation (including agriculture and aquaculture) and urbanisation are the largest contributors to coastal wetland modification (Airoldi et al., 2021; Bugnot et al., 2021), and although recent data have revealed an expansion of wetlands in some places, the net trend shows a decline in coastal wetland extent (Murray et al., 2022). Australia also faces a legacy of degraded freshwater and coastal wetland habitat, despite a small population and a relatively short 250 years of urban, industrial, and agricultural development (Kemp et al., 2007; Lewis et al., 2021). In the Great Barrier Reef (GBR) catchment area, the loss and degradation of wetlands are reducing the GBR's resilience to other pressures (e.g., slower coral recovery following marine heatwave or cyclone activity; Hughes et al., 2017) due to ongoing pollutant runoff (Adame et al., 2019a; Brodie & Waterhouse, 2012; Lewis et al., 2021), as well as reduced habitat availability for species with freshwater life stages (Arthington et al., 2015; Waltham et al., 2019). This has sparked management targets seeking to maintain and improve the extent, and condition, of wetlands (DEHP, 2016). In addition to agriculture and urban development demands, there is increasing pressure to alter wetlands to capitalise on both their carbon sequestration (Alongi et al., 2016; Hagger et al., 2022) and water quality improvement services (McJannet et al., 2012; Waltham et al., 2021), with potentially negative consequences for some ecosystems (Sheaves et al., 2014). Successfully addressing these multiple issues will inevitably be reliant on applying a range of methods, with known efficacy, to restore or create wetlands that can be adapted to a local context (see Question 4.7, Waltham et al., this Scientific Consensus Statement (SCS) for more information).

The coastal and floodplain areas of the GBR region (Figure 1) are spectacular, dynamic, and hold incredible value (Arthington et al., 2015; Lucas et al., 1997), however, extensive land use change has modified these habitats and agricultural development now dominates the coastal landscape (Lewis et al., 2021; O'Brien et al., 2016; Waterhouse et al., 2016). This land use change has resulted in considerable negative consequences to catchment hydrology (Brodie et al., 2013; Waterhouse et al., 2016), nearshore coastal water quality dynamics (Bainbridge et al., 2012; Wolanski et al., 1980), and connectivity of the GBR floodplains, undermining the functioning of the many diverse coastal and estuarine ecosystems (Davis et al., 2017). Urban and industrial development has also expanded along the GBR coast. A review of the spatial extent and distribution of engineered structures (including roads, pontoons, seawalls, marinas, ports, and boat ramps), reveals that more than 10% of the GBR coast's linear extent has been developed (Waltham & Sheaves, 2015).

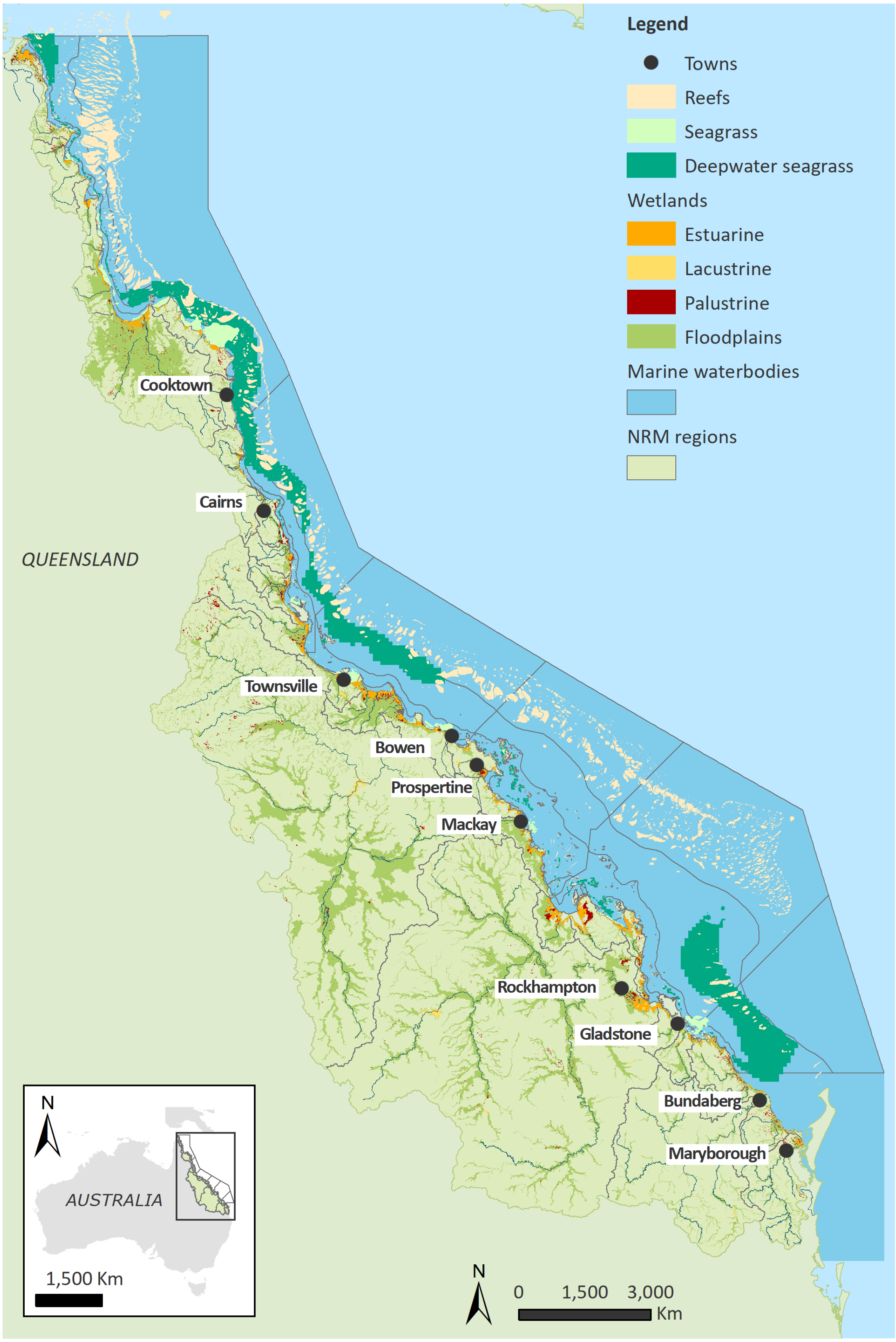


Figure 1. Map showing major rivers and cities, GBR Natural Resource Management (NRM) regions, marine waterbodies and floodplains and marine habitats in the GBR and the adjacent catchment area: seagrass, coral reefs, and inland wetland habitats, including estuarine, lacustrine, and palustrine wetlands habitats (Map prepared by Caroline Petus, TropWATER).

The extent of wetlands across the GBR catchment area has been mapped by the Queensland Government with the latest iteration released in 2019 (DES, 2019a). The mapping uses a modified version of the Ramsar definition that excludes riparian zones above the saturation level and intermittently water-covered floodplains. According to the Queensland Government Wetland*Info* website (https://wetlandinfo.des.qld.gov.au/wetlands/), in 2017 approximately 90.5% of pre-development (before European settlement) estuarine areas (excluding open water), 96.1% of pre-clear lacustrine, 78.8% of pre-development palustrine, and 83.5% of pre-development riverine wetlands remained across the GBR catchment (DES, 2019b). As shown in Table 1, these figures vary between wetland types and NRM regions, with substantial declines in some areas. The loss of wetlands has been most significant in the Wet Tropics region (30.5%) and Burnett Mary region (28.5%). The greatest losses are in palustrine wetlands across all regions (except Cape York), particularly in the Wet Topics and Mackay Whitsunday regions (approximately 49% and 44% loss respectively). Riverine wetlands are also showing greater losses, ranging between approximately 10% and 36% (excluding Cape York). Many of these changes have been associated with vegetation clearing or the instalment of drainage networks in the lower parts of the catchment, which has broader implications for the quality and quantity of surface runoff from the catchments to the GBR (Waterhouse et al., 2016).

Urban and agricultural development accounts for most of the historical decline in natural wetland areas, and these declines in extent are continuing. For example, there was a net loss of 7,688 ha of natural wetlands between 2001 and 2017 (i.e., excluding artificial/highly modified), including 6,255 ha of riverine wetlands accounting for, 605 ha of estuarine salt flats and saltmarshes, and 569 ha of coastal and subcoastal tree swamps (*Melaleuca* spp. and *Eucalyptus* spp.) on non-floodplains and 537 ha floodplains. In contrast, the total area of wetlands increased, but the majority of this increase was due to the development of artificial/highly modified wetlands (including dams, ring tanks, and irrigation channels), created primarily for irrigation storage or through bunding (constructing a wall to exclude saltwater and retain freshwater (DES, 2019b). The condition and values of the remaining wetlands across the GBR catchments are not well documented. This is an important consideration when assessing the values and ecosystem services of GBR wetlands, and a gap in the knowledge required to inform a more comprehensive whole-of-system approach to GBR management.

*Table 1. Percentage of wetlands remaining and lost in NRM regions of the GBR catchment area, by wetland type. Values are based on the Wetland*Info *2017 wetland extent and pre-development extent data. The areas do not include marine or estuarine waters but do include estuarine wetland vegetation (e.g., mangroves and tidal flats), and exclude artificial and highly modified wetlands. Source: DES (2019b).*

NRM Region	2017 area/pre-development wetland extent (i.e., percent remaining)					**Total % Loss**
	Estuarine	Lacustrine (e.g., lakes)	Palustrine (e.g., swamps)	Riverine	Total	
Cape York	100	99.2	99.3	99.8	99.6	**0.4**
Wet Tropics	93.4	99.3	51.4	70.7	69.5	**30.5**
Burdekin	89.6	99.8	91	90.9	90.8	**9.2**
Mackay Whitsunday	97.1	na	56.4	88.2	89.3	**10.7**
Fitzroy	85.7	87.8	80.8	81.8	83.2	**16.8**
Burnett Mary	98.1	100	68.5	63.8	71.5	**28.5**

This review examines the role that natural/near-natural wetlands play in the provision of ecosystem services and how the service of water quality treatment is compatible or at odds with other services (e.g., habitat, carbon sequestration). This review is important and timely given increasing interest in environmental markets for the outcome of blue carbon, water quality and biodiversity nature repair in Australia.

1.1 Question

Primary question	**Q4.9** What role do natural/near-natural wetlands play in the provision of ecosystem services and how is the service of water quality treatment compatible or at odds with other services (e.g., habitat, carbon sequestration)?

Authors' interpretation of the question:

The focus of this question is to demonstrate the positive and negative effects that water quality improvement can have on natural and near-natural wetland ecosystem services, and how water quality is at odds with or supports these services.

Wetlands cover a small proportion of the Earth's surface yet provide vital ecosystem services to human life - providing approximately $47 trillion dollars of ecosystem services each year (Davidson et al., 2019). Of these, water-related services form a significant proportion of the monetary value provided by natural wetlands (Davidson et al., 2019). However, the ways and extent to which water-related services, particularly water quality treatment, can both benefit and disadvantage the provision of other ecosystem services need to be assessed.

For the purposes of this synthesis, the Ramsar treaty's definition of wetlands is used, as it has been widely adopted in international policy and aligns with Australian federal and state government programs, and the general census among practitioners in the GBR catchment area. The Ramsar treaty defines wetlands as 'areas of marsh, fen, peatland, or water, whether natural or artificial, permanent, or temporary, with water that is static or flowing, fresh, brackish, or salt, including areas of marine water the depth of which at low tide does not exceed six metres' (Ramsar Convention Secretariat, 2016). Wetlands therefore include marine systems such as coastal lagoons, rocky shores, and coral reefs, estuarine systems such as deltas, tidal marshes, mangrove swamps and constructed wetlands, and urban features such as reservoirs, fishponds, flooded mineral workings, rock seawalls, sewage farms, and canals (DES, 2015). In this review, wetlands will refer to lacustrine, palustrine, estuarine, and riverine wetlands, i.e., excluding subtidal and subterranean wetlands, thereby excluding coral reefs, seagrass meadows, and oyster reefs.

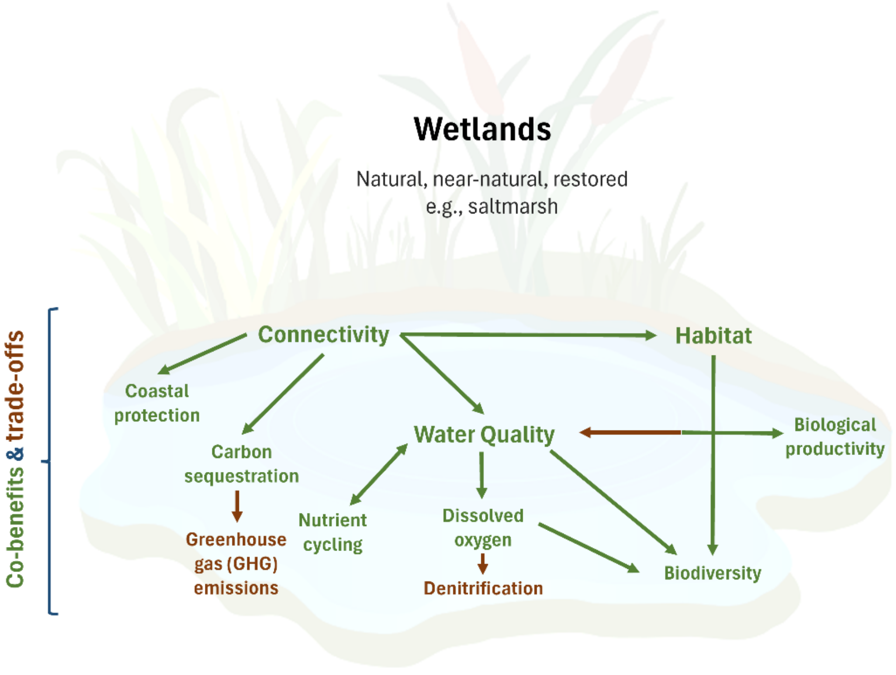
The terms 'natural' or 'near-natural' refer to wetlands that are not: 1) constructed by artificial means, or 2) geothermal wetlands. Wetlands constructed to 'offset impacts on, or restore, an existing or former natural wetland' are considered here as restored wetlands (Ministry for the Environment, 2021). These include riparian wetlands that have been restored to enhance either nitrogen and phosphorus retention or biodiversity.

Water quality refers to 'the physical, chemical, and biological characteristics of water and the measure of its condition relative to the requirements for one or more biotic species and/or to any human need or purpose' (Australian Government Initiative, 2019). Therefore, water quality treatment refers to the process of intercepting, slowing down and/or removing pollutants from water, via chemical and biological processes.

For water quality to be compatible with another ecosystem service, it is expected that an improvement in water quality would result in an improvement in the compatible ecosystem service, or vice versa (e.g., improved water quality would result in increased biodiversity). For services to be at odds with water quality, it is expected that a decline in water quality would result in the improvement of or increase in the 'at odds' service, or vice versa (e.g., a reduction in dissolved oxygen concentration would increase rates of denitrification).

1.2 Conceptual diagram

The conceptual diagram (Figure 2) graphically summarises the positive and negative relationships between the provision of water quality and the provision of other wetland ecosystem services. The direction and magnitude of these relationships are driven by variables such as local hydrology, land-use change, and the type of wetland.



Kluber et al., 2014; Liu et al., 2021; Mahoney et al., 2021; Martin et al., 2021; Suir et al., 2019; Williamshen et al., 2021; Wood et al., 2017

Figure 2. Conceptual model of some of the ecosystem services of restored saltmarsh habitats, the restoration measures used to achieve these services, and the co-benefits and trade-offs among these ecosystem services.

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 primary linkages for this question 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? **Q8.1** What are the co-benefits e.g., biodiversity, soil carbon, productivity, climate resilience, of land management to improve water quality outcomes for the Great Barrier Reef?

2. Method

A formal Rapid Review approach was used for the 2022 Scientific Consensus Statement (SCS) synthesis of evidence. Rapid reviews are a systematic review with a simplification or omission of some steps to accommodate the time and resources available[6]. For the SCS, this applies to the search effort, quality appraisal of evidence and the amount of data extracted. The process has well-defined steps enabling fit-for-purpose evidence to be searched, retrieved, assessed and synthesised into final products to inform policy. For this question, an Evidence Summary method was used.

2.1 Primary question elements and description

The primary question is: ***What role do natural/near-natural wetlands play in the provision of ecosystem services and how is the service of water quality treatment compatible or at odds with other services (e.g., habitat, carbon sequestration)?***

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?

Further details relating to the process of defining and refining the element question is provided in Table 2, with important definitions included in Table 3.

Table 2. Description of question elements for Question 4.9.

Question S/PICO elements	Question term	Description
Subject/ Population	Ecosystem services	**Subject -** Ecosystem service, wetland service, ecological service, nature-based solutions. Ecosystem services: habitat, carbon sequestration, blue carbon, carbon storage, carbon stock, fix, biodiversity, social, cultural, provision, flood, erosion, fish, bird, wave, cyclone, recreation, treatment, filter, protein, fuel, fibre, food, freshwater, nursery, mental health. *See Appendix 2 for a full list of ecosystem services estimated to be provided by natural and near-natural wetlands.*
	Water quality	**Water quality**: nutrients (e.g., nitrogen, phosphorus), pollution, light, irradiance, turbidity, pesticide, herbicide, fungicide, salinity, sediment, heavy metal dissolved oxygen.

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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

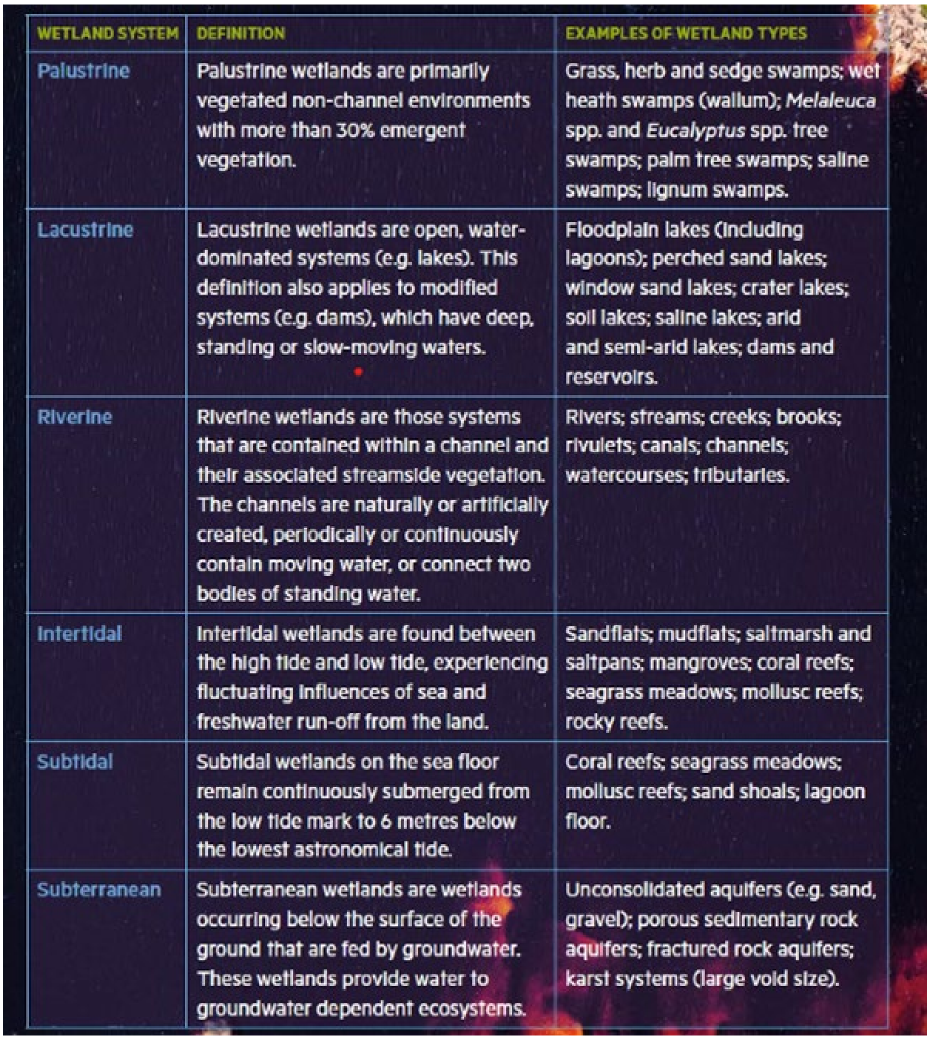
Question S/PICO elements	Question term	Description
Intervention, exposure & qualifiers	Wetlands	**Intervention** - Natural/near-natural wetlands, restored wetlands. Wetland: natural, near natural, lacustrine, palustrine, estuarine, melaleuca, marsh, riverine, restored.
Outcome & outcome qualifiers	Examples included in this review	Improved/reduced habitat. Increased/decreased carbon sequestration. Improved/declining water quality. Enhanced/reduced biodiversity. Increased/decreased social and cultural amenity etc. Increased/reduced provisioning. Increased/reduced environmental, biological, cultural outcomes.
Comparator	Compatible or at odds with	**Compatible** – i.e., synergies, increased, benefit, improved, co-benefits, positive feedback, enhanced, promote, support, facilitate. At odds with - i.e., conflict, reduced, negative, decreased, negative feedback, degraded, trade-off. Other ecosystem services: Habitat, carbon sequestration, carbon storage, carbon stock, blue carbon, fixing carbon, water quality, biodiversity, provision, flood, erosion, fish, bird, wave, cyclone, recreation, treatment, filter, protein, fuel, fibre, food, freshwater, nursery, culture, social, mental health.

Table 3. Definitions for terms used in Question 4.9.

<table>
<tr><th colspan="2">Definitions</th></tr>
<tr><td>Wetlands</td><td>

‘Wetlands are areas of marsh, fen, peatland, or water, whether natural or artificial, permanent, or temporary, with water that is static or flowing, fresh, brackish, or salt, including areas of marine water the depth of which at low tide does not exceed six metres’ (Ramsar Convention Secretariat, 2016).

Subtidal and subterranean wetlands, i.e., coral reefs, seagrass meadows, oyster reefs and aquifers will be excluded.



<table>
<tr><th>WETLAND SYSTEM</th><th>DEFINITION</th><th>EXAMPLES OF WETLAND TYPES</th></tr>
<tr><td>Palustrine</td><td>Palustrine wetlands are primarily vegetated non-channel environments with more than 30% emergent vegetation.</td><td>Grass, herb and sedge swamps; wet heath swamps (wallum); <i>Melaleuca</i> spp. and <i>Eucalyptus</i> spp. tree swamps; palm tree swamps; saline swamps; lignum swamps.</td></tr>
<tr><td>Lacustrine</td><td>Lacustrine wetlands are open, water-dominated systems (e.g. lakes). This definition also applies to modified systems (e.g. dams), which have deep, standing or slow-moving waters.</td><td>Floodplain lakes (including lagoons); perched sand lakes; window sand lakes; crater lakes; soil lakes; saline lakes; arid and semi-arid lakes; dams and reservoirs.</td></tr>
<tr><td>Riverine</td><td>Riverine wetlands are those systems that are contained within a channel and their associated streamside vegetation. The channels are naturally or artificially created, periodically or continuously contain moving water, or connect two bodies of standing water.</td><td>Rivers; streams; creeks; brooks; rivulets; canals; channels; watercourses; tributaries.</td></tr>
<tr><td>Intertidal</td><td>Intertidal wetlands are found between the high tide and low tide, experiencing fluctuating influences of sea and freshwater run-off from the land.</td><td>Sandflats; mudflats; saltmarsh and saltpans; mangroves; coral reefs; seagrass meadows; mollusc reefs; rocky reefs.</td></tr>
<tr><td>Subtidal</td><td>Subtidal wetlands on the sea floor remain continuously submerged from the low tide mark to 6 metres below the lowest astronomical tide.</td><td>Coral reefs; seagrass meadows; mollusc reefs; sand shoals; lagoon floor.</td></tr>
<tr><td>Subterranean</td><td>Subterranean wetlands are wetlands occurring below the surface of the ground that are fed by groundwater. These wetlands provide water to groundwater dependent ecosystems.</td><td>Unconsolidated aquifers (e.g. sand, gravel); porous sedimentary rock aquifers; fractured rock aquifers; karst systems (large void size).</td></tr>
</table>

Source: Queensland Museum (2022) Wetlands of Queensland, Queensland Museum Network, Brisbane.

</td></tr>
<tr><td>Natural/near-natural wetlands</td><td>

Wetlands that are not: 1) constructed by artificial means, 2) geothermal wetlands. Wetlands constructed to ‘offset impacts on, or restore, an existing or former natural wetland’ are considered here as ‘near-natural’ wetlands.

For this review, natural and near-natural wetlands will refer to lacustrine, palustrine, estuarine, and riverine wetlands, excluding subtidal and subterranean wetlands, thereby excluding coral reefs, seagrass meadows, oyster reefs and aquifers etc.

Natural wetlands refer specifically to wetlands without any anthropogenic structural or hydrological change to the wetland, or within its catchment.

Near-natural wetlands refer to wetlands without any anthropogenic structural change to the wetland, but with anthropogenic structural or hydrological change occurring within the broader catchment.

</td></tr>
</table>

Definitions	
Restored Wetlands	**Restored or rehabilitated wetlands** refer to wetlands where ecological and/or hydrological processes have been recovered where naturally wetlands previously existed. These may have been drained in an agricultural landscape for example and can include the construction of levées and dykes.
Ecosystem Services	**Ecosystem services** are the benefits people obtain from ecosystems. These include provisioning services such as food, water, timber, and fibre; regulating services that affect climate, floods, disease, wastes, and water quality; cultural services that provide recreational, aesthetic, and spiritual benefits; and supporting services such as soil formation, photosynthesis, and nutrient cycling (Millennium Ecosystem Assessment, 2005).
Water quality	Water quality refers to the chemical, physical, biological, and radiological characteristics of water. It is a measure of the condition of water relative to the requirements of one or more biotic species and/or to any human need or purpose. (ANZECC & ARMCANZ, 2000). Measurements of denitrification and other nitrogen processes such as denitrification, anammox and dissimilatory nitrate reduction to ammonium will be included.
Water quality treatment	**Water quality treatment** will include chemical and biological processes such as denitrification, changes in concentration, dissolved oxygen content and physical processes such as sediment accumulation. Water quality treatment will be measured as an *in situ* and/or downstream metric and will use before and after measures to determine improvements to / reductions in water quality.
Compatible	**Compatible**: one ecosystem service result (e.g., increased dissolved oxygen content), leads to improvements and/or benefits in the outcomes of another (e.g., increased fisheries, biodiversity, and cultural values).
At odds with	**At odds with:** one ecosystem service result (e.g., improved freshwater habitat), leads to negative outcomes in another (e.g., reduced carbon sequestration).

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 using several literature search databases. These included:

- Scopus
- Web of Science
- Google Scholar

b) Search terms

A list of the search terms used to conduct the online searches is provided in Table 4.

Table 4. Search terms for S/PICO elements of Question 4.9.

Question element	Search terms
Subject/Population	Ecosystem service, ecological service, wetland service, nature-based solutions Habitat, carbon sequestration, blue carbon, carbon storage, carbon stock, carbon fixation, biodiversity, social, cultural, provision, flood, erosion, fish, bird, wave, cyclone, recreation, treatment, filter, protein, fuel, fibre, food, freshwater, nursery, mental health Water quality, nutrients, nitrogen, phosphorus, pollution, light, irradiance, turbidity, pesticide, herbicide, fungicide, salinity, sediment, heavy metal, dissolved oxygen
Exposure or Intervention	Wetland, natural, near-natural, lacustrine, palustrine, estuarine, melaleuca, marsh, riverine, restored
Outcome	

c) Search strings

A set of search strings were defined by the authors and confirmed with the SCS Coordination Team. The list of search strings used to conduct the online searches is presented in Table 5.

Table 5. Search strings used for electronic searches for Question 4.9.

Search strings
Scopus & Web of Science: *Limited to studies 1990-2022, in English and only published journal articles.* ((eco* W/3 service*) OR (wetland W/4 service*) OR “nature-based solution*”) AND (“water quality” OR nutrients OR nitr* OR phosph* OR pollut* OR light OR irradiance OR turbidity OR pesticide OR herbicide OR fungicide* OR salin* OR sediment* OR “heavy metal*” OR “dissolved oxygen”) AND Wetland AND (natural OR “near natural” OR lacustrine OR palustrine OR estuarine OR melaleuca OR marsh* OR riverine OR restored) AND (habitat OR “carbon sequest*” OR “blue carbon” OR “carbon stor*” OR “carbon stock*” OR fix OR biodivers* OR social OR cultural OR provision* OR flood OR erosion OR fish* OR bird* OR wave OR cyclone OR recreation* OR treatment OR filter OR protein OR fuel OR fibre OR food OR freshwater OR nursery OR “mental health” OR trade-off* OR tradeoff* OR co-benefit*)
Google Scholar: *Limited to the first 200 results, studies 1990-2022, in English, and only published journal articles.* "ecosystem service*" OR "ecological service*" OR "nature based solution*" AND wetland AND natural OR "near natural" OR lacustrine OR palustrine OR estuarine OR melaleuca OR marsh AND "water quality" AND habitat OR “carbon sequest*” OR “blue carbon” OR “carbon stor*” OR “carbon stock*” OR biodivers* OR social OR cultural OR provision* OR flood OR erosion OR fish* OR bird* OR wave OR cyclone OR recreation*OR treatment OR filter OR protein OR fuel OR fibre OR food OR freshwater OR nursery

d) Inclusion and exclusion criteria

A set of search inclusion and exclusion criteria were defined by the authors and confirmed with the SCS Coordination Team. The list of the search criteria is presented in Table 6.

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

Question element	Inclusion	Exclusion
Subject / Population	Ecosystem services, including water quality	Studies unrelated to ecosystem service provision or water quality and its connection (positive, negative, or neutral) to the provision of other ecosystem services. Human values- or perception-based studies (e.g., farmer's values of ecosystem services).
Exposure or Intervention	Natural, near-natural, and restored wetlands	Subtidal wetlands: coral reefs, seagrass meadows, mollusc reefs, sand shoals, lagoon floor etc. Subterranean wetlands, e.g., aquifers (unless related to ecosystem service provision of wetlands). Constructed/created/treatment wetlands (unless compared with the function and services of natural/restored wetlands).
Comparator (if relevant)	Trade-off	-
Outcome	Ecosystem service provision	Studies unrelated to ecosystem service provision.
Language	English	Non-English papers
Study type	Meta-analyses Published, peer reviewed papers. Studies using BACI design. Studies directly investigating ecosystem service provisioning (e.g., carbon sequestration, habitat provision etc.) Economic valuations of wetland ecosystem services Tools for monitoring restoration success – using ecosystem services as an indicator	Observations of, and investigations into, impacts upon wetlands e.g., anthropogenic-induced wetland loss/degradation, pollution events, and climate change impacts. *(Unless referring to the loss of/reduction in ecosystem service provision, measures ecosystem service provision prior to an event or compares to a pristine/reference wetland e.g., BACI design).* Studies that only mention ecosystem services and do not directly measure, evaluate, investigate, or quantify them (e.g., quantify hydrology, but not in reference to increased water flow and subsequent increases in carbon sequestration and biodiversity etc.). Studies monitoring/measuring wetland loss but not referencing the loss of ecosystem services. Studies of single species/genus and their function/service provision, unless related back to ecosystem service provision of the entire wetland. Studies of failed ecosystem restoration – unable to restore wetland ecosystem services/function and don't describe the loss of wetland ecosystem services/function.

3. Search Results

A total of 262 studies were identified through online searches for peer reviewed and published literature after screening. Seventeen studies were identified manually through expert contact and personal collection, which represented 14% of the total eligible evidence. In total, 12 studies were eligible for inclusion in the synthesis of evidence (Table 7, Figure 3). Three studies were unobtainable after screening, without contacting authors directly or seeking assistance from university library services.

Table 7. Search results table, separated by A) Academic databases, B) Search engines (i.e., Google Scholar) and C) Manual searches. The search results for A and B are provided in the format X (Z) of Y, where: X (number of relevant evidence items retained); Y (total number of search returns or hits); and Z (number of relevant returns that had already been found in previous searches).

Date (d/m/y)	Search strings	Sources	
A) Academic databases		Scopus	Web of Science
28/11/2022	*((eco* W/3 service*) OR (wetland W/4 service*) OR "nature-based solution*") AND* *("water quality" OR nutrients OR nitr* OR phosph* OR pollut* OR light OR irradiance OR turbidity OR pesticide OR herbicide OR fungicide* OR salin* OR sediment* OR "heavy metal*" OR "dissolved oxygen") AND* *wetland AND (natural OR "near natural" OR lacustrine OR palustrine OR estuarine OR melaleuca OR marsh* OR riverine OR restored) AND* *(habitat OR "carbon sequest*" OR "blue carbon" OR "carbon stor*" OR "carbon stock*" OR fix OR biodivers* OR social OR cultural OR provision* OR flood OR erosion OR fish* OR bird* OR wave OR cyclone OR recreation* OR treatment OR filter OR protein OR fuel OR fibre OR food OR freshwater OR nursery OR "mental health" OR trade-off* OR tradeoff* OR co-benefit*)*	*106 of 661*	*0 (27) of 51*
B) Search engine (Google Scholar)			
29/11/2022	*ecosystem service*" OR "ecological service*" OR "nature based solution*" AND wetland AND natural OR "near natural" OR lacustrine OR palustrine OR estuarine OR melaleuca OR marsh AND "water quality" AND habitat OR "carbon sequest*" OR "blue carbon" OR "carbon stor*" OR "carbon stock*" OR biodivers* OR social OR cultural OR provision* OR flood OR erosion OR fish* OR bird* OR wave OR cyclone OR recreation* OR treatment OR filter OR protein OR fuel OR fibre OR food OR freshwater OR nursery*	*2 (0) of 17,500 (first 200)*	
	Total items online searches	***108 (86%)***	
C) Manual search			
Date	Source	Number of items added	
29/11/2022	*Author personal collection*	*7*	
03/02/2023	*Other SCS searches*	*10*	
	Total items manual searches	***17 (14%)***	

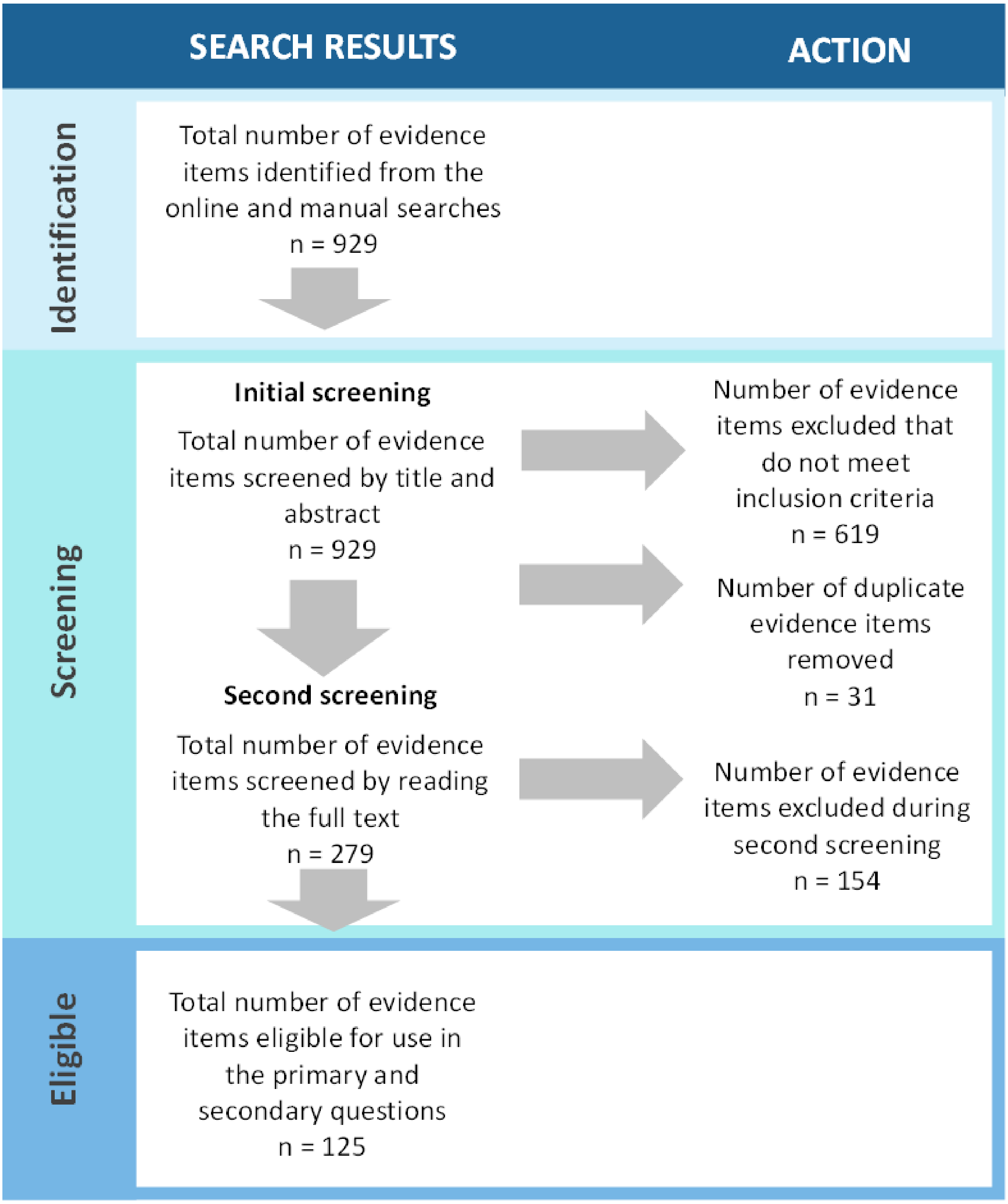


Figure 3. Flow chart of results of screening and assessing all search results.

4. Key Findings

4.1 Narrative synthesis

4.1.0 Summary of study characteristics

From this review, the number of source items in the initial screening revealed a long list of publications that highlight the specific interest in the restoration of natural and near-natural wetlands for a range of ecosystem service outcomes. While a large number of studies are available for temperate studies, the review focused on tropical and subtropical locations to maintain relevance to the GBR catchment area. Based on the key search word strings, most of the studies were on wetland research in the United States (35%), China (11%), South America (11.3%) and Australia (10%). The remaining studies were from South Africa (5%), India (5%), Spain (2%), Saudi Arabia (1%), and other tropical locations (e.g., Philippines, Bangladesh).

The habitat setting that had the highest number of studies was estuarine (32%), followed by riverine (22%), palustrine (11%), and lacustrine (1%). Interestingly 17% of studies had a combination of these habitats, while the remainder were not clear in their description of which habitat the study was focused on. This last point presents a major challenge for a review such as this one given an obvious lack of detail that was clearly not picked up during the peer review process. In terms of whether studies focused on natural, near-natural or restored locations, the majority (46%) indicated the study was in a near-natural setting, 11% occurred in a natural wetland setting, and 23% in a restored habitat setting – with the remaining studies from a combination of these settings.

The majority of studies (65%) focused on restoring ecosystem services (carbon, biodiversity), while 10% focused on water quality outcomes, and 25% of studies focused on restoring both ecosystem services and water quality outcomes. As shown in Table 8, most studies were observational (30.5%, or an observational and modelling approach, 5%) whereby they were a survey or case study, usually one-off or occurred over a short period. Other study types had a modelling focus (~18.5%), a review (~18.5%) or an experimental (including mesocosm) approach (12%), with the remaining studies having a theoretical (14%) or conceptual approach (2%).

An interesting aspect of this review was understanding the ecosystem services provided as a result of restoration actions. For example, the majority of studies (35%) focused on nutrient processing, 23% focused on soil carbon stocks and accumulation potential, while the remaining studies had a single occurrence (<2%), including biodiversity, endemic species habitat, sediment trapping, photosynthesis, pollution, habitat and water quality cycle (<1.5%).

Table 8. Summary of study types from the 125 studies used within the body of evidence of Question 4.9.

Study type	Count
Conceptual	2
Experimental	14
Experimental mesocosm	1
Modelling	23
Observational	38
Observational & Modelling	6
Review	23
Theoretical	18
Total	**125**

For a small number of studies (12 studies), 33% were focused on restoration for local cultural value protection, 16% of studies were focused on recreational values, with the remaining studies focused on: aesthetics, community value, food security, shelter during inclement weather (Table 8).

As part of the formal method for this review, the number of studies that had Indigenous engagement was also examined (see also Section 4.4). From the 125 studies, 4% of studies contained evidence of engagement with Indigenous groups.

4.1.1 Summary of evidence to 2022

An important element of this review was understanding what variables influence whether the services examined were compatible or at odds with water quality (Table 9). Nearly half of the studies (49%) did not report this or provide enough details for this to be evaluated. Of the remaining studies, among the frequently reported trade-offs with natural or near-natural wetlands were changes in connectivity as a consequence of poor management, or direct impacts such as the installation of tidal flow restriction devices. As a consequence, decreases in freshwater through-flow generally result in greater extremes in salinity, temperature and dissolved oxygen in fragmented tidal creeks. The change in flow, connectivity and water quality associated with human infrastructure and tidal restriction devices can have significant impacts on local biodiversity, with greater flora and fauna diversity observed in unfragmented relative to fragmented tidal creeks (Valentine-Rose et al., 2007). Abbott et al. (2020) found similar results in a small wetland system in the GBR catchment area, in which the installation of a bund wall had restricted tidal flow, resulting in a depauperate aquatic fish assemblage consisting of invasive fish species (such as *Gambusia holbrooki*, gambusia) and several native species (*Melanotaenia splendida*, eastern rainbow fish and *Hypseleotris compressa*, empire gudgeon). Immediately following tidal reconnection, in which the tide was able to reach new upstream areas of the wetland, the diversity of fish increased, featuring diadromous species with an estuarine/freshwater lifecycle, including tarpon (*Megalops cyprinoides*), barramundi (*Lates calcarifer*), and banded scat (*Selenotoca multifasciata*). In a study on the Okavango Delta (Botswana), Mosepele et al. (2022) reported that the dynamics of a dry and wet floodplain was the main contributing factor towards enhanced ecosystem production in an otherwise oligotrophic and semi-arid environment. In that study, seasonal flooding not only changed the physical landscape of the delta by reconnecting isolated lagoons and creating a multitude of diverse micro-habitats, but it also enhanced nutrient dynamics in both the terrestrial and aquatic systems. However, an important trade-off exists between the potential food provision for local communities near these wetlands and water-related ecosystem services, such as water provision, quality, flood attenuation, and carbon storage.

Water quality condition in wetlands is believed to underpin many co-benefits (Chatanga et al., 2020). In particular, improved water quality conditions typically result in increased biodiversity and the multiple ecosystem services that result from diverse populations of flora and fauna (Butler et al., 2013; Duffy & Kahara, 2011). When favourable, water quality has been found to increase the diversity and abundance of fish (Abbott et al., 2020; Mahoney et al., 2021; Pinto et al., 2010), plankton (Sarkar et al., 2021; Sileshi et al., 2020), and macroinvertebrates (Sileshi et al., 2020). In turn, these increases in local biodiversity have contributed to the provision of additional wetland ecosystem services, including food provision through fish farming (Pinto et al., 2010), recreation from fishing (Butler et al., 2013; Thompson & Sultana, 2010), increased food and habitat provision for migratory birds (Thompson & Sultana, 2010), which can increase recreational opportunities and activity through bird-watching and wetland aesthetics(Ghermandi et al., 2020). However, the relationship between water quality and biodiversity can be affected by external factors such as rainfall (Sarkar et al., 2021), changes in nutrient loading (Blackwell & Pilgrim, 2011), and weed density (Abbott et al., 2020). A complex relationship between water quality and biodiversity is in hypersaline wetlands, in which biodiversity is greatly reduced due to the physiological challenges of living in these extreme environments. Yet, these unique systems offer habitat for highly specialised and often endemic and endangered species (Saccó et al., 2021). Therefore, the wetland service of water quality for these species is very different to the requirements of species with a lower saline tolerance (Więski et al., 2010) and as such, trade-offs in wetland services need careful consideration – as actions for a particular outcome or goal might result in problems or limited services in the pursuit of another goal (Butler et al., 2013; Rebelo et al., 2019).

Vegetation is also a key component of ecosystem service provision within wetlands – with mangroves providing coastal protection through sediment accumulation and preventing coastal erosion through wave and surge attenuation (Gorman & Turra, 2016; Kelleway et al., 2017). Mangroves, saltmarsh and other wetland vegetation sequester carbon that would otherwise be released into the atmosphere

(Craft, 2012; Ewers et al., 2019; Kelleway et al., 2016), and cycle nutrients that helps to improve water quality (Schutte et al., 2020). Mangroves and other wetland vegetation also provide multiple resources for human use, acting as a food source or providing habitat for food sources (Mosepele et al., 2022), wetland vegetation can be a source of medicinal products (Kelleway et al., 2017), as well as provide fibre, fuel, and raw construction materials (Butler et al., 2013; Krauss et al., 2022; Meli et al., 2014). Lastly, through its provisioning services, wetland vegetation also contributes to wetland cultural services such as recreational fishing and hunting (Kelleway et al., 2017; Sarkar et al., 2021) and education (Chatanga et al., 2020).

Although the vegetation community within a wetland performs and provides multiple ecosystem services, excessive vegetative growth, for example invasive weeds, presents a challenge to wetland water quality, particularly when in amounts either covering the entire water surface or extending through the entire water column. In tropical north Queensland, the overgrowth of aquatic weeds has significantly hampered restoration efforts by reducing dissolved oxygen concentrations within the water and, as a result, reducing local fish biodiversity (Abbott et al., 2020). When present in excessive amounts, weeds pose a significant threat to wetland water quality and biodiversity, however when their spread and abundance are managed, aquatic weeds could be useful for the objective of improving water quality through increasing dissolved oxygen concentrations and in nutrient processing (Adame et al., 2021). For example, the invasive plant species *Spartina alterniflora* is proficient at removing soil nitrogen within the upper 50 cm of the soil profile, but exhibits comparably lower soil nitrogen removal, relative to native plant species, when examining the full depth of the soil profile (Li et al., 2020). Therefore, the risk of weed overgrowth and detrimental water quality and biodiversity impacts, versus the water quality benefits of weedy aquatic vegetation and the cost of weed removal and ongoing maintenance is a trade-off and a balance needing careful consideration.

Erosion that occurs in natural and near-natural wetland channels or banks has been identified as a challenge in the protection and restoration of wetland ecosystem services and values (Thompson & Friess, 2019). In particular, erosion of Nebraskan playas results in sediment accumulation within the wetland, which decreases the wetland volume and removes and degrades habitat quality for local frog species (Beas & Smith, 2014). The threat of erosion can also undermine banks, causing the transfer of sediment away from wetlands to downstream areas and changing local hydrology, usually increasing water flow volume and velocity (Wiener et al., 2022). However, despite this negative consequence, bank erosion processes can undermine edge vegetation, causing it to topple into wetlands and providing snag habitats for aquatic species. In addition, sedimentation of wetlands caused by human intervention can be advantageous in raising the elevation of the wetland, which can assist with denitrification rates (Velinsky et al., 2017).

Land use changes in catchments were repeatedly reported as impacting directly on wetland ecosystem services (see Questions 3.4, Wilkinson et al., and 3.5, Bartley & Murray, this SCS). This impact was generally described in the literature as directly contributing to the loss of wetlands or heavily altering/reducing the hydrology or delivery of poor water quality to wetlands (Ma et al., 2019; Pinto et al., 2010; Yin et al., 2021). One impact is sediment inputs from catchment areas which can be delivered to wetlands where poor catchment management practices are apparent. Sediment delivered to wetlands can become trapped depending on the hydrology and sediment grain size, which can contribute to lost habitat for wetland species (Beas & Smith, 2014). For example, in catchments with a high sediment load amphibian species in wetlands can be influenced by habitat loss associated with sediment inputs (Beas & Smith, 2014; Reeves et al., 2016).

Wetlands provide unique opportunities to tackle climate change as they can sequester and store large amounts of carbon from the atmosphere (Osland et al., 2018; Vinod et al., 2018; Yoskowitz & Hutchison, 2018). In this review, several studies (11%) focused on examining the carbon sequestration services that wetlands provide, with the rates of sequestration influenced by the age of the system and degree of disturbance (Marton et al., 2014), vegetation type/species and density (Banerjee & Paul, 2022) and degree of tidal water ingress over wetland areas (Iram et al., 2022), with higher rates of tidal connection contributing to higher rates of soil carbon accumulation reported (Fennessy et al., 2019). Understanding and measuring the carbon storage potential in coastal wetlands has the potential to attract new funding opportunities via environmental market mechanisms (Krauss et al., 2022).

Modelling studies of natural and near-natural wetlands (either restoration or engineered treatment wetlands) for water quality services (23%) were also a focus for many of the studies examined here. Generally, these studies were focused on understanding how land use changes in catchments alter water quality conditions, with landscape change typically found to reduce water quality (Pan et al., 2022). For example, Kahara et al. (2022) concluded that losses of wetlands in Central Valley (California) have led to a significant reduction in the amount of nutrients that are removed and therefore the amount of nutrients reaching coastal waters has increased. There is an obvious link between hydrology in wetlands and the efficacy of nutrient removal (see Question 4.7, Waltham et al., this SCS).

Table 9. Regulating, provisioning, cultural and supporting ecosystem services provided by natural, near-natural and restored wetlands, as identified by the body of evidence.

Service category	Ecosystem Service	References (Examples, not extensive)
Regulating	Biological control	Msofe et al., 2020
	Carbon sequestration	Brown et al., 2019; Chen & Lee, 2022; Coverdale et al., 2014; Craft, 2012; Duncan et al., 2016; Ewers et al., 2019; Hinson et al., 2019; Kelleway et al., 2016; Li et al., 2020; Livesley & Andrusiak, 2012; Ma et al., 2015; Pendleton et al., 2012; Sheehan et al., 2019; St. Laurent et al., 2020; Stringer et al., 2016; Wood et al., 2017; Xiaonan et al., 2008; Zamora et al., 2020
	Climate regulation	Jenkins et al., 2010
	Coastal protection	Adame et al., 2015; Tiner, 2005
	Erosion control	Blanco-Sacristán et al., 2022; Reed et al., 2018
	Flood regulation/protection	Duffy & Kahara, 2011; Kadykalo et al., 2016; Rebelo et al., 2019; Yang et al., 2016
	Greenhouse gas regulation	Kluber et al., 2014
	Hazard reduction	Mandishona & Knight, 2022
	Invasive species control	Meli et al., 2014
	Microclimate control	Guo et al., 2017
	Water quality & purification	Acreman et al., 2021; Adhikari et al., 2011; Cao et al., 2020; De Troyer et al., 2016; Gorman & Turra, 2016; Hes et al., 2021; Kaplan et al., 2015; Souza & Silva, 2011; Zhang et al., 2021
Provisioning	Agriculture	Aguilos et al., 2021; Hogan et al., 2012
	Biochemical products	Mandishona & Knight, 2022
	Fodder provision	Blackwell & Pilgrim, 2011; Monge-Salazar et al., 2022
	Food provision	Sarkar et al., 2021; Sinclair et al., 2021
	Fibre production	Butler et al., 2013
	Freshwater provision	Chung et al., 2021; Rubio et al., 2017
	Fuel	Krauss et al., 2022
	Genetic materials	Mandishona & Knight, 2022
	Medicinal products	Kelleway et al., 2017
	Mental health benefits	Ghermandi et al., 2020
	Public health	Mitsch & Day, 2006
	Raw materials	Meli et al., 2014
	Shelter	Krauss et al., 2022
	Timber	DeAngelis et al., 2016; Zhu et al., 2011
	Waste management	Dash et al., 2022
	Water storage	Ganesan et al., 2016; Hu et al., 2020; Smith et al., 2011

Service category	Ecosystem Service	References (Examples, not extensive)
Cultural	Aesthetic	Ghermandi et al., 2020
	Community value	Davids et al., 2021
	Cultural (unspecified)	Mitsch & Day, 2006
	Education	Chatanga et al., 2020
	Hunting	Kelleway et al., 2017
	Recreational fishing	Butler et al., 2013
	Recreation and Tourism	Merriman et al., 2018
	Spirituality	Kelleway et al., 2017; Mandishona & Knight, 2022
Supporting	Biodiversity	Gómez-Anaya & Novelo-Gutiérrez, 2015; Kong et al., 2020; Marois & Mitsch, 2015; Mishra et al., 2021; Passos et al., 2022; Sun et al., 2019; Weinstein et al., 2021; Więski et al., 2010; Winckler et al., 2017
	Biogeochemical cycling	Meli et al., 2014
	Biotic interactions	Meli et al., 2014
	Habitat provision	Tiner, 2005; Wang et al., 2009; Zhang & Fang, 2021
	- Endangered species habitat	Kelleway et al., 2017
	- Endemic species habitat	Sieben & Chatanga, 2019
	Hydrology	Moore et al., 1999
	Nutrient cycling	Cejudo et al., 2022; Sánchez Colón & Schaffner, 2021; Ho & Chambers, 2019; Liao & Inglett, 2012; Macy et al., 2021; Schutte et al., 2020; Steinmuller et al., 2020; Theriot et al., 2013
	Photosynthesis	Calvo-Cubero et al., 2014
	Pollination	Butler et al., 2013
	Primary productivity	Adame et al., 2010; Calvo-Cubero et al., 2014
	Sediment trapping	Daniel et al., 2015; Wiener et al., 2022; Woznicki et al., 2020
	Soil fertility	Meli et al., 2014
	Soil formation	Mandishona & Knight, 2022

Table 10. Ecosystem services provided by natural, near-natural and restored wetlands, as identified by the body of evidence, and their relationship to the ecosystem service of water quality.

Ecosystem service	Compatible with water quality	At odds with water quality	Influencing variables	Reference
Biodiversity	Improved water quality resulted in increased fish biodiversity.	-	Weed density	Abbott et al., 2020
	-	Denitrification may result in depleted dissolved oxygen levels, impacting fish presence and biodiversity.		Adame et al., 2021
	-	Sediment trapping by wetlands reduces frog habitat availability and quality.	-	Beas & Smith, 2014
	-	Changes in water quality can result in shifts in species composition.	Nutrient loading	Blackwell & Pilgrim, 2011
	Compatible	-	-	Butler et al., 2013
	Compatible	-	-	Duffy & Kahara, 2011
	‘Salinity, site type, and Secchi depth played important roles in predicting (fish) abundance and diversity’.	-		Mahoney et al., 2021
	‘The increasing nutrient concentration in the water, (…), influences aquaculture production and affects the aquatic communities’ diversity.’	-	-	Pinto et al., 2010
	Hypersaline environments - not many species can tolerate them, but home to highly adapted and hyper-saline tolerant species (9 species found in salinities of >310 g L^{-1}).	-	-	Saccò et al., 2021
	Reduced rainfall, wetland area and depth have increased nutrient concentrations in Mathura wetland. As a result 17% of species recorded in 2002 have been lost, with plankton diversity reduced to 46% of the diversity observed in 2000.	-	Rainfall	Sarkar et al., 2021
	From the analyses, ammonium (NH_4^+), total nitrogen (TN), and dissolved oxygen (DO) were significant in determining the distribution of macroinvertebrate families; total phosphorus (TP), nitrate (NO_3^-) and NH_4^+ were important in diatom species distribution.	-	-	Sileshi et al., 2020
	‘Decreased connectivity resulted in greater extremes in salinity, temperature and dissolved oxygen in fragmented tidal creeks, which also likely contributed to biotic	-	-	Valentine-Rose et al., 2007

Ecosystem service	Compatible with water quality	At odds with water quality	Influencing variables	Reference
	differences between unfragmented and fragmented tidal creeks'.			
	'Species richness at the site scale decreased by over five times across the salinity gradient from fresh to salt…'.	-	-	Więski et al., 2010
Carbon sequestration	Compatible	-	Tidal inundation, Forest age, Hurricanes	Adame et al., 2015
	Compatible	At odds	Seasonality, Vegetation biomass	Banerjee & Paul, 2022
	-	'Due to enrichment of the soil organic C pool from rhizosphere material and exudates', dissimilatory nitrate reduction to ammonium was favoured over denitrification.	-	Ledford et al., 2021
	-	A lower C:N ratio may have enhanced denitrification in marshland, therefore higher quantities of soil carbon may reduce denitrification.	-	Li et al., 2020
	High quantities of soil carbon increased NO_3^- removal from the landscape.	-	-	Marton et al., 2014
Coastal protection	Compatible	-	-	Adame et al., 2015
	-	'Rates of accretion and elevation change in ature-based Solutions projects are significantly correlated to the concentration of total suspended matter (TSM) in the water column'.	Sediment availability Elevation within the tidal frame	Liu et al., 2021
Habitat – endemic species	Hypersaline environments - not many species can tolerate them, but home to highly adapted and hyper-saline tolerant species (9 species found in salinities of >310 g L^{-1}).	-	-	Saccò et al., 2021
Food and fibre production	-	At odds	-	Butler et al., 2013
	'The decline in fish farming production appears to be mainly related to decreasing water quality.'	-	-	Pinto et al., 2010
	-	'An important trade-off appears to exist between the potential food provision of these wetlands and water-related ecosystem services, such as water provision, purification, (…) pristine wetlands score higher for water-	-	Rebelo et al., 2019

Ecosystem service	Compatible with water quality	At odds with water quality	Influencing variables	Reference
		related ecosystem services and carbon storage, and wetlands degraded by agriculture tend to score lower.'		
Greenhouse gas regulation	-	With nutrient cycling, at high NO_3^- concentrations, N_2O emissions were recorded.	-	Blackwell & Pilgrim, 2011
Hydrology	A '…pulsed hydrology likely contributed to comparable denitrification rates between natural and restored riparian buffers'.	-	-	Marton et al., 2014
	'Decreased connectivity resulted in greater extremes in salinity, temperature and dissolved oxygen in fragmented tidal creeks…'.	-	-	Valentine-Rose et al., 2007
Nutrient cycling	Processing nutrients improves water quality for downstream habitats.	Denitrification may result in depleted dissolved oxygen levels.	-	Adame et al., 2021
Pollination	Compatible	-	-	Butler et al., 2013
Primary productivity	Plant uptake may improve silica buffering in the restored marsh.	Plant growth oxygenates marsh soils and may therefore inhibit denitrification and water quality improvement .	-	Calvo-Cubero et al., 2014
	'Phosphate trapping, nitrate removal, sediment trapping and toxicant removal were positively correlated with plant height, leaf traits and root-to-shoot mass ratio'.	-	-	Chatanga et al., 2020
Recreational and commercial fisheries	Compatible	-	-	Butler et al., 2013
	'In 2010–11, the total fish production of the wetland was 104.04 tons, but the production declined to 61.25 tons marking a huge reduction of 41.1% in fish landing in 2017–18…'.	-	Rainfall	Sarkar et al., 2021
Sediment trapping	'As such, the nutrient and trace metal retention and assimilative capacity of these alluvial systems are primarily dictated by the sediment types and accretion rates…'.	-	Sediment type Accretion rate Sediment supply Type of wetland Hydrogeomorphic conditions Vegetation characteristics	Wiener et al., 2022
Water storage	Reduced sedimentation (as a result of erosion) results in greater water storage volume of wetlands.	-	-	Daniel et al., 2015

Ecosystem service outcomes from restoration of coastal wetlands in the Great Barrier Reef

In the GBR catchment area, the number of natural and near-natural wetland published studies has steadily increased over the past few years. This gradual increase in the number of studies has been supported by funding through the National Environmental Science Programme (NESP) Tropical Water Quality Hub (Australian Government) but also through other initiatives with the Queensland Government (e.g., Land Restoration Fund). The extent of studies and information now available has been important in providing a foundation to begin to influence policy and management strategies with the most noteworthy being the Queensland Government's Catchment and Wetland Strategy 2016-2021 (which is currently being updated).

In reviewing the evidence here, hydrology is important for water quality improvement (processing of nutrients and pesticides and capture of sediments), with a high residence time translating into higher nutrient and pesticide removal efficacy (depending on the chemical properties of the pesticide). For aquatic species, weed removal without a regular maintenance program generally leads to excessive overgrowth and thereby poor habitat quality, and in extreme cases, fish kills (Abbott et al., 2020). Part of this weed overgrowth is because of nutrients from the catchment, but also the amount of freshwater that is released onto lower floodplains, creating pressure on the palustrine areas in terms of freshwater weeds and poor water quality conditions.

With the advent of Reef Credits, blue carbon credits, and more recently the Australian Government's Nature Repair Plan (DCCEEW, 2022), there exist opportunities in the GBR coastal area for blue carbon projects – either through engineering wetlands designed to intercept and process available nutrients and sediments, or removing earth walls, allowing tidal waters to ingress which could potentially generate blue carbon credits (these low-lying areas would transition to mangrove and saltmarsh areas which sequester carbon). However, even transitioning ponded pasture areas (earth walls built to restrict tidal water ingress and expand cattle grazing) to blue carbon ecosystems (e.g., tidal marshes or mangrove ecosystems) can result in nitrous oxide and methane reduction (Jenkins et al., 2010). There is also a call for caution to consider carefully removing or modifying earth walls or tidal restrictions built for ponded pasture wetlands which are used for cattle grazing, which in some places effectively provide some of the last remaining freshwater ecosystems (Abbott et al., 2020). In addition, the assumption is that once the tidal wall is breached marine vegetation (including supratidal species like *Melaleuca*) will colonise and provide carbon sequestration abatement.

Coastal wetlands in the GBR have been exposed to a range of invasive species, from freshwater fish to aquatic plants. The introduction of these species has been generally considered a major challenge for landholders, communities, industry and government. Efforts to control invasive species have been attempted but with little success in limiting the spread of species. The most obvious and widespread invasive species in the GBR catchment area are freshwater aquatic weeds that continue to reduce many wetland services on GBR floodplains. Some examples of these negative impacts include increased restrictions in hydrology, poor water quality and reduced habitat opportunities (Abbott et al., 2020).

The Clean Energy Regulator (Australian Government) prepared a Blue Carbon method to activate market mechanisms for industry and investment schemes to fund the restoration of coastal wetlands, including mangroves and tidal marshes for their greenhouse gas (GHG) mitigation services (Clean Energy Regulator, 2021). The method focuses on tidal re-introduction via a managed realignment of earthen bund walls, tidal control devices or their total removal, with Australian Carbon Credit Units awarded for GHG abatement with coastal wetland restoration. However, there are barriers to the success of blue carbon projects. For example, project developers need to be cognizant of catchment hydrology where wet years might limit tidal ingress (Abbott et al., 2020; Fennessy et al., 2019). However, whether laws permit reflooding, understanding who owns the rights to carbon, along with the liabilities for potential impacts on adjacent land and biota, requires more research.

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

This synthesis is the first systematic review of the data and learnings of GBR ecosystem services associated with natural and near-natural wetland and their restoration since the 2017 SCS.

- Since the 2017 SCS, research efforts have followed a values-based approach, which has been developed by the Queensland Government to recognise the components and processes of wetland systems where restoration or engineering efforts have occurred.
- While the ecosystem services provided by wetlands are vast and provide immense tangible and intangible value, further research efforts are required within the GBR catchment area to quantify the vast array of services these vital ecosystems provide.

Since 2016, the range of studies investigating the ecosystem services provided by natural, near-natural and restored wetlands in the GBR catchment area have included: water treatment efficacy and nutrient cycling in natural and near-natural wetlands (Adame et al., 2019b; Adame et al., 2021) and fish biodiversity and water quality in restored wetlands (Abbott et al., 2020). These studies have followed a values-based approach (a framework developed by the Queensland Government) focusing on understanding and evaluating the components, processes, and threats to then provide solutions for wetland protection or restoration. This approach is important and has shown that more desirable outcomes are possible for the beneficiaries (user groups or sectors), which has the added advantage of reducing pervasive and maintenance-intensive outcomes. This approach must also consider long-term funding arrangements for maintenance, without which, there is a high likelihood that the restoration site will return to a degraded state.

4.1.3 Key conclusions

- Natural and near-natural wetlands in the GBR catchment include lacustrine (e.g., lakes), palustrine (e.g., vegetated swamps, billabongs), estuarine, and riverine wetlands. These wetlands support many ecosystem services including regulating services such as improved water quality and carbon sequestration, supporting services such as nutrient cycling and habitat provision, cultural services such as aesthetics and recreation, and provisioning services including food, water and other resources. However, these services are under threat in response to expansion of coastal agriculture development, as well as urban and industrial expansion.
- This synthesis identified a small number of research studies in the GBR catchment area compared to studies on natural and near-natural wetland from overseas, with most studies from the USA (35%), China (11%), South America (11%), and Australia (10%). Most studies have focused on estuarine settings (32%), 22% on riverine systems, 12% on palustrine/lacustrine, 17% investigated a combination of habitats, whilst 17% were from unidentified settings.
- In tropical/subtropical wetlands, stressors that contribute to poor wetland water quality can impact the ecosystem services wetlands provide. For instance, connectivity and hydrology have an important role in protecting water quality and other wetland ecosystem services; disruption to connectivity or hydrology can change water chemistry with flow on effects to aquatic organisms (e.g., fish kills).
- In GBR coastal and floodplain areas where historical wetland losses are high, the capacity of the remaining wetlands to process the volume of pollutants they receive is likely to be reduced. Therefore, restoration efforts and engineering interventions may be required to increase the water quality improvement efficiency, and the associated delivery of associated ecosystem services, for the wetlands remaining within the GBR catchment area.
- Trade-offs between water quality improvement and other services in natural and near-natural wetlands can include instances where hydrology or connectivity are affected. For example, seasonal wetland flooding has been found to result in greater connectivity among wetlands, micro-habitat creation, enhanced nutrient dynamics and carbon storage, flood protection, freshwater provision, and improved local water quality, but may lead to less favourable conditions for agricultural production.
- While wetlands can be restored to enhance water quality conditions, the maintenance following restoration works or intervention activities is critical. Without a long-term maintenance plan and a mechanism to fund these works, restoration sites have a high chance of returning to a degraded state.
- Mangroves, saltmarshes, and other floodplain native vegetation communities provide coastal protection, sequester carbon, and process nutrients that help to improve water quality.

However, a limited number of studies have indicated that natural and near-natural wetlands have a wide-ranging capacity for both pollutant export and retention. While the international literature shows that the ecosystem services provided by wetlands are considerable, more research is needed to quantify these ecosystem services (e.g., environmental, economic, and social value) within the GBR catchment area.

- The Queensland Government has developed a values-based framework for the restoration, rehabilitation, and protection of coastal wetlands. This framework focuses on the components and processes in wetlands that maximise restoration success and ecosystem services for beneficiaries (user groups such as tourism, fishing, recreational and cultural). A whole-of-system approach is required so that the interconnected components and processes of the wetland systems, and landscape more broadly, are examined and understood, and management approaches are aligned with restoration goals.
- Ongoing monitoring and evaluation of restored, natural, and near-natural wetlands in the GBR catchment area is required to better understand the potential impacts of restoration actions on wetland values, water quality, and other ecosystem services. The Queensland Government is currently developing frameworks designed to provide managers with a tool to consistently examine and evaluate restoration projects in Queensland.
- Inclusion of all beneficiaries in a co-design process early in the project cycle (design, implementation, and maintenance) is important for defining and achieving ecosystem service goals. The potential implications of future climate change projections, such as sea level rise and more severe weather events (e.g., cyclones), for wetland treatment and restoration projects must also be considered.
- There is a need for policies and planning to achieve long-term protection and conservation of the remaining natural and near-natural wetlands in the GBR catchment area.

4.1.4 Significance of findings for policy, management, and practice

The natural and near-natural wetlands in the GBR catchment area are unique and hold incredible value. With the expansion of coastal agriculture and development, these same wetlands are under pressure to continue providing these services into the future. In the past five years, there has been considerable investment of time (staff) and resources (funding for studies) to understand the components and processes of wetlands. There has been a concerted effort to align the goods and services that wetlands provide with government policy – for example the recognition of the contribution of wetlands to reef resilience and ecosystem health in the Reef 2050 Long Term Sustainability Plan, in addition to a GBR Wetlands Network (consisting of members from NRM groups, government, industry, universities, community, Indigenous groups) and community of practice groups (e.g., Treatment Wetlands). These resources are critical in the sharing of knowledge, data and training of practitioners.

4.1.5 Uncertainties and/or limitations of the evidence

- Ongoing monitoring and evaluation are not undertaken in natural and near-natural wetlands prior to, or following, completion of the restoration project or activity. This is challenging as the success of restoration activities (i.e., achieving and sustaining restoration goals) might not be fully known or understood, to help inform future projects (lessons learned). Long-term monitoring of water quality conditions is supported in the GBR, as part of the Marine Monitoring Program where water quality samples are routinely collected and reported via various reporting outlets. A comparable level of monitoring is needed for coastal wetlands.
- The number of research studies on ecosystem services in natural and near-natural wetlands (using the definition that has been applied in this review) is small in the GBR catchment area compared to the quantity of studies elsewhere in Australia and overseas.
- Processes that facilitate more co-design and inclusion of a range of stakeholders in the development and implementation of restoration projects so that the goals reflect all beneficiaries are needed. This will also address some of the uncertainties that exist around assessing the full impacts of restoration projects on wetland values and ecosystem services.

- There is a high level of uncertainty in the understanding of the efficacy of natural and near-natural wetlands in the GBR to improve water quality. This could be addressed through the development of a water quality model that links pollutant removal efficacy back to the ecosystem services agreed to by the beneficiaries. Several studies are available, but more investment is required when considering the potential role wetlands have in improving water quality (based on overseas examples).
- More detailed studies overcoming these limitations (e.g., sampling in a single wet/dry season) are needed to reduce the substantial variation observed in how effective wetlands are in removing contaminants.

4.2 Contextual variables influencing outcomes

A summary of the contextual variables that are influencing the question outcome or relationship in Question 4.9 is outlined in Table 11.

Table 11. Summary of contextual variables for Question 4.9.

Contextual variables	Influence on question outcome or relationships
Climate change	In a seasonally open floodplain in West Bengal, India, climate change has been found to reduce the average water depth (74.3%), increase nitrate concentrations (44.4%), reduce the floodplain area (77.7%), result in macrophyte infestation (80%), declines in plankton diversity (54%), macro-zoobenthos diversity (31%), fish diversity (22.8%), and fish production (Sarkar et al., 2021). Moreover, the associated changes in rainfall, temperature, evapotranspiration and surface radiation have been found to impact the water conservation function of wetlands (Hu et al., 2020). Climate change and the resulting changes in ground cover, and land management, will also have flow-on implications for catchment runoff loads of sediment, nutrients, and pesticides to the GBR. These future changes are unknown but require resources and planning. What is also expected is that, in low-lying areas along the GBR coast, sea level rise is projected to flood coastal habitats, such as forested wetlands, and agricultural land. Sea level rise may result in the landward expansion of mangrove and saltmarsh vegetation by providing habitat through sediment accumulation, which in turn increases local biodiversity, sequestering carbon and providing coastal protection. However, rates of sea level rise may be so rapid that, if not properly managed, coastal forested wetlands and the carbon stored in their soils and biomass may be at risk (Aguilos et al., 2021).
Climate variability	The IPCC Sixth Assessment Report finds that storm activity, extreme weather and heavy precipitation events are projected to increase in frequency and severity in the future, as a result of climate change. The increased frequency and severity of such activity will likely result in more catchment runoff of nutrients and sediments that could be channelled through wetlands for treatment. Whether the existing network of wetlands (in terms of hydrology) is appropriate to sufficiently process catchment nutrient and sediment loads (see Question 4.7, Waltham et al., this SCS) under future climate projections is unknown.
Hydrology	Hydrology in natural and near-natural wetlands is an important attribute to understand and examine in any ecosystem service project particularly given the link between improved hydrology and water quality conditions in wetlands (Canales-Delgadillo et al., 2019; Fennessy et al., 2019; Kaplan et al., 2015). Without this understanding, the water quality data context is difficult to impossible to comprehend. Many studies have included at least some hydrological data, but many do not. An example of a detailed hydrological and water quality study in the GBR catchment area used auto-samplers on the inlet and outlet to the wetland, collecting water samples across the hydrograph. This approach is complex to set up, but generates a time/flow weight understanding of water quality across the entire hydrograph period (McJannet et al., 2012). Hence,

Contextual variables	Influence on question outcome or relationships
	sampling method is also critical, as grab samples will generally miss the first flow and peak flow stage, which are necessary in developing event mean concentrations. Examining all water source inputs into wetlands is also critical. The most obvious is groundwater, which can be a persistent source of nutrients into wetlands, and is generally overlooked in many studies and models (Wadnerkar et al., 2021).
Sediment	Sedimentation and sediment transport can be affected by multiple variables within a catchment – such as land use and storm activity. However, the role of sediment within a wetland can influence the ecosystem services provided by natural, near-natural and restored wetlands. Sedimentation can elevate the wetland and thereby help with resilience to sea level rise (moderating inundation) as well as support conditions that favour denitrification (Velinsky et al., 2017) and coastal protection (Duncan et al., 2016), but can negatively impact habitat availability for some taxa (Beas & Smith, 2014). Sedimentation can affect the temperature, depth, and hydrology of a wetland, as well as the adsorption of pollutants – affecting water quality. Sediment composition and geomorphic setting can lead to among-site variability in ecosystem service provision by wetlands (Stringer et al., 2016).
Invasive species	Presently, most natural or near-natural wetlands along the GBR coastline have either invasive aquatic weed or fish species which is causing major challenges on native flora and fauna. Invasive aquatic plants in wetlands can also present a water quality problem as they can alter dissolved oxygen conditions when in excessive amounts for example (Abbott et al., 2020). The invasive plant *Spartina alterniflora* has also been found to influence soil-based nitrogen removal, causing significant increases in soil nitrogen removal within the upper 50 cm of the soil profile, but with comparably lower soil nitrogen removal throughout the entire soil profile relative to native plant species (Li et al., 2020).
Mainte-nance	The maintenance in terms of removing weeds, sediment accumulation, rubbish, and invasive species is critical for protection or enhancement of agreed ecosystem services of natural and near-natural wetlands (Abbott et al., 2020; Kesavan et al., 2021). Without a long-term plan of maintenance that includes future work costs, protection of wetland habitats will inevitably be compromised. For any wetland project, either the construction of treatment wetlands or the restoration of natural or near-natural settings, a long-term maintenance plan is critical.
Cost effective-ness	The costs to undertake and maintain restoration efforts in natural and near-natural wetlands is not generally known (this topic has been investigated in a companion synthesis – Question 4.8, Star et al., this SCS). There is a need for budget provision for maintenance of wetland restoration, which could be defined under one of several models, e.g., a consortium funding model, or through market mechanisms that provide an additional source of income to land holders. However, the cost of project development, engineering works and maintenance require consideration in the project development.
Acid sulfate soils	Whilst acid sulfate soils were not covered in great depth within the body of evidence, it is important to highlight that the drainage of wetlands for urban development and agriculture can disturb and/or create ideal conditions for the development of acid sulfate soils. Moreover, the re-wetting of wetlands containing acid sulfate soils (e.g., as a wetland restoration initiative), can potentially lead to large-scale sulfuric acid generation and runoff, compromising wetland ecosystem service provision (Luke et al. 2017). The sulfuric acid in these soils can leach into groundwater and urban drainage systems, compromising potable water quality. Acid soils and drainage water can negatively impact local wildlife - reducing biodiversity, reducing fisheries and agricultural production, as well as damaging infrastructure.

4.3 Evidence appraisal

Relevance

The relevance of the overall body of evidence was Moderate (6/9). The relevance of the body of evidence to the question, spatial and temporal relevance were each rated as Moderate, scoring 2.2, 2.1, and 1.6 out of 3 respectively. Of the 125 articles included in the synthesis of Question 4.9, 43 were rated High for relevance to the question, 65 were ranked as Moderate and 17 as Low. Approximately 26% (32 of 125) of studies included in the review were rated High for spatial relevance, ~60% (75 of 125) were rated as Moderate and ~14% (18 of 125) were rated as Low. For temporal relevance, 20 studies (16%) were ranked as High, 41 studies as Moderate (33%) and 64 studies as Low (51%). Overall, the content and approach of several studies were of Moderate to High relevance in answering Question 4.9 and had Low to Moderate spatial and temporal applicability. Within the body of evidence, the reduced spatial and temporal applicability is due to the high volume of modelling, theoretical, and review studies, which might be considered to generate information on ecosystem services but may not generate results that are representative of a wide range of spatial or temporal situations.

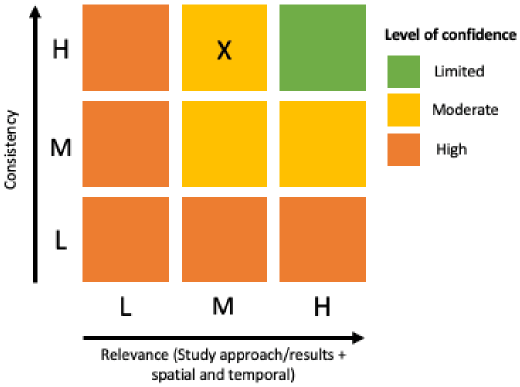
Consistency, Quantity and Diversity

Due to the limited number of studies conducted within the GBR catchment area (5 of 125 studies), the literature search was expanded to include studies conducted within tropical and subtropical climates globally. Of the 125 studies, 30.5% were observational, 18.5% were modelling and 16% were theoretical/conceptual. The high number of modelled or theoretical studies may impose some limitations regarding the application of results to ‘in-field’ contexts but help to inform elements of the question (i.e., ‘*What role do natural/near-natural wetlands play in the provision of ecosystem services?*’). Thirty-one percent of studies (n = 38) within the body of evidence are based on field-collected data and are therefore of greater relevance to Question 4.9. Despite the high proportion of theoretical and modelling studies within the body of evidence, the diversity and consistency of the body of evidence were rated as High, due to the number and variety of studies included, and the level of agreement of findings among them (see Table 1 and Appendix 2).

Confidence

Due to the Moderate relevance and High consistency and diversity of the studies included, the overall confidence within the body of evidence is Moderate (Table 12).

Table 12. Summary of results for the evidence appraisal of the whole body of evidence in addressing the Question 4.9. 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	
-To the Question	Moderate	
-Spatial (if relevant)	Moderate	
-Temporal (if relevant)	Moderate	
Consistency	High	
Quantity	High (125 studies)	
Diversity	High (31% observational, 18% modelled, 18% reviews, 14% theoretical, 12% experimental and 2% conceptual)	

4.4 Indigenous engagement/participation within the body of evidence

As part of the formal methods for this review, the number of studies that had Indigenous engagement was also examined. The inclusion of Indigenous groups in the design of wetland monitoring and restoration of these important ecosystems is becoming increasingly recognised in ensuring projects fulfil broad objectives and expectations (Saunders et al., 2022). In this review, approx. 4% of evidence items featured Traditional Owner participation. These included:

- Huxham et al. (2015) - Applying Climate Compatible Development and economic valuation to coastal management: A case study of Kenya's mangrove forests.
- Gandarillas et al. (2016) - Assessing the services of high mountain wetlands in tropical Andes: A case study of Caripe wetlands at Bolivian Altiplano.
- Thompson and Friess (2019) - Stakeholder preferences for payments for ecosystem services (PES) versus other environmental management approaches for mangrove forests.
- Abbott et al. (2020) - Bund removal to re-establish tidal flow, remove aquatic weeds and restore coastal wetland services—North Queensland, Australia.
- Davids et al. (2021) - Civic ecology uplifts low-income communities, improves ecosystem services and well-being, and strengthens social cohesion.

4.5 Knowledge gaps

A summary of the proposed knowledge gaps is outlined in Table 13.

Table 13. Summary of knowledge gaps for Question 4.9.

Gap in knowledge (based on what is presented in Section 4.1)	Possible research or Monitoring & Evaluation (M&E) question to be addressed	Potential outcome or Impact for management if addressed
Biodiversity in natural and near-natural wetlands.	Studies examining fish and crustaceans in coastal wetlands are available, but studies examining other organisms are limited. For example, reptiles, vegetation, migratory birds etc.	Understanding the full extent of flora and fauna species in wetlands would provide important data and baseline information for sites which could be useful for nature repair restoration efforts.
Water quality conditions over different hydrograph flow events.	What is the shape of the nutrient and sediment concentration graph for different land uses and sized rainfall events in natural and near-natural wetlands?	These data would assist the design of restoration efforts and examining the water quality efficacy of wetlands of different types.
Invasive species	What is the current distribution of invasive species in natural and near-natural wetlands in the GBR catchment area? What is the future risk of species range increases under different climate conditions? What is the risk of new invasive species showing up in GBR wetlands?	Surveillance monitoring for new invasive species would provide early warning detection and allow authorities to respond quickly to the new threat. Scientific studies on the impact that these invasive species present to native species would also allow managers to respond accordingly to range expansion and increasing numbers of invasive species.
Climate change with respect to changing rainfall and flow through natural and near-natural wetlands	What is the response of wetland ecosystem services under more variable hydrology (i.e., increase erosion susceptibility or sedimentation accumulation).	Understanding the sediment characteristics, processes, and dynamics in wetlands (levels of sediment accretion). These data would assist with informing maintenance needs in the wetlands and impacts of climate change.

5. Evidence Statement

The synthesis of the evidence for **Question 4.9** was based on 125 studies, primarily undertaken outside of the Great Barrier Reef, and published between 1990 and 2022. The synthesis includes a *High* diversity of study types (31% observational, 18% modelled, 18% reviews, 14% theoretical, 12% experimental and 2% conceptual), and has a *Moderate* confidence rating (based on *High* consistency and *Moderate* overall relevance of studies).

Summary of findings relevant to policy or management action

Natural and near-natural wetlands in the Great Barrier Reef catchment include lacustrine (e.g., lakes), palustrine (e.g., vegetated swamps, billabongs), estuarine, and riverine wetlands. These wetlands support many ecosystem services including regulating services such as improved water quality and carbon sequestration, supporting services such as nutrient cycling and habitat provision, cultural services such as aesthetics and recreation, and provisioning services including food, water and other resources. However, these services are under threat in response to expansion of coastal agriculture development, as well as urban and industrial expansion. In tropical/subtropical wetlands, stressors that compromise wetland water quality can impact the ecosystem services that wetlands provide. For instance, connectivity and hydrology have an important role in protecting water quality and other wetland ecosystem services; disruption to connectivity or hydrology can change water chemistry with flow on effects to aquatic organisms (e.g., fish kills). In Great Barrier Reef coastal and floodplain areas where historical wetland losses are high, the capacity of the remaining wetlands to process the volume of pollutants they receive is likely to be reduced. Therefore, restoration efforts and engineering interventions may be required to increase the water quality improvement efficiency, and the associated delivery of associated ecosystem services, for the wetlands remaining within the Great Barrier Reef catchment area. While wetlands can be restored to enhance water quality conditions, the maintenance following restoration works or intervention activities is critical. Without a long-term maintenance plan and a mechanism to fund these works, restoration sites have a high chance of returning to a degraded state. Wetland risk mitigation presents the greatest opportunity to enhance and protect the range of wetland ecosystem services provided within the Great Barrier Reef catchment. Although there is considerable research and management interest, greater commitment is needed to fund monitoring and evaluation of restoration works, as well as for maintenance. There is also a need for policies and planning to achieve long-term protection and conservation of the remaining natural and near-natural wetlands in the Great Barrier Reef catchment area.

Supporting points

- This synthesis identified a small number of research studies in the Great Barrier Reef catchment area compared to studies on natural and near-natural wetland from overseas, with most studies from the USA (35%), China (11%), South America (11%), and Australia (10%). Most studies have focused on estuarine settings (32%), 22% on riverine systems, 12% on palustrine/lacustrine, 17% investigated a combination of habitats, whilst 17% were from unidentified settings.
- Since 2016, studies investigating the ecosystem services provided by natural, near-natural, and restored wetlands in the Great Barrier Reef catchment area have included assessment of water treatment efficacy and nutrient processing, fish biodiversity and water quality in restored wetlands, in addition to carbon storage potential and avoided greenhouse emissions. Water quality in wetlands underpins many co-benefits, such as biodiversity and the ecosystem services that result from diverse populations of flora and fauna (e.g., fish, plankton, and macroinvertebrates), including increased food and habitat for birds, and greater potential for recreation such as bird watching, wetland aesthetics and fishing.
- Mangroves, saltmarshes, and other floodplain native vegetation communities provide coastal protection, sequester carbon, and process nutrients that help to improve water quality. However, a limited number of studies have indicated that natural and near-natural wetlands have a wide-ranging capacity for both pollutant export and retention. While the international literature shows that the ecosystem services provided by wetlands are considerable, more

research is needed to quantify these ecosystem services (e.g., environmental, economic, and social value) within the Great Barrier Reef catchment area.

- Trade-offs between water quality improvement and other services in natural and near-natural wetlands can include instances where hydrology or connectivity are affected. For example, seasonal wetland flooding has been found to result in greater connectivity among wetlands, micro-habitat creation, enhanced nutrient dynamics and carbon storage, flood protection, freshwater provision, and improved local water quality, but may lead to less favourable conditions for agricultural production.
- The Queensland Government has developed a values-based framework for the restoration, rehabilitation, and protection of coastal wetlands. This framework focuses on the components and processes in wetlands that maximise restoration success and ecosystem services for beneficiaries (user groups such as tourism, fishing, recreational and cultural). A whole-of-system approach is required so that the interconnected components and processes of the wetland systems, and landscape more broadly, are examined and understood, and management approaches are aligned with restoration goals.
- Ongoing monitoring and evaluation of restored, natural, and near-natural wetlands in the Great Barrier Reef catchment area is required to better understand the potential impacts of restoration actions on wetland values, water quality, and other ecosystem services. The Queensland Government is currently developing frameworks designed to provide managers with a tool to consistently examine and evaluate restoration projects in Queensland.
- Inclusion of all beneficiaries in a co-design process early in the project cycle (design, implementation, and maintenance) is important for defining and achieving ecosystem service goals. The potential implications of future climate change projections, such as sea level rise and more severe weather events (e.g., cyclones), for wetland treatment and restoration projects must also be considered.

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 4.9

Theme 4: Dissolved nutrients – catchment to reef

Question 4.9 What role do natural/near-natural wetlands play in the provision of ecosystem services and how is the service of water quality treatment compatible or at odds with other services (e.g., habitat, carbon sequestration)?

Author Team

Name	Organisation	Expertise	Role in addressing the Question	Sections/Topics involved
1. Nathan Waltham	Centre for Tropical Water and Aquatic Ecosystem Research	Aquatic ecology, Environmental management, Wetland restoration	Lead Author	All Sections
2. Catherine Lovelock	University of Queensland	Mangroves, blue carbon science and policy	Contributor	All Sections
3. Fernanda Adame	Australian Rivers Institute, Griffith University	Blue carbon, water quality processes, restoration ecology	Contributor	All Sections
4. Katie Motson	Centre for Tropical Water and Aquatic Ecosystem Research	Aquatic ecology, landscape and climate change ecology	Contributor	All Sections

Appendix 2: Ecosystem services identified in Question 4.9 body of evidence

Ecosystem Service:	Count
Aesthetics	2
Agricultural	4
Biochemical products	1
Biodiversity	**56**
Biogeochemical cycling	1
Biotic interactions	1
Carbon sequestration	**73**
Climate regulation	5
Coastal protection	5
Community value	1
Cultural	6
Development	4
Education	3
Endangered species habitat	1
Erosion control	5
Fish	1
Flood mitigation	14
Food provision	25
Freshwater use	1
Gas flux	2
Genetic materials	1
Groundwater	1
Habitat provision	14
Hazard reduction	1
Hydrology	8
Invasive species control	2
Land clearing	4
Land reclamation	1
Medicine	1
Mental health	1
Nutrient cycling	**44**
Pest & Disease Control	1
Photosynthesis	1
Pollination	2
Public health	2
Raw materials	8
Recreation	7
Safety	1
Sediment trapping	1
Sedimentation	5
Shelter	1
Shoreline protection	2
Soil carbon loss	2
Soil fertility	1
Soil formation	1
Spirituality	2
Tourism	2
Vegetation	4
Water cycle	2
Water provision	8
Water quality	**70**
Water storage	2
Wood fuel	3
Total	**417**

Appendix 3: Wetland ecosystem services identified in Waltham et al. (2021)[8]

Table 1. Final ecosystem services estimated to be provided by wetlands created as part of the Riversdale-Murray Scheme. Class and codes are from the Common International Classification of Ecosystem Services (Haines-Young and Potschin, 2012). Pedigree scores indicate confidence in service provision estimates, ranging from 1 (low confidence) to 4 (total confidence), in line with those proposed by Costanza et al. (1992).

Section	Class	Code	Application in Riversdale-Murray scheme	Pedigree
Provisioning (Biotic)	Wild plants (terrestrial and aquatic, including fungi, algae) used for nutrition	1.1.5.1	Indigenous community harvest (purpose unknown) observed by some farmers and relayed to us in person	1
	Fibres and other materials from wild plants for direct use or processing (excluding genetic materials)	1.1.5.2	Indigenous community harvest (purpose unknown) observed by some farmers and relayed to us in person	1
	Wild animals (terrestrial and aquatic) used for nutritional purposes	1.1.6.1	Farmers and their family reported fishing in lagoons in interviews. Indigenous community harvest (purpose unknown) observed by some farmers and relayed to us in person and in interviews	4
	Fibres and other materials from wild animals for direct use or processing (excluding genetic materials)	1.1.6.2	Indigenous community harvest (purpose unknown) observed by some farmers and relayed to us in person. Potential could include crocodile hide	1
Regulation & Maintenance (Biotic)	Visual screening.	2.1.2.3	Farmers mentioned (in person) trees from wetland riparian screening unsightly land.	2
	Control of erosion rates	2.2.1.1	Riparian vegetation may be reducing bank erosion	1
	Hydrological cycle and water flow regulation (Including flood control, and coastal protection)	2.2.1.3	Change in farm inundation frequency observed in Appendix A2.5 Drainage, and hydrological modelling changes modelled and published by Karim et al (2012)	3
	Wind protection	2.2.1.4	Tall Eucalyptus trees were observed in the riparian vegetation at some lagoon, and these may be protecting crops from wind, though yet to be quantified	1
	Pollination (or 'gamete' dispersal in a marine context)	2.2.2.1	Wetland riparian vegetation may be supporting insect vectors that assist crop pollination. Not quantified.	1
	Maintaining nursery populations and habitats (Including gene pool protection)	2.2.2.3	Field surveys caught Barramundi across many wetlands of various sizes, indicating habitat support (Godfrey et al. 2016; Appendix A2.3 Fisheries provision)	3

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[8] Waltham, N.J., Canning, A., Smart, J.C.R., Hasan, S., Curwen, G. and Butler, B. (2021) Financial incentive schemes to fund wetland restoration across the GBR catchment: Learning from the Riversdale-Murray Scheme and other schemes. Report to the National Environmental Science Program. Reef and Rainforest Research Centre Limited, Cairns (97pp.).

Section	Class	Code	Application in Riversdale-Murray scheme	Pedigree
	Regulation of the chemical condition of freshwaters by living processes	2.2.5.1	The wetlands likely provide some level of nutrient and sediment removal. Indirect estimates of *potential* denitrification rates in ideal conditions (likely over-estimating actual rates) are provided in Appendix A2.4.	2
	Regulation of chemical composition of atmosphere and oceans	2.2.6.1	The wetlands will likely store carbon in deposited sediments and riparian vegetation. This is not quantified.	1
	Regulation of temperature and humidity, including ventilation and transpiration	2.2.6.2	Open water and forested vegetation typically have a much lower albedo than crops and soil, which is likely to reduce ambient temperature. Wetlands can also increase humidity as retained water evaporates. The specific effect of this from these wetlands has not been quantified.	1
Cultural (Biotic)	Characteristics of living systems that that enable activities promoting health, recuperation or enjoyment through active or immersive interactions	3.1.1.1	Multiple farmers have mentioned using the wetlands for fishing, kayaking, boating, skiing and walking in person and in interviews.	3
	Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through passive or observational interactions	3.1.1.2	Multiple farmers have mentioned visiting wetlands to enjoy the nature and to relax. They also mentioned personal satisfaction from completing the restoration.	3
	Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge	3.1.2.1	Several scientific papers have arisen from examining these wetlands (Pearson et al. 2013; Godfrey et al. 2016; Karim et al. 2012).	4
	Characteristics of living systems that enable education and training	3.1.2.2	Farmers have gained considerable knowledge from restoring and observing these wetlands.	2
	Characteristics of living systems that are resonant in terms of culture or heritage	3.1.2.3	Indigenous people have been observed collecting from the lagoons, and this may resonate with their heritage/culture.	1
	Characteristics of living systems that enable aesthetic experiences	3.1.2.4	Numerous farmers have mentioned in person and in interviews the pleasure they get from wetlands improving farm aesthetics.	3
	Characteristics or features of living systems that have an existence value	3.2.2.1	The wetlands support a diverse array of freshwater fish (Pearson et al. 2013; Appendix A2.2 Fish biodiversity).	3
	Characteristics or features of living systems that have an option or bequest value	3.2.2.2	Farmers mentioned during visits and in interviews the satisfaction they get from providing a resource for their grandchildren to enjoy in the future.	3
Provisioning (Abiotic)	Surface water used as a material (non-drinking purposes)	4.2.1.2	Some farmers have used stored water for irrigation. The extent to which this occurs has not been quantified.	1