INTEGRATED COASTAL AND MARINE WATER QUALITY:

Research and development priorities for solutions to reduce land-based sources of pollution affecting coral reefs (and other coastal habitats)

CORDAP R&D TECHONOLOGY ROADMAP

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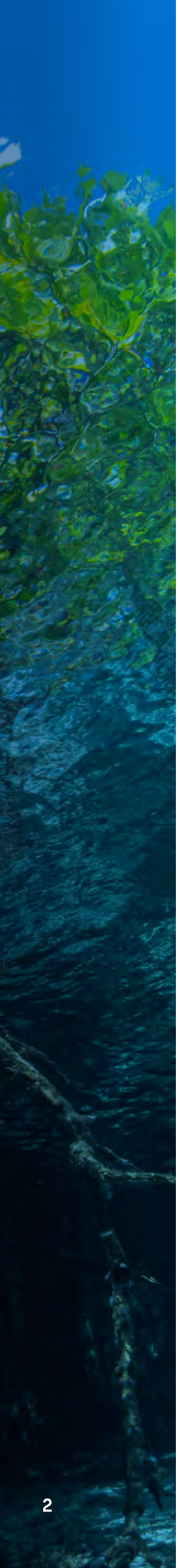
The University Of Queensland Australia
Cefas
Wildlife Conservation Society
The Nature Conservancy



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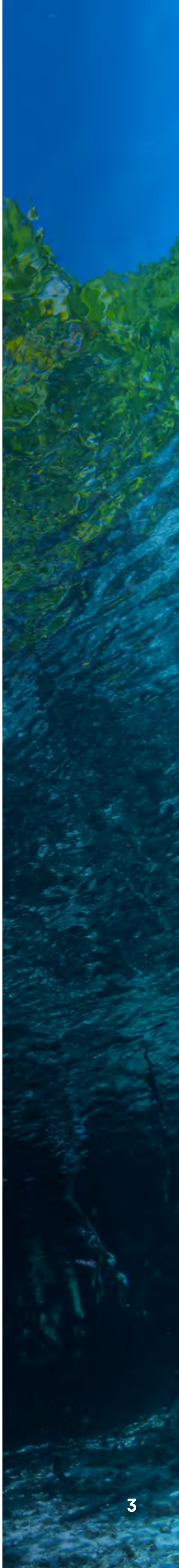

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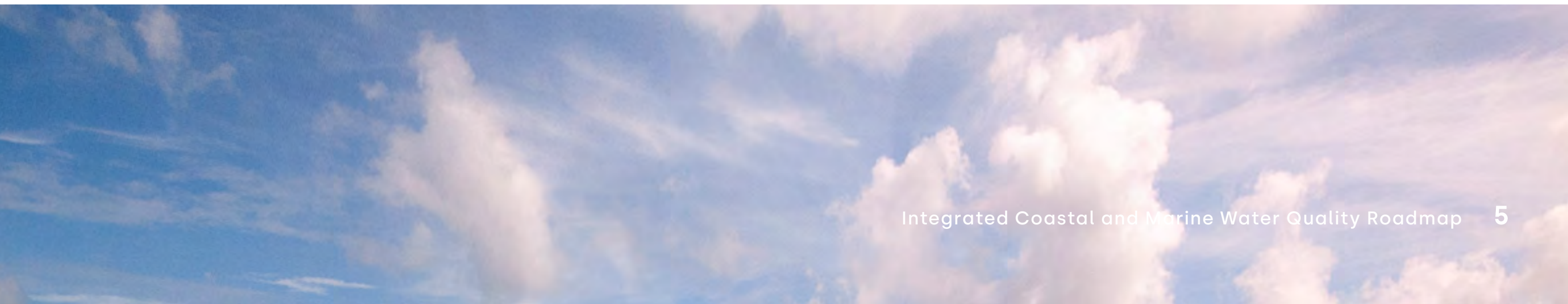


Photo Katerina Katopis / Ocean Image Bank

Abbreviations

AI: Artificial Intelligence

BACI: Before–After–Control–Intervention

CCWG: Cesspool Conversion Working Group

CORDAP: G20 Coral Research & Development Accelerator Platform

DPSIR: Drivers–Pressures–State–Impact–Response

FAO: Food and Agriculture Organization of the United Nations

LMIC: Low- and Middle-Income Countries

MPA: Marine Protected Area

MRV: Monitoring, Reporting, and Verification

NAP: National Action Plan

NbS: Nature-based Solutions

NBSAPs: National Biodiversity Strategy and Action Plans

NDC: Nationally-Determined Contributions

NGO: Non-Government Organisation

NP-GAN: Nutrient Pollution Global Action Network

O&M: Operations and Maintenance

R&D: Research and Development

SAC: Scientific Advisory Committee

SIDS: Small Island Developing States

SMP: Spatial Management Prioritisation

UN: United Nations

WASH: Water, Sanitation, and Hygiene

WQIP: Water Quality Improvement Plan

WWTP: Wastewater Treatment Plant

Photo Jona Uluinaceva

Scope of work

Improving water quality is one of the most actionable local-to-regional interventions available to strengthen coral reef resilience under climate change. The Integrated Coastal and Marine Water Quality Roadmap was developed through a collaborative, multi-stakeholder process to identify Research and Development (R&D) priorities for solutions to land-based pollution that threaten coral reef ecosystems. Its overarching goal is the acceleration of innovative science to improve coastal water quality. Reducing land-based pollution through targeted local interventions can create the conditions needed for coral reef recovery, while delivering wider benefits for coastal ecosystems, communities, and fisheries, and strengthening the effectiveness of restoration and protection investments. The scope and prioritisation of this roadmap were informed by the Fiji workshop, which brought together technical experts, practitioners, and regional stakeholders to test assumptions, identify and refine priority areas, and ensure the outputs reflected practical implementation needs.

This roadmap primarily addresses land-based pollution pathways affecting coral reefs, particularly nutrients, sediments, pathogens, organic matter, and selected contaminants linked to sanitation and agricultural activities. Throughout the roadmap, coral reefs are treated as both the primary receiving environment and the benchmark for success, with priority areas focused on reducing land-based pollution at its source, interrupting transport pathways, and strengthening nature-based buffering to deliver measurable improvements in reef water quality at the ecosystem level. The roadmap, therefore, emphasises reef-relevant indicators — such as microbial contamination, nutrient enrichment, turbidity, sedimentation, benthic algal cover, coral disease incidence, coral recruitment, and post-bleaching recovery — to ensure that research and innovation can be evaluated against outcomes that matter for reef persistence and resilience with benefits for reef-dependent communities.

Plastics, industrial effluents, port pollution, oil spills, aquaculture waste, and emerging contaminants are excluded from our discussion and acknowledged as critical future research areas.

1 Executive Summary

Photo Jona Uluinaceva

This roadmap provides a strategic framework for prioritising research and development on water quality solutions that reduce land-based pollution affecting coral reefs and connected coastal habitats. Its purpose is to bring together catchment-to-reef water quality research, identify the most urgent evidence gaps, and link feasible interventions to measurable outcomes.

It is designed to help funders, researchers, governments, and practitioners align investments and implementation efforts by identifying priority research, innovation, and scaling needs, and by establishing the indicators required to demonstrate improvements in coastal water quality and coral reef condition over time. This roadmap is needed now because accelerating climate impacts are narrowing the window for effective local action, and improving water quality remains one of the most practical and scalable opportunities to strengthen coral reef resilience. It provides CORDAP and the wider coral community with a strategic framework for prioritising water quality solutions that can be developed, validated, financed, and scaled to deliver measurable reef outcomes.

This roadmap draws directly from a participatory workshop held in Fiji in October 2025 involving researchers, government agencies, industry, community representatives, and technical experts. The International Water Quality Solutions for Coastal Habitats workshop in Fiji brought together global experts to collaborate on solutions to land-based sources of pollution affecting coastal habitats. Hosted by the Centre for Environment, Fisheries, and Aquaculture Science (Cefas), G20 Coral Research and Development Accelerator Platform (CORDAP), the Wildlife Conservation Society (WCS), and The Nature Conservancy (TNC), the workshop focused on developing innovative approaches to improve water quality for coastal habitats and communities. Key outcomes included the formulation of this CORDAP Technology Roadmap and continued progress on coastal pollution toolkits, both of which support ongoing efforts under the United Nations (UN) Ocean Decade endorsed program “Nutrient Pollution Global Action Network (NP-GAN)” and other international frameworks. This collaborative initiative aims to strengthen water pollution interventions and management by outlining clear R&D priorities and advancing practical solutions across sanitation, agriculture, and nature-based strategies.

This roadmap outlines a practical, research-driven strategy to improve coastal water quality from catchments to coral reefs. Developed through a participatory workshop and expert consultation, it identifies three priority areas (Figure 1) for research, innovation, and investment. The three priority areas are intentionally designed to address different but complementary parts of the catchment-to-reef system: source control through sanitation, source and pathway management across agriculture and land-sea systems, and nature-based interventions that intercept, buffer, and reduce pollutant delivery to reefs.

Roadmap to improve coastal water quality

Priority areas for innovation & investment

1 Improved sanitation to reduce domestic wastewater pollution area

Reducing pathogen, nutrient, and organic loads from sewered and non-sewered sanitation systems in tropical and subtropical contexts that discharge into coastal waters, to prevent eutrophication, reduce disease risk, and reduce pressure on impacted coral reefs and adjacent reef-dependent habitats.

2 Best practice management of agriculture & integrated land-sea systems

Minimising nutrient, sediment, and runoff from agriculture, livestock, and land-based debris pathways that directly impact near-shore coral reefs, improving water quality, reducing algal overgrowth and supporting reef health through catchment-to-coast management.

3 Effective nature-based solutions (NbS) to improve coral reef water quality

Restoring and protecting ecosystems such as wetlands, riparian zones, and mangroves to intercept and filter pollutants before they reach coral reefs, while enhancing coastal ecosystem resilience, reef connectivity, and climate adaptation benefits.

Figure 1. The three R&D priority areas to support solutions to reduce water pollution on coral reefs and within other coastal habitats.

The roadmap serves as both a strategic R&D agenda and a practical coordination framework that links scientific innovation to on-ground implementation, policy mechanisms, and community priorities. The workshop highlighted the urgent need for coordinated R&D efforts linking catchment-scale interventions with coastal ecosystem responses. Across the three priority areas there was a repeated call for the creation of water quality guidelines based on relevant environmental indicators which incorporate ecosystem sensitivity to pollution. These guidelines would support better management and policy recommendations towards a 'safe operating space' for coastal and marine ecosystems.

The collective outputs defined priority themes where targeted R&D could drive practical, scalable improvements in water quality and ecosystem health. Participants emphasised that addressing pollution at the source, interrupting it along the pathway, and mitigating impacts in the receiving environment all require integrated solutions combining technology, targeted monitoring, decision-support guidance, and community engagement. R&D priorities were assessed through a structured process that considered feasibility, potential impact, and cost-effectiveness, with additional attention to scalability and equity where these factors influenced likely uptake and long-term value.

This roadmap delivers a prioritised research agenda and practical framework for action, identifying investment priorities across monitoring, innovation, and knowledge transfer. It places emphasis on co-design with local and Indigenous communities, government authorities, private sector, civil society, and other relevant stakeholders. By advancing and scaling interventions that reduce land-based pollution from catchment to reef, supported by sustainable financing, effective governance, robust monitoring, and community stewardship, this roadmap aims to improve coral reef water quality and resilience at scale.

Photo The Ocean Agency / Ocean Image Bank

1.1. Summary table of priority areas and R&D priorities

Priority area 1

Improved sanitation to reduce domestic wastewater pollution

Mapping and quantifying pollutant loads for coral reef ecosystems

- Develop tools to quantify the wastewater pollution load entering the marine environment;
- Quantify the spatial and ecological impacts of wastewater pollution and the benefits of improved sanitation for coral reefs;
- Quantify the economic costs of wastewater pollution and return on investment of reef protective interventions;
- Advance One Water valuation frameworks to capture system-wide co-benefits, including public health outcomes, ecosystem service benefits, climate adaptation and resilience, and water security. These frameworks take an integrated view of water investments by valuing benefits across environmental, social, health, and economic systems, helping decision-makers compare sanitation, wastewater, and reef-protective interventions on the basis of their wider public value rather than treatment performance alone.

Evidence-based standards and guidelines for coral reef protection

- Develop evidence-based wastewater discharge standards (for sewered and non-sewered sanitation), water quality guidelines, and policy frameworks aligned with coral reef protection goals;
- Incorporate One Water principles into standards and guidelines, ensuring they reflect environmental, public health, and water resource outcomes, not solely sanitation compliance;
- Translate science into clear, enforceable regulatory frameworks that can guide permitting, planning, and investment decisions.

Successful solutions – Deploying context-appropriate, nutrient-reducing wastewater systems protective of coral and associated ecosystem health

- Invest in integrated, island- and regional-scale wastewater planning grounded in One Water and source-to-sea/ridge-to-reef frameworks, bringing together natural resource agencies, utilities, public health actors, and communities to identify solution portfolios that optimise environmental, health, and water security outcomes;
- Develop decision-support tools to guide investment in integrated solution portfolios, including Nature-based Solutions, decentralized systems, and centralized infrastructure, tailored to coral reef geographies that integrate One Health and ridge-to-reefs approaches to guide investment and selection of context-appropriate wastewater systems for coral reef geographies;
- Generate awareness of alternative wastewater management approaches and create enabling conditions for uptake (e.g., public outreach, cross-agency collaboration, pilot projects to demonstrate treatment performance);
- Strengthen institutional coordination for solution identification and delivery, moving beyond fragmented utility-led sewer planning toward cross-sectoral approaches aligned with One Water objectives;
- Translate wastewater standards and guidelines into actionable permitting pathways, financing mechanisms, and implementation models that enable deployment of reef-protective systems at scale.

1.1. Summary table of priority areas and R&D priorities (continued)

Priority area 2	
Best practice management of agriculture and integrated land-sea systems	**Understanding the system – Reef exposure pathways and hotspots (agriculture ➜ coast ➜ reefs)** • High-resolution hotspot mapping and load apportionment (nutrients, sediments, pesticides) using integrated field data, remote sensing, and models to prioritise reefs and sub-catchments for action; • Reef-facing exposure and response links: quantify how land-based loads and plume metrics translate into reef thresholds and outcomes (water clarity, algal cover, recruitment, disease risk, recovery); • Innovation in delivery pathway modelling (storm pulses, groundwater, legacy stores) to predict when/where pollutants reach reefs and the time-lags to improvement.
	Successful solutions – Reef-protective innovations in farm practice and land management • Develop, pilot, and scale precision agriculture and runoff-reduction technologies (e.g., variable-rate nutrient application, smart irrigation, manure treatment/containment, erosion controls) with measurable reef benefits; • Performance and cost-effectiveness evidence: evaluate intervention portfolios (technology + practice + NbS) using robust designs that link catchment change to reef outcomes; • Innovation in incentives and adoption systems (certification/supply-chain levers, blended finance) to accelerate uptake and maintenance at scale; • Assess interactions and trade-offs across space/time (legacy nutrients, climate extremes) to optimise sequencing and placement for maximum reef benefit.
	Monitoring and evaluation (including new technologies) • Develop and validate low-cost sensors, automated samplers and reef-ready monitoring packages for nutrients (N and P), turbidity/sediments, and priority pesticides/contaminants (including storm-event capture); • Advance remote sensing/drone methods for sediment and nutrient plume detection, erosion features, land-use risk indicators, and intervention tracking, integrated with ground truth and coral reef monitoring; • Build interoperable data platforms, dashboards, and decision-support tools to link farm actions > catchment loads > reef exposure > reef response; • Innovate in evaluation approaches and uncertainty reporting so programmes can credibly demonstrate reef outcomes.
	Collaboration, capacity building, and knowledge transfer • Co-design innovation pilots with farmers, communities, Indigenous partners, and agencies, ensuring technologies are usable, affordable, and maintained; • Create communities of practice and shared learning networks to accelerate scaling, share failure learning, and harmonise reef-facing indicators; • Develop toolkits, training, and extension packages (including digital tools) to support adoption of new practices or technologies and consistent monitoring.

1.1. Summary table of priority areas and R&D priorities (continued)

Priority area 3	
Effective Nature-based Solutions to improve coral reef water quality	**Demonstrate what works: Reef-protective NbS trials** • Field-test and compare NbS for reef-facing pollutant interception + reef response (clarity, algal cover, recruitment, disease signals); • Quantify feasibility/maintenance and storm-pulse performance; • Produce transferable reef-protective design specifications for scaling.
	Reef thresholds & cumulative impact modelling • Define reef-relevant thresholds/targets for nutrients, turbidity/sediment, and priority contaminants (including pulse exposure); • Model pollution × warming/bleaching/disease interactions to predict recovery benefits of NbS; • Translate thresholds into decision tools for NbS sizing or placement.
	Coastal NbS & co-location to protect priority reefs (blue green infrastructure) • Optimise living shorelines to reduce sediment resuspension, improve light, and reduce plume exposure; • Test co-location with point sources (outfalls/stormwater), including seaweed/microalgae biofilters + hybrids; • Assess ecological safety and O&M pathways; • Restore and deploy constructed wetlands as nature-based, catchment-to-reef buffers that intercept and treat nutrient and sediment loads from runoff and co-located point sources before reaching reefs.
	Reef-ready MRV technologies • Develop low-cost sensors and utilise remote sensing/AI to measure exposure reduction and reef response; • Standardised reef-facing indicators and monitoring, reporting, and verification protocols for comparability; • Dashboards linking NbS condition > exposure reduction > coral health.
	Valuation frameworks for reef outcomes • Valuation frameworks linking NbS to coral reef services, including fisheries, tourism, and coastal protection, and to One Health benefits from improved reef water quality and coral health. In this context, One Health benefits refer to linked gains for people, ecosystems and local economies, such as reduced health risks from contaminated water, safer fisheries and recreation, healthier reef habitats, and more resilient livelihoods.

2 Roadmap overview

2.1 Introduction

Coral reefs are among the most biodiverse ecosystems on the planet, providing essential services to over 500 million people worldwide (Moberg & Folke, 1999; Woodhead *et al.*, 2019). These services include food security, storm protection, and support for coastal livelihoods through tourism and fisheries. Globally, almost one billion people now live within 100 kilometers of coral reefs, placing enormous pressure on these ecosystems through land-based pollution (Wilkinson, 1996; Sing Wong *et al.*, 2022). Deforestation, conversion of land for agriculture, and urbanisation have resulted in significant increases in sediment, nutrient, and contaminant pollution draining into coral reef systems (Dubinsky & Stambler, 1996; Wenger *et al.*, 2015; Carlson *et al.*, 2019; El-Naggar, 2020). Pollutants enter marine systems from both land-based sources (e.g., agricultural runoff, urban waste, stormwater, land-based litter) and sea-based sources (e.g., shipping, waste oil spills, discarded fishing gear) (Nyenje *et al.*, 2010; Qadir *et al.*, 2020; Devlin & Brodie, 2023; Devlin *et al.*, 2023). Pollutants — which range from plastics and microplastics to persistent organic contaminants, heavy metals, or nutrients — disrupt fundamental ecosystem processes: they alter species trophic interactions, degrade habitat structure, reduce resilience to stressors like warming, deoxygenation and acidification, and ultimately diminish ecosystem services critical to human societies (Steckbauer *et al.*, 2020). These pollutants impact corals directly by harming essential fish species (e.g. hypoxia caused by eutrophication can lead to mass fish kills), compromising ecosystem resilience to climate change, increasing coral disease outbreaks, and reducing coral cover, reef complexity, and biodiversity (Wilson *et al.*, 2006; Riegl *et al.*, 2009; Wear & Thurber, 2015; El-Naggar, 2020; Good & Bahr, 2021; Wear *et al.*, 2024).

Marine pollution stands as one of the most formidable environmental challenges of the twenty-first century, driven by the ubiquity of harmful substances and pollutants entering waterways, and by their far-reaching ecological, societal, and economic consequences, particularly in tropical and subtropical coastal ecosystems (Neuman, 1970; Painting *et al.*, 2007; Devlin & Brodie, 2023; Kurniawan *et al.*, 2024). Land-based sources of pollution are jeopardising near-shore and marine ecosystems' water quality, with serious repercussions to the many coastal communities who depend upon them for fisheries, tourism, cultural heritage, and coastal protection (Kritzer *et al.*, 2014; Chaijaroen, 2022). The costs of pollution (direct and indirect) are high, ranging from lost fisheries productivity to species declines to increased remediation expenses to human health impacts (McNeely, 1992; Laffoley *et al.*, 2020; Ogidi & Akpan, 2022). Addressing land-based pollution's environmental and socio-economic pressures is one of the most effective ways to improve outcomes for coral reef ecosystems but requires joint action across technology, communities, governance, and financing.

2.2 Project rationale

Land-based sources of pollution are complex, multi-sector challenges affecting coral reef ecosystems, economies, and communities (Wilson *et al.*, 2006; Smith *et al.*, 2017; Wakwella *et al.*, 2022; Wenger *et al.*, 2023). Pollutants originate from agriculture, sanitation, urban drainage, and waste systems, moving through hydrological pathways into coastal waters (Devlin & Brodie, 2023). Once in waterways, these contaminants alter ecosystem function, reduce resilience to climate stress, and undermine fisheries, tourism, and livelihoods (McClanahan *et al.*, 2002; MacNeil *et al.*, 2019; El-Naggar, 2020; Good & Bahr, 2021). Land-based activities are now the top local anthropogenic threat for over 30% of coral reefs worldwide (Andrello *et al.*, 2022). These pressures can also undermine conservation interventions such as Marine Protected Areas (MPAs), making ecosystems more vulnerable to climate change impacts (Lamb *et al.*, 2016; Suchley & Alvarez-Filip, 2018; Wenger *et al.*, 2023; Carrasco Rivera & Wenger, 2026). Without addressing pollution, efforts to restore coral reefs will be significantly harder to sustain and scale. The evidence base shows that improving water quality is a prerequisite for successful coral restoration and for achieving long-term ecological outcomes expected of MPAs and other locally managed areas (Ceccarelli *et al.*, 2024); coral reef restoration is more effective when carried out alongside local actions that reduce threats to reefs, such as improving water quality (Duarte *et al.*, 2025).

Reduction of land-based sources of pollution is critical to rebuilding marine life and protecting human health, a sentiment echoed in Target 7 of the Global Biodiversity Framework, which specifically calls for "[a reduction of] pollution risks and the negative impact of pollution from all sources, by 2030, to levels that are not harmful to biodiversity and ecosystem functions and services" (Stephens, 2023). Despite this, it remains significantly underfunded compared to other ocean priorities, receiving just 4.1% of all philanthropic funding for oceans between 2020-2024 (Lewis *et al.*, 2025). Addressing this gap is essential to securing a resilient future for coral reef ecosystems and our oceans, through accelerated action to reduce pollution and strengthen resilience against climate change impacts.

With coral reefs and human welfare facing mounting pressures from climate change, land-based sources of pollution, and other anthropogenic activities, the need for actionable guidance is more urgent than ever. The guidance document developed through this project will provide a critical resource for practitioners and decision-makers, bridging the gap between scientific knowledge and practical application. By including a roadmap for future R&D needs, this project will also drive the innovation necessary to address pollution at scale, ensuring long-term success for coral reef conservation efforts.

The primary objectives of this roadmap are:

- **Fill current evidence gaps and advance innovative solutions that can further mitigate water pollution and improve ecosystem resilience;**
- **Provide guidance to the CORDAP Scientific Advisory Committee (SAC) on research priorities on water quality solutions to support coral reefs.**

2.3 Strategic objectives

OVERALL OBJECTIVE:

The desired outcome is healthy, resilient coral reef ecosystems where pollution is reduced at its source, managed along its pathways, and mitigated through nature-based and technological solutions — sustaining biodiversity, livelihoods, and cultural values.

To support and accelerate healthy reef outcomes, the roadmap provides a framework to:

- Advance scalable technologies, management tools, and nature-based interventions for water quality improvement;
- Foster integration of research, policy, and practice across land-based and marine sectors;
- Strengthen monitoring and data systems to link management actions to ecosystem outcomes;
- Build institutional and community capacity for effective pollution reduction programs;
- Catalyse innovation and partnerships across government, academia, industry, and local communities.

Given the complexity of catchment-to-reef pollution pathways, focusing solely on monitoring or clean-up is insufficient. What is required is solution-oriented research that identifies, assesses, and scales interventions capable of reducing pollutant exposure at coral reefs and improving reef condition. Such research is critical for several key reasons:

- First, mapping and quantification of pollution sources, pathways, and sinks is foundational for coral reefs. Without understanding where reef-relevant pollutants originate, how they are transported and transformed, and when/where they reach reefs, interventions risk being ineffective or misdirected. This evidence base supports more effective targeting of interventions through improved source attribution and impact evaluation.
- Second, innovative technologies and systems approaches are needed to prevent pollutants from reaching reefs and to enable verification of outcomes at reef scales. For example, this could include low-cost sensors and plume-detection technologies, improved treatment and containment systems, and circular-economy approaches that reduce pollutant leakage into rivers and coastal waters.
- Third, land-based pollution interacts with other reef stressors (e.g., ocean warming, coastal acidification, coastal deoxygenation) and can amplify bleaching susceptibility, disease risk, and recovery time (Klein *et al.*, 2019). Research that integrates pollution solutions within ecosystem-based and systems-level frameworks is therefore more likely to strengthen coral reef resilience than approaches that address symptoms in isolation.
- Finally, interventions must be scalable, context-sensitive, and designed with enabling conditions in mind (e.g., governance arrangements, financial mechanisms, and social uptake) so they can be implemented and maintained long enough to deliver reef benefits. This requires R&D that bridges natural sciences, engineering, and social sciences to address and close gaps in intervention research and improve the translation of evidence into practice in coral reef settings.

Land-based water pollution is a multi-dimensional threat with deep ecological, human, and economic consequences. Prioritising research on how to prevent and mitigate pollution through human, environmental, and economic pathways — not just where and what it is — is central to shifting from reactive clean-up approaches toward proactive, integrated, and sustainable management of our oceans.

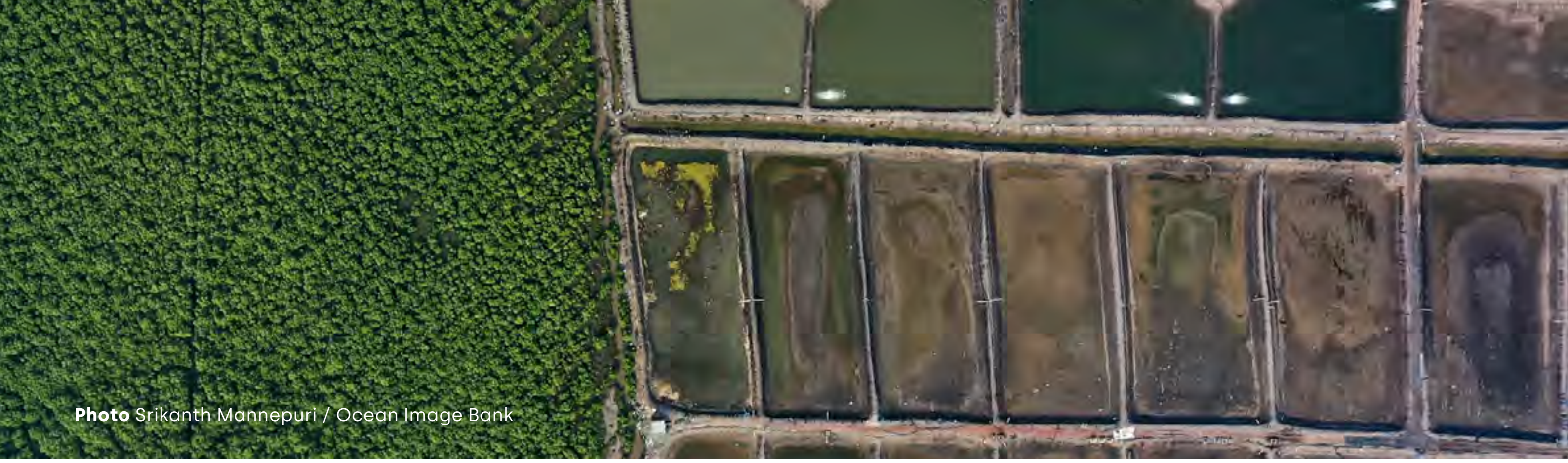


Photo Srikanth Mannepuri / Ocean Image Bank

2.4 Scope and structure

The roadmap is structured around three priority areas, reflecting updated workshop outcomes and stakeholder feedback:

2.4.1 Priority area 1: Improved sanitation to reduce domestic wastewater pollution

Sanitation refers to the systems, infrastructure, and practices that ensure human waste is safely managed, protecting public health and the environment. Sanitation is a foundational component of WASH (Water, Sanitation and Hygiene) services, involving access to a “decent, private toilet where human waste is disposed of safely” and to infrastructure capable of withstanding climate pressures such as floods and droughts. Effective sanitation includes wastewater collection, treatment, and disposal systems, ranging from sewered networks to on-site solutions such as septic tanks, latrines, or dry sanitation. These systems are designed to contain or treat wastewater to varying degrees, reducing the release of pathogens and contaminants to soil, groundwater, and surface waters, though nutrient removal is typically not incorporated into system design.

Beyond toilets and treatment units, sanitation also encompasses the broader policy, institutions, finance, and regulatory environment required to ensure waste is managed safely across diverse environments. Sanitation systems must be adapted to the local environmental, social, and governance contexts that influence which systems can be implemented and how they will function. They must also be supported by guidelines that help governments and utilities select appropriate technologies and maintain safe operation over time. In this way, sanitation is not just an infrastructure service but a public health and environmental protection system, essential for reducing pollution loads, preventing disease, and safeguarding downstream ecosystems.

2.4.2 Priority area 2: Best practice management of agriculture & integrated land-sea systems

This priority area focuses on reducing nutrient, sediment, and contaminant losses from landscapes by improving how crops, livestock and agroforestry systems are designed and managed. Effective management begins with understanding the dominant pollution pathways (i.e., fertiliser runoff, erosion from unprotected slopes, degraded riparian zones and manure mismanagement) and addressing these pressures at their source.
This includes practices such as precision nutrient management, erosion-control structures, improved feed and waste-handling systems, vegetated buffers, and on-farm or constructed wetlands that intercept pollutants before they enter rivers and coastal zones. However, experience across many regions shows that access to soil and water testing, extension support, and affordable technologies remains limited, constraining the uptake of best-practice approaches.

Photo Envato

Equally important is ensuring that agricultural improvements are supported by coordinated governance and landscape-level planning. Fragmented land tenure, limited enforcement, and the absence of integrated catchment planning make it difficult to align actions across farms and villages. Best management therefore requires not only on-farm technical measures but also policies, incentives, and partnerships that motivate change across the wider system. This involves improving the quantification of diffuse pollutant loads, understanding ecosystem sensitivity, and developing decision-support tools that link inland land-use management to coastal water quality outcomes. Addressing agricultural pollution effectively requires catchment-to-coast alignment, targeted monitoring, and adaptive strategies that integrate ecological, social, and economic factors to achieve meaningful reductions in sediment, nutrient, and contaminant flows to marine environments.

2.4.3 Priority area 3: Effective Nature-based Solutions to improve coral reef water quality

Nature-based Solutions (NbS) harness ecological processes to capture, transform, or retain pollutants while simultaneously delivering multiple co-benefits, including carbon sequestration, biodiversity enhancement, shoreline protection, and livelihood opportunities. These systems (e.g., constructed wetlands, mangroves, riparian buffers, living shorelines, seagrass farms) mimic or restore semi-natural functions that improve water quality and ecosystem resilience. Because they rely on biological processes rather than engineered hardware, NbS are often more adaptable to changing environmental conditions, making them particularly valuable in regions facing increased rainfall variability, storm surges, and sea-level rise.

NbS are also increasingly recognised as cost-effective, scalable, and climate-resilient alternatives to traditional “grey” infrastructure (Morris *et al.*, 2024). Their ability to provide multiple services simultaneously — pollution reduction, habitat creation, carbon storage, and cultural values — offers a higher return on investment when viewed through an integrated environmental and socio-economic lens. Despite their potential, the uptake of NbS remains limited by uncertainties around performance under different climatic and hydrological conditions, complex permitting and regulatory pathways, complicated land tenure below the low water mark, operations and maintenance requirements, and the challenge of consistently valuing ecosystem services in cost–benefit analyses. These barriers can slow investment, constrain innovation, and make it difficult for governments and communities to fairly compare NbS with conventional infrastructure improvements.

Photo Dani Escayola / Ocean Image Bank

2.4.4 Addressing each priority area in the roadmap

Each priority area sets out current knowledge gaps and research priorities needed to scale innovation and implementation. By strengthening the evidence base, the roadmap will help policymakers, researchers, and practitioners identify and prioritise the most effective interventions. It will also outline cost-effective, context-appropriate R&D solutions to pollution reduction, ensuring that strategies are practical and tailored to local environmental and socio-economic conditions.

Improved coordination across research, policy, and investment streams is also required as many of the solutions sit outside of the innovation R&D space, with a requirement for collaboration and alignment among stakeholders, governments, and the research community. R&D solutions need to be considered within an integrated approach to ensure that scientific advances are rapidly translated into actionable policies and on-ground outcomes. An integrated framework will help ensure that recommended R&D can contribute to tangible reductions in nutrient, sediment, and contaminant loads entering waterways and coastal systems.

As detailed in Figure 2, integrating multiple R&D interventions within a single management framework can improve coral reef health while delivering resilience benefits for reef-dependent coastal communities.

Figure 2. How the implementation of the roadmap can help improve ecological health and improve resilience of coral reef and coastal communities.

Photo Envato

2.5 R&D assessment methodology

Effective management requires addressing pollutant sources in catchments, controlling transport along pathways, and mitigating impacts in receiving environments such as estuaries, lagoons, and reefs. Responses to pollution should be conceptualised within a Catchment-to-Coast Systems Framework, recognising that interventions can occur at multiple points along the Drivers–Pressures–State–Impact–Response (DPSIR) pathway. Effective mitigation, therefore, spans actions that address underlying drivers, reduce pressures, improve or restore environmental state, manage impacts, and implement targeted response measures, with approaches refined through regional application in reef and estuarine programs. We use five factors — **Source, Pathway, Receptor, Enabling Conditions, Monitoring and Indicators** — as a structured lens for defining key actions and focus areas to develop R&D priorities across each theme in the roadmap. This framework ensures that there are a range of interventions that address pollution at its origin, inform transport pathways, and strengthen ecosystem resilience. By integrating monitoring requirements and forward-looking research needs, the approach provides a comprehensive, systems-based method for prioritising actions that are both practical today and adaptive to emerging challenges (Figure 3).

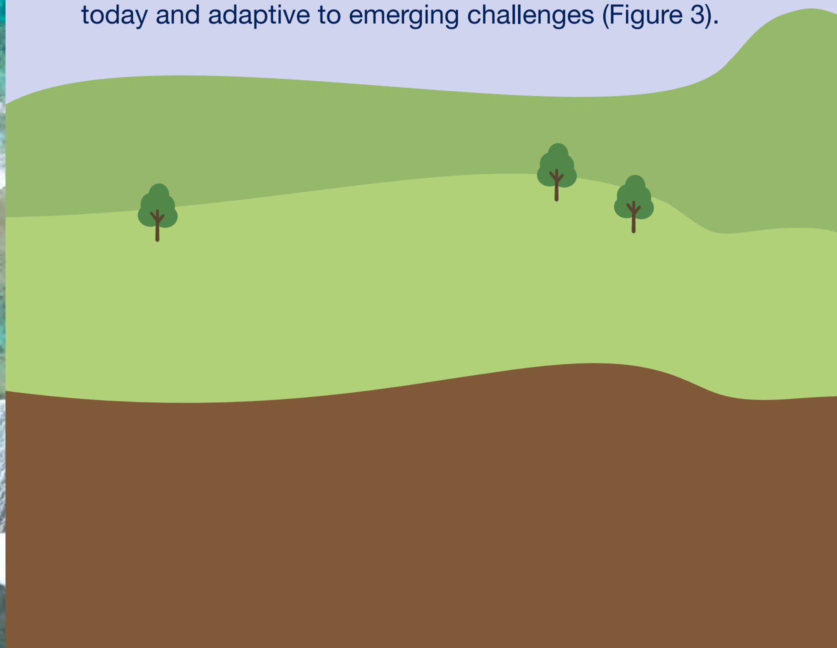


Figure 3. Catchment-to-reef system components used in this roadmap's R&D framework (Sources, Pathways, Receptors, Responses, and Monitoring & Indicators) to trace pollutant movement and target innovations and metrics that reduce coral reef exposure and improve reef outcomes. Figure continues on page 21.

1 Sources

Point and diffuse sources that generate reef-relevant pollutants (nutrients, sediments and pathogens) in catchments and coastal settlements.

Example applications

On-site wastewater containment/treatment options; farm nutrient and manure management to reduce dissolved N and P losses; managing land-based debris inputs.

3 Receptors

Receiving environments where pollutant exposure translates into ecological effects, with coral reefs as the primary receptor (and connected seagrass/mangrove/estuarine habitats where relevant).

Example applications

Reef response metrics used to evaluate solutions (e.g., turbidity/sedimentation at reefs, benthic algal cover, coral disease incidence, recruitment, and post-bleaching recovery); targeted reef recovery tools (e.g., managing algal overgrowth, temporary shading/seaweed curtains).

2 Pathways

Transport routes moving pollutants from land to reefs, including surface runoff, river discharge, groundwater seepage, storm and flood pulses, and coastal circulation that delivers sediment/nutrient plumes to nearshore reefs.

Example applications

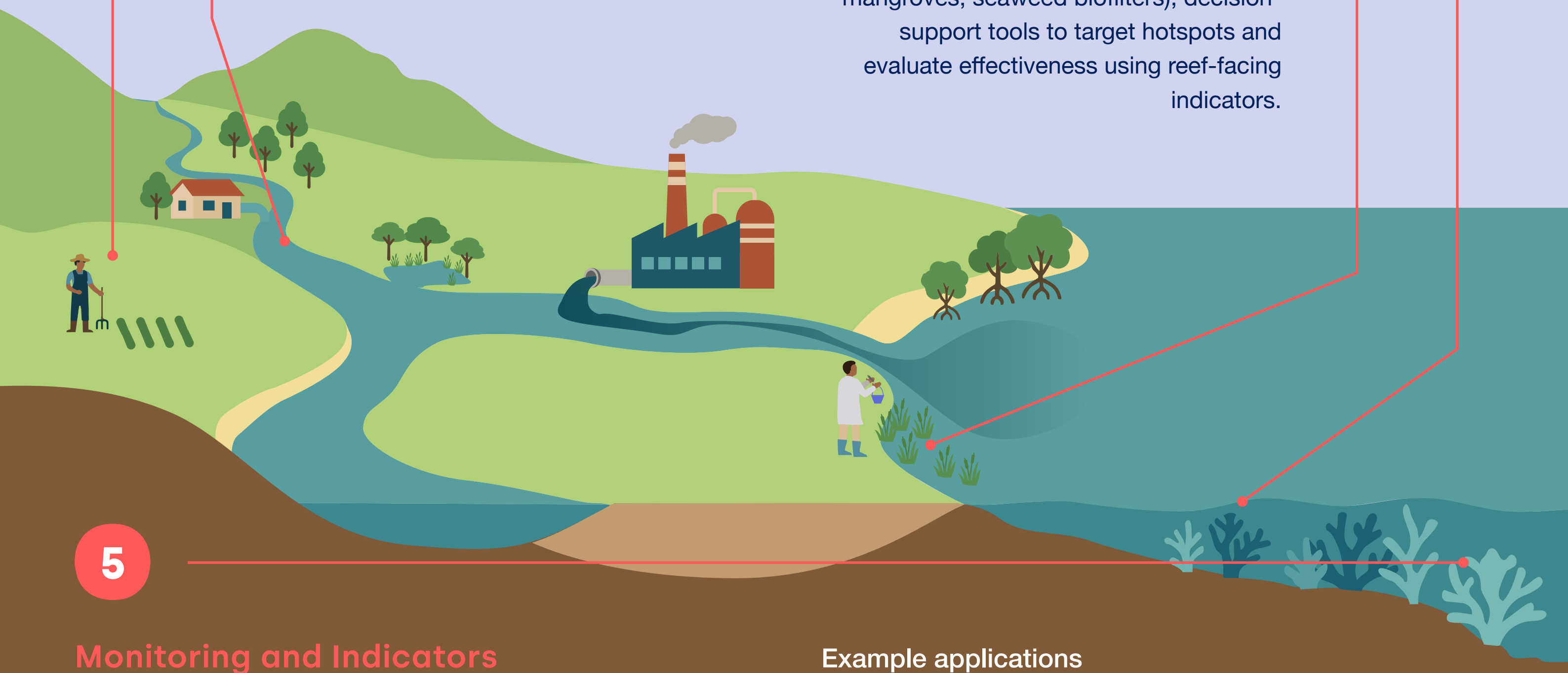
Riparian buffers and constructed wetlands; mangrove/seagrass restoration to trap sediments and attenuate plumes; erosion and sediment controls (e.g., sediment traps) targeted to hotspot sub-catchments.

4 Responses

Interventions and enabling actions that reduce pollutant loads, interrupt pathways, or improve reef outcomes (spanning technology, Nature-based Solutions, behaviour change, and the evidence needed to support implementation).

Example applications

Piloting and scaling sanitation upgrades; deploying NbS (wetlands, riparian buffers, mangroves, seaweed biofilters); decision-support tools to target hotspots and evaluate effectiveness using reef-facing indicators.



5 Monitoring and Indicators

Measurements used to track change from catchment interventions to reef outcomes, spanning water-quality variables (nutrients, turbidity/suspended sediments, microbial indicators) and reef condition/response indicators.

Example applications

Low-cost sensor networks for nutrients and turbidity; remote sensing/drone detection of sediment and wastewater plumes; monitoring benthic algal cover, coral disease, recruitment, and recovery after bleaching to evaluate intervention effectiveness.

Many interventions need to be designed, targeted, and evaluated across multiple spatial scales — across sub-catchments and basins, and at coastal receiving areas — because reef benefits depend on cumulative load reduction from many sources. This requires integrated datasets across sectors (e.g., agriculture, sanitation, water, and local government) to identify priority hotspots and to understand how source controls, pathway interventions, and coastal buffering combine to change reef-facing exposure. Modelling and remote sensing can then support scenario testing (e.g., alternative mixes and placements of interventions), helping to anticipate where investments are most likely to deliver sustained water quality improvements and measurable benefits for coral reefs and reef-dependent ecosystem services.

The same applies over time: water quality responses can be immediate (e.g., reduced pollutant pulses during storms), delayed (e.g., mobilisation of legacy nutrients and sediments), or only detectable after multi-year ecological recovery on reefs. Intervention design and R&D therefore need to account for timing, lag effects, maintenance requirements, and climate variability, and to pair implementation with adaptive monitoring, early warning systems where relevant, and long-term datasets. These temporal considerations reinforce the need for an integrated catchment-to-reef framework that links actions to measurable reef-scale outcomes.

This framework links land-based pollution sources (e.g., sanitation, agriculture, urban runoff) to catchment-to-reef transport pathways and the resulting exposure and impacts on coral reef systems and reef-dependent ecosystem services (including fisheries, tourism, and coastal protection). These system components collectively inform R&D priorities for coral reef water quality solutions, from source control through to monitoring and decision thresholds that enable evaluation, learning, and adaptive refinement over time (Figure 4).

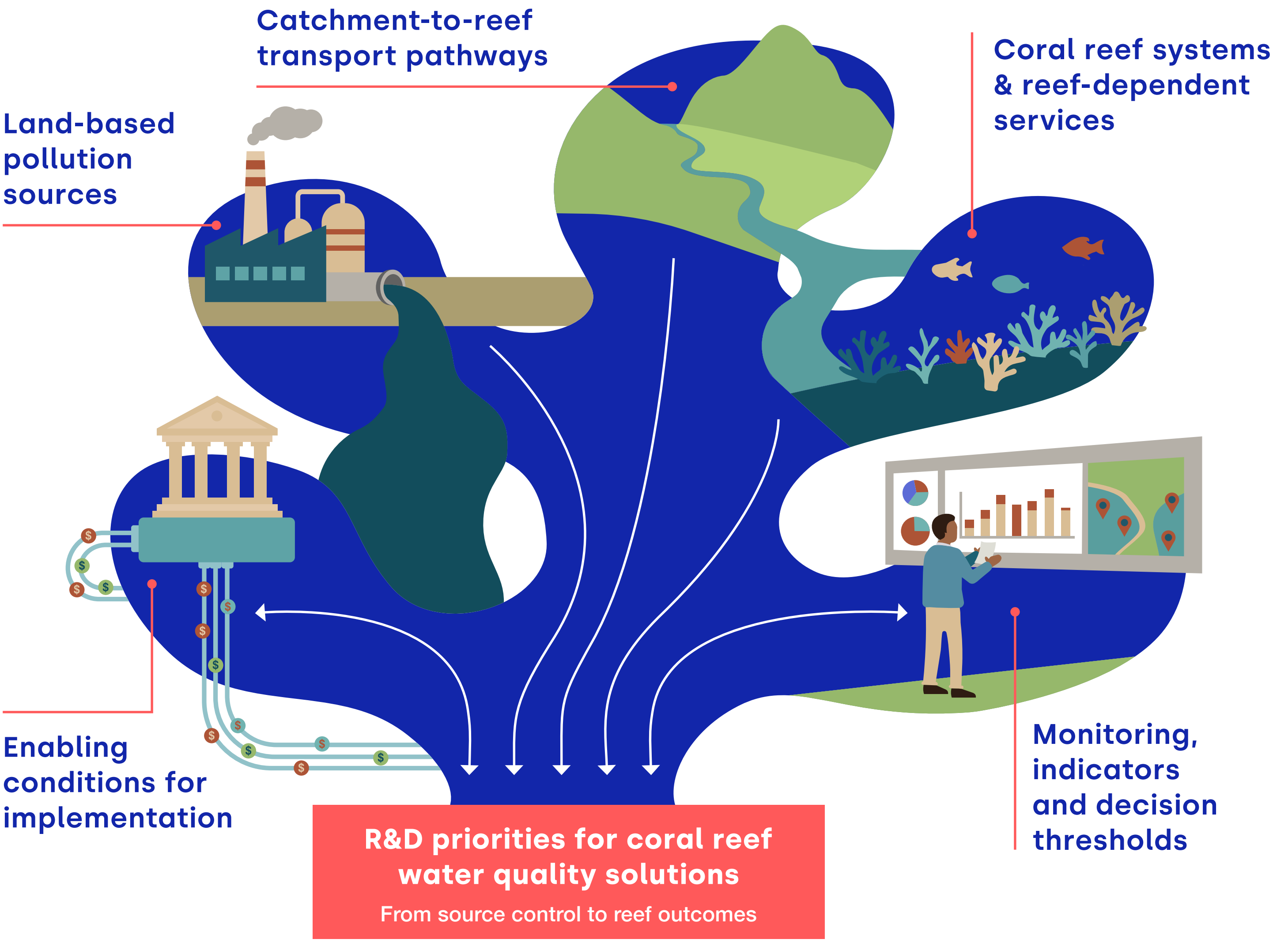


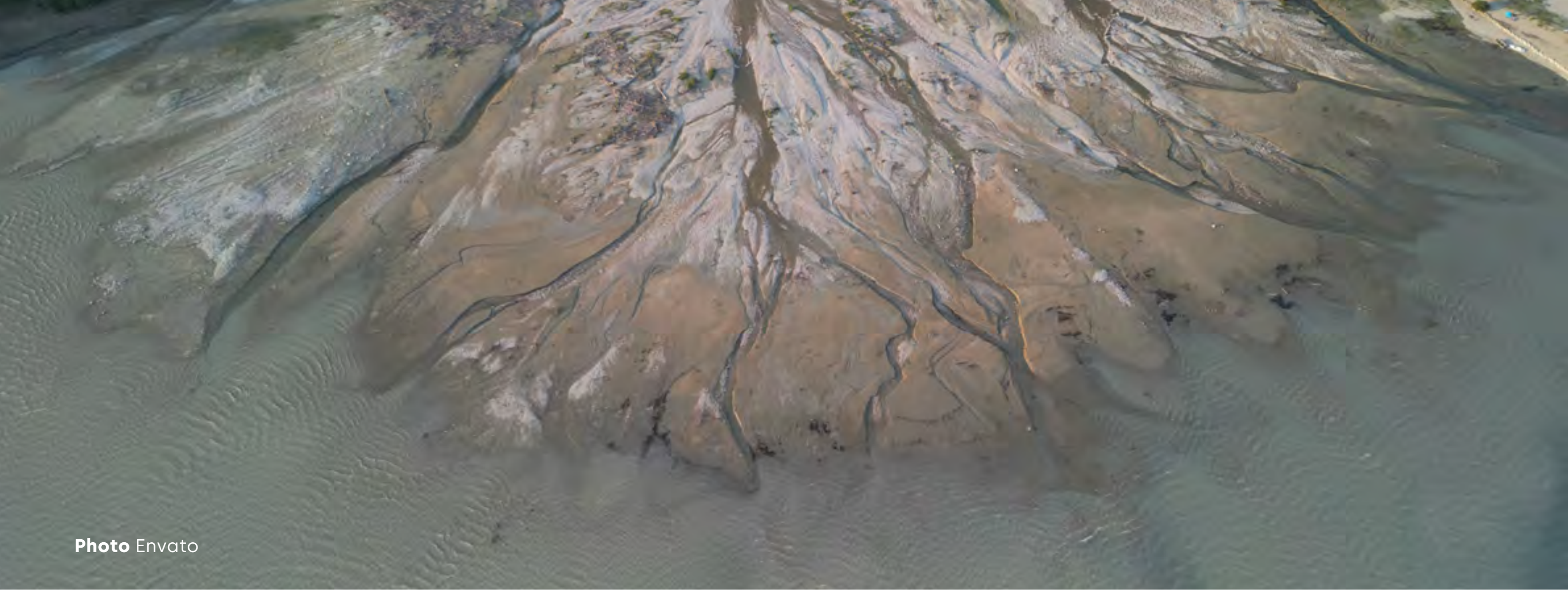
Figure 4. Conceptual framework for prioritising research and development (R&D) to improve water quality outcomes for coral reef systems.

2.6 Criteria scoring for R&D priorities

R&D priorities were identified through a five-day workshop involving international experts and representatives from national agencies, bringing together a broad range of scientific, technical, and policy perspectives. Upon identification of each R&D priority, a structured prioritisation process was undertaken during the workshop. Subject matter experts were organised into dedicated thematic groups and participated in a focused session to rank the R&D priorities. This ranking was carried out using a consistent assessment framework based on three key criteria: feasibility, potential impact of the intervention, and cost-effectiveness. Each priority was subsequently scored against these criteria to support a transparent and evidence-based prioritisation of actions. The rationale underpinning the scoring for feasibility, impact, and cost-effectiveness is described in Table 1.

Table 1. R&D assessment criteria and definitions on which scores are given for each R&D priority.

Assessment criteria	Priority score		
	High	Medium	Low
Feasibility of implementation	The intervention or research approach relies on existing methods, infrastructure, and expertise; can be initiated with current technology and within typical project timelines.	Requires some method development, capacity building, or cross-sector coordination before implementation; achievable within a medium-term research horizon with moderate effort.	Dependent on significant technological development, novel expertise, or complex institutional arrangements that present substantial barriers to near-term implementation.
Impact	Strong evidence or scientific consensus that the intervention delivers measurable, meaningful improvements to water quality or marine ecosystem health at ecologically relevant scales.	Plausible and promising potential for impact, but evidence is limited, context-dependent, or not yet demonstrated at meaningful scale.	Impact is indirect, marginal, or highly uncertain; benefits are likely to be incremental rather than transformative or are dependent on a narrow set of conditions being met.
Cost-effectiveness	Delivers significant water quality or ecosystem outcomes relative to investment; cost efficiencies are well-documented or reasonably predictable, making a strong case for funding prioritisation.	Reasonable return on investment expected, but with notable uncertainties around cost trajectories, scaling costs, or the ratio of outcomes to expenditure.	High upfront costs, uncertain returns, or limited scalability relative to cost; investment case requires further evidence before confident prioritisation.



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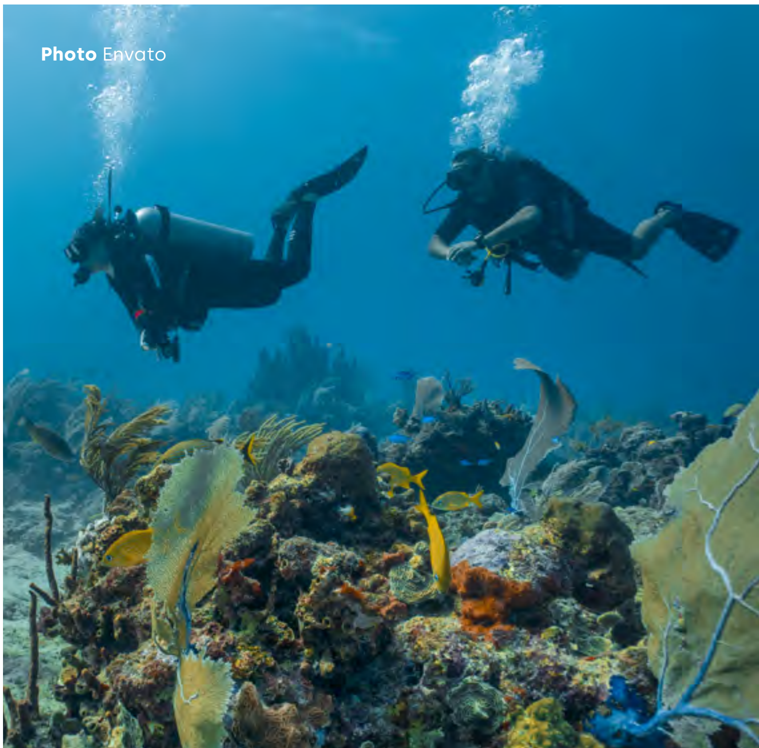
2.6.1 Feasibility

Assessing the feasibility of an R&D activity begins with a clear initial assessment of the pollution problem, where the scale, extent, and complexity of the issue directly determine the required effort, time, and resource investment. Effort estimation should also account for data accessibility and availability, since data gathering, reviewing, and analysing existing datasets can range from quick desktop reviews to substantial multi-partner investigations, depending on the information gaps that must be filled before action can begin. Additionally, programme-level R&D planning emphasises the importance of aligning the expected workload with policy drivers, multidisciplinary expertise, and long-term outcomes, ensuring that effort is proportional to the evidence needed to deliver impactful, strategically relevant outputs across marine policy and management domains.

Feasibility should consider spatial scales (sub-catchment, basin, coastal receiving area) required to achieve cumulative improvements. For example, under effort, the R&D should consider the type of data integration required across different stakeholders (i.e., agriculture, environment, water, and local government) that allows prioritisation of "hotspots" where land-based pollution most strongly affects coastal ecosystems. It should also consider if the intervention(s) require knowledge of water quality responses over varying timescales, from immediate pollutant capture to multi-year ecological recovery. Achieving sustained improvements in coastal water quality requires whole-of-system integration, and adaptive governance can be successful in connecting actions from catchments to coast, but this can increase effort in terms of time and cost.

It also involves considering the practical challenges of expanding technologies, including operational constraints, reliability risks, and the need for appropriate legal and logistical frameworks, as illustrated by long-term autonomous monitoring systems where even small technical failures can jeopardise large datasets. Scalable R&D should further support capacity building, collaborative frameworks, and end-to-end systems that can be adopted locally while maintaining data quality at national or global levels, ensuring that solutions remain feasible, cost-effective, and impactful when applied far beyond initial pilot sites.

For example, advanced modelling tools and remote sensing technologies can also support scenario analysis, enabling managers to test alternative investment portfolios and predict long-term benefits for reef health and ecosystem services. Adaptive monitoring, early-warning systems, and longitudinal datasets are critical to detect trends, evaluate program performance, and refine strategies over time that can improve overall impact across different systems.



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2.6.2 Impact

Impact is a critical criterion in R&D decision-making because it determines whether research investments actually translate into meaningful environmental, societal, and economic benefits. In the context of land-based sources of pollution, high-impact R&D accelerates progress through interventions that reduce pollution pressures efficiently and at scale and accelerate the time between problem identification and the implementation of a solution. This helps bridge the gap between knowledge generation and real-world outcomes – an essential consideration as coral reefs, coastal communities, and marine economies face intensifying pressures from pollution and climate change.

Impact-oriented R&D also ensures that research addresses the most consequential risks to ecosystems and society. Climate-driven changes in rainfall, runoff, and hydrology amplify nutrient loading and pollution stress in coastal waters, affecting biodiversity, fisheries, and water quality. High-impact R&D helps anticipate these linked risks by targeting the processes most likely to drive degradation or threaten livelihoods, allowing managers to focus resources where change will matter most. Similarly, integrated, system-wide R&D is essential for achieving national policy goals related to nature recovery, clean water, and climate resilience — another reflection of why the impact of research outcomes must be central to prioritisation.

Finally, emphasising impact ensures that R&D supports broader societal and economic benefits. Land-based sources of pollution affect tourism, fisheries, public health, and infrastructure, and the consequences of inaction are often more severe and more costly than early intervention. Pollution undermines economies and human wellbeing, and the costs of inaction often exceed the benefits of delayed or remedial responses. Impact assessment should therefore consider not only scientific innovation, but also contributions to societal resilience, sustainable development, and long-term environmental health.

2.6.3 Cost-effectiveness

Cost-effectiveness in R&D prioritisation means directing investment toward interventions that deliver the greatest environmental and societal benefit relative to their associated costs. This includes prioritising actions that target the most significant pollutant pressures, particularly sediments and nutrients, which are consistently recognised as major drivers of water quality decline and coral reef degradation. Cost-effective R&D should also focus on practical, scalable solutions that generate evidence for faster implementation and sustained impact. Additionally, programmes must consider whole-system impacts and cumulative pressures to ensure investments reduce risks at appropriate scales and avoid economic or environmental losses caused by insufficient evidence, as identified in marine and fisheries R&D policy assessments. Overall, a cost-effective approach directs R&D funding toward interventions that are actionable, scientifically robust, and capable of delivering measurable improvements in marine ecosystem resilience.

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3

Priority area 1
Improved sanitation to reduce domestic wastewater pollution

3.1 Sources, pathways, and receptors of pollution

3.1.1 Sources

Inadequate wastewater and faecal-sludge management remain significant drivers of microbial, nutrient, and chemical pollution in tropical and subtropical coastal catchments (Wenger *et al.*, 2023). Across many regions, aging septic systems, informal settlements lacking engineered containment, and poorly maintained on-site units discharge untreated or partially treated effluent directly into groundwater and drainage channels (Lebu *et al.*, 2024). During storms or seasonal flooding these systems are quickly overwhelmed, mobilising pathogens and nutrients into rivers, lagoons, and nearshore marine environments (Huang *et al.*, 2025). This elevated contamination accelerates eutrophication, drives harmful algal blooms, undermines drinking-water safety, and risks exposing coastal communities to gastrointestinal and skin infections (Reopanichkul *et al.*, 2009; Wear & Thurber, 2015; Kuempel *et al.*, 2024).

Globally, sanitation challenges are intensified by rapid urbanisation, high tourism pressures, and limited enforcement of environmental standards (Lebu *et al.*, 2024). Many lower- and middle-income countries face large service gaps, where a high proportion of households rely on on-site sanitation that functions poorly. Tourism-driven coastal towns often experience seasonal population surges that exceed treatment capacity, causing discharges of untreated, excess effluent to enter sensitive marine ecosystems such as coral reefs, seagrass meadows, and mangrove forests (Pásková *et al.*, 2024). Inadequate regulation and changing patterns of use correlate to the increased detection of emerging contaminants in nearshore waters (Richardson & Kimura, 2016). These contaminants include pharmaceuticals, personal-care products, and antimicrobial residues, adding to ecological and public health risks (Ziylan-Yavas *et al.*, 2022). These problems are not isolated: downstream pollution frequently crosses borders through shared watersheds, regional ocean currents, and transboundary fisheries which makes sanitation a global issue that demands coordinated investment, stronger governance, and research-driven solutions (Ahmed *et al.*, 2025).

Photo Renata Romeo / Ocean Image Bank

3.1.2 Pathways

Direct seepage and overflow from on-site sanitation systems (e.g., pit latrines, septic tanks, and makeshift containment units) represent one of the most widespread pathways of pollution in low-lying and rapidly growing coastal regions. When these systems are poorly designed, aging, or never desludged, wastewater leaks into surrounding soils and drains, transporting pathogens, nutrients, and organic matter into surface channels. In many tropical settings, leaching from poorly sealed sanitation systems introduces nutrients and pathogens into shallow aquifers, which then discharge into lagoons and reef flats and can create diffuse and persistent pollution plumes. Runoff from open defecation zones and unregulated drainage contribute further to this issue, particularly in informal settlements where wastewater networks are absent or poorly maintained. Together, these sources create chronic, low-level contamination that steadily degrades marine environments including coral reefs.

Extreme weather events and hydrological conditions further intensify these pollution pathways (van Vliet *et al.*, 2023; Zou *et al.*, 2023). Heavy rainfall, flash flooding, and high tides mobilise stored contaminants from latrines, septic tanks, and solid-waste accumulations, rapidly transporting them into coastal waters. In flood-prone deltas, atoll islands, and mangrove-lined coastlines, inundation can lead to direct household-to-ocean pollutant transfer, bypassing any form of treatment.

During storms, wastewater treatment ponds and settling basins frequently exceed capacity, releasing partially treated effluent into waterways (Suchowska-Kisielewicz & Nowogoński, 2021). These episodic surges can deliver large volumes of contaminants in short periods, driving algal blooms, oxygen depletion, and elevated bacterial loads in sensitive marine ecosystems. These pressures highlight the need for integrated sanitation upgrades, nature-based buffering systems, and risk-informed planning to prevent further degradation of coral reefs.

3.1.3 Receptors

For coral reefs specifically, inadequate sanitation increases exposure to nutrients, organic matter, and microbial pathogens that can drive algal overgrowth, reduce oxygen and water clarity, elevate coral disease risk, and suppress coral recruitment – reducing the likelihood of reef recovery after bleaching and other acute stress events.

3.1.4 Monitoring and indicators

Monitoring should link sanitation pressures to reef-facing outcomes, combining microbial indicators (e.g., faecal markers), nutrient concentrations, chlorophyll-a, turbidity, and dissolved oxygen with reef response metrics such as algal cover, coral disease incidence, recruitment, and recovery after bleaching.

3.2 Responses & enabling actions: Identified R&D priorities

R&D priorities focus on advancing the technologies, methods, and system designs needed to overcome persistent gaps in sanitation treatment, regulations, and finance. Research on containment systems aims to improve design and monitoring approaches that reduce lifecycle costs, extend system durability, and support more effective financing and maintenance arrangements. The identified priorities include social and institutional research to refine service models and identify sustainable financing mechanisms. R&D should support the integration of Nature-based Solutions with engineered systems, generating evidence on pollutant removal efficiency, co-benefits, and long-term performance of these solutions. For coral-reef outcomes, priorities should explicitly link sanitation upgrades to measurable changes in nearshore water quality and reef response indicators (e.g., microbial contamination, nutrient enrichment, algal cover, coral disease incidence, recruitment success, and recovery trajectories after bleaching). Overall, the R&D priorities need to ensure that interventions are scientifically robust, cost-effective, and tailored to the realities of small island states, rural communities, and rapidly growing coastal regions. Building on this framing, the workshop identified the R&D priorities below, which are summarised in the table and then elaborated in the following sub-sections to clarify the evidence, tools, and evaluation metrics needed to reduce sanitation-derived pollution reaching coral reefs. Consultations during and after the workshop have identified the following R&D priorities for improving sanitation to protect coral reefs (Table 2).

Table 2. Summary table of R&D priorities and rankings identified for the Improved Sanitation to Reduce Domestic Wastewater Pollution priority area.

		Assessment factor		
Evidence gaps	**R&D priorities addressing gaps**	**Feasibility**	**Impact**	**Cost-effectiveness**
Theme: Mapping and quantifying pollutant loads for coral reef ecosystems				
Lack of information on source and pathways of pollution from sanitation.	Develop tools to map coral reef distribution and quantify the wastewater pollution load entering the marine environment.	High	High	High
	Quantify the spatial and ecological impacts of wastewater pollution and the benefits of improved sanitation for coral reefs.	High	High	Medium
	Quantify the economic costs of wastewater pollution and return on investment of reef protective interventions.	High	High	Medium
Theme: Evidence-based standards and guidelines for coral reef protection				
Disconnect between regulations and scientific evidence regarding pollutant impacts on ecosystems.	Development of evidence-based wastewater discharge standards, water quality guidelines, and policy frameworks aligned with coral reef protection goals.	Medium	High	High


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3.2.1 Develop tools to quantify the wastewater pollution load entering the marine environment

WHY THIS IS NEEDED:

Sanitation-derived pollution is often diffuse, intermittent (e.g., storm pulses), and poorly documented, which makes it difficult to identify priority hotspots and to demonstrate benefits at receiving reefs. A spatially explicit, transparent load-estimation approach is a prerequisite for targeting investments, comparing intervention options, and tracking whether sanitation improvements translate into measurable reductions in reef-facing exposure.

Developing tools to map human populations and quantify wastewater pollution loads entering the marine environment is essential because sanitation impacts are cumulative throughout catchments, can be spatially uneven, and are often poorly identified. Without reliable, spatially explicit information on where people live, how wastewater is managed, and how effluent moves through catchments, any pollution sources remain underestimated or misidentified. These gaps in knowledge contribute to the ineffectiveness of regulations, limited infrastructure investment, and poor enforcement. Robust tools are needed to link population distribution, sanitation system type, treatment performance, hydrological pathways, and receiving environments to then enable decision-makers to prioritise interventions where they will deliver the greatest water quality and ecosystem benefits.

Effective development of these tools requires integrated research, sufficient and sustained funding, and support from policy. Research should aim to improve the understanding of wastewater load coefficients and pathogen and nutrient fate modelling, and to validate these using water quality and ecological monitoring data. Funding will be necessary to support data collection, model development, and long-term database maintenance, particularly in rapidly growing or under-resourced catchments. Policy support is also critical to enable data sharing across agencies, standardise reporting requirements, and embed these tools into planning, regulatory assessment, and investment decisions to ensure they move beyond research outputs to practical decision-making instruments.

WHAT IS NEEDED:

Development of a set of interoperable tools (data layers, methods, and simple decision interfaces) that combine population distribution, sanitation system types and performance, hydrology and transport pathways, and coastal receiving areas to estimate wastewater loads (nutrients and microbial contamination, and where feasible emerging contaminants) reaching the marine environment and, where relevant, coral reefs.

PRIORITY R&D TOPICS TO PRODUCE TOOLS REQUIRED FOR MAPPING AND QUANTIFYING POLLUTANT LOADS:

- **Develop and validate sanitation load coefficients for coral reef-connected settings:** quantify nutrient and microbial loads from common on-site and decentralised systems (including failure/overflow and desludging performance), and incorporate seasonality (e.g., tourism surges) and extreme rainfall to improve estimates of what reaches nearshore coral reefs;
- **Build a coral reef-connected sanitation geospatial evidence base:** compile and harmonise core spatial layers (sanitation system locations/typologies, outfalls and overflow points, service coverage, population and tourism seasonality, groundwater vulnerability, drainage/streams, and reef receiving areas) to enable consistent hotspot mapping for coral reef exposure;
- **Quantify uncertainty and pulse risk to coral reefs:** develop and test uncertainty methods for sanitation load estimates, including failure/overflow rates, desludging performance, tourism surges, and extreme rainfall/high-tide events, and express outputs as confidence ranges for reef-facing exposure hotspots;
- **Develop tiered catchment-coastal delivery models to coral reef sites:** advance and compare modelling approaches (screening to coupled plume models) that represent groundwater discharge, river delivery, dilution/decay, and coastal circulation to estimate when and where sanitation pollution reaches nearshore coral reefs;
- **Validate and attribute sanitation influence at coral reefs:** design field studies that pair microbial source tracking/tracers and nutrient measurements with plume observations (*in situ* and remote sensing) to confirm predicted hotspots and to test detectability of changes in coral reef response indicators (e.g., algal cover, coral disease signals);
- **Develop transferable coral reef-relevant protocols and minimum data standards:** define minimum datasets, calibration/validation steps, and recommended coral reef-facing indicators so approaches can be replicated across CORDAP geographies and compared across projects;
- **Deliver decision-support outputs for coral reef-protective sanitation upgrades**: produce reproducible workflows and user-facing products (maps, dashboards, scenario tools) that show expected reductions in reef exposure under alternative sanitation improvements and enable before-after evaluation at priority reefs.

OUTPUTS AND HOW THEY WILL BE USED:

- Hotspot maps of sanitation-derived loads to coastal waters/reefs, with uncertainty bounds;
- Scenario outputs to prioritise intervention placement and to support evaluation (before-after comparisons);
- A repeatable method that can be applied across geographies using minimum datasets, with optional higher-tier modules where data allow.

FUNDING AND CAPACITY NEEDS:

Sustained funding is required for baseline data acquisition, tool development, and long-term maintenance (including updates as populations, infrastructure, and climate risks change). Investment is also needed for field validation and for capacity building so local agencies and partners can run the tools, interpret outputs, and integrate results into sanitation upgrade planning and reef-water-quality monitoring.

Photo Matt Curnock / Ocean Image Bank

3.2.2 Quantify the spatial and ecological impacts of wastewater pollution and the benefits of improved sanitation for coral reefs

WHY THIS IS NEEDED:

Sanitation impacts are highly uneven across catchments and coastlines, and reef responses vary with hydrodynamics, habitat configuration, and disturbance history. Spatially explicit evidence is needed to identify where sanitation-derived pollution causes the greatest reef risk, which interventions are most likely to deliver detectable reef benefits, and how benefits vary across seasons and extreme events.

WHAT IS NEEDED:

Develop empirical and model-based links between sanitation loads and (i) nearshore water-quality exposure and (ii) coral reef response metrics. This includes defining appropriate spatial scales for assessment (e.g., sub-catchment to reef site), selecting sentinel indicators, and establishing dose-response relationships where feasible.

PRIORITY R&D TOPICS TO QUANTIFY THE SPATIAL AND ECOLOGICAL IMPACTS FROM WASTEWATER POLLUTION:

- **Select priority settings:** choose representative coral reef-connected catchments (e.g., small islands, tourism hubs, informal settlement settings) and define coral reef receiving areas;
- **Design sampling and monitoring:** deploy microbial tracers, nutrients, chlorophyll-a, turbidity, and dissolved oxygen measurements across gradients from sources to coral reefs, capturing baseline and event-driven pulses;
- **Quantify coral reef responses:** measure coral reef indicators likely to respond to improved sanitation (e.g., benthic algal cover, coral disease incidence, recruitment, and recovery trajectories) using repeatable protocols;
- **Model exposure and attribution:** integrate load estimates (Section 3.2.1) with transport/plume models to relate sanitation sources to reef exposure, and test alternative attribution approaches (e.g., source tracking, hydrodynamic modelling);
- **Evaluate intervention effects:** apply before-after-control-intervention (BACI) style designs where possible to detect changes following sanitation upgrades and quantify time-lags and uncertainty.

OUTPUTS AND HOW THEY WILL BE USED:

- Maps and models showing where sanitation-derived pollution most strongly affects coral reef exposure and condition;
- Evidence on which coral reef indicators respond to sanitation improvements, and over what timescales;
- Transferable study designs and protocols to support evaluation in other locations.

3.2.3 Quantify the economic costs of wastewater pollution and return on investment of reef protective interventions

WHY THIS IS NEEDED:

Sanitation upgrades compete with other infrastructure priorities, and the benefits for coral reefs and communities are often undervalued because costs of inaction are diffuse, delayed, and externalised. Robust economic evidence is needed to quantify avoided damages (e.g., reef-related tourism and fisheries losses, public health costs, and increased treatment costs), compare intervention options, and build the case for sustained investment in sanitation improvements that reduce reef-facing pollution.

WHAT IS NEEDED:

Develop valuation approaches and decision tools that connect sanitation pressures and interventions to (i) changes in coastal/reef water quality, (ii) reef condition and ecosystem services, and (iii) economic outcomes for households, businesses, and government. This should include consistent methods that can be applied across settings and scaled from site to national assessments. Frameworks should explicitly align outputs with national decision-making frameworks (e.g., nationally-determined contributions (NDCs), national action plans (NAPs), national development plans, tourism strategies, public health plans, and budget processes) so that sanitation investments can be assessed in terms that are relevant to government and financing institutions.

PRIORITY R&D TOPICS TO QUANTIFY THE COSTS AND BENEFITS OF ADDRESSING SANITATION DERIVED WATER POLLUTION:

- **Define pathways and endpoints:** specify which sanitation interventions are being assessed and the water-quality and reef endpoints used (e.g., microbial indicators, nutrients, turbidity, coral disease risk, algal cover, recruitment);
- **Quantify exposure and effectiveness:** link load estimates (Section 3.2.1) with expected reductions from interventions and translate to changes in nearshore concentrations/plumes;
- **Select valuation methods:** apply and compare approaches such as avoided damage costs, cost–benefit analysis, ecosystem-service valuation, and willingness-to-pay, with transparent assumptions;
- **Incorporate time and uncertainty:** account for lag times (e.g., ecological recovery), discounting, sensitivity analysis, and uncertainty bounds to avoid over-precision;
- **Test decision use-cases:** pilot the approach with real planning questions (e.g., which towns/catchments first; which technology mix) and iterate based on user feedback.

OUTPUTS AND HOW THEY WILL BE USED:

- Comparable cost–benefit results for sanitation options (including uncertainty) linked to reef-facing outcomes;
- Decision-support products for prioritising investment by hotspot, intervention type, and expected benefits;
- Reusable valuation templates and guidance that can be adapted across regions;
- Advance One Water valuation frameworks to capture system-wide co-benefits, including public health outcomes, ecosystem service benefits, climate adaptation and resilience, and water security.

FUNDING AND CAPACITY NEEDS:

Investment is needed to compile economic baselines, run pilot studies, and maintain datasets over time. Capacity building is also required to ensure local agencies can apply methods consistently and interpret results alongside ecological evidence.

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3.2.4 Develop evidence-based wastewater discharge standards (on-site and off-site), water quality guidelines, and policy frameworks aligned with coral reef protection goals

WHY THIS IS NEEDED:

Discharge thresholds and water-quality guideline values are often not designed for reef-connected settings, and may not reflect local hydrology, cumulative loads, or coral reef sensitivity. R&D is needed to develop evidence and methods that define defensible, coral reef-relevant benchmarks and translate them into usable guidance for sanitation system performance and discharge management.

WHAT IS NEEDED:

The development of an evidence base and technical approach for sanitation performance benchmarks and discharge targets that are protective of coral reefs and human health. This includes: (i) identifying critical pollutants/indicators, (ii) linking concentrations/loads to reef response thresholds, and (iii) specifying monitoring and compliance metrics that can be applied to on-site and off-site systems.

PRIORITY R&D TOPICS TO DELIVER EVIDENCE-BASED WASTEWATER DISCHARGE STANDARDS, GUIDELINES, AND POLICY FRAMEWORKS:

- **Define indicator sets:** prioritise reef-relevant indicators (e.g., microbial tracers, nutrients, oxygen demand proxies, turbidity) and align with feasible monitoring methods;
- **Compile treatment performance evidence:** synthesise performance data for common on-site, decentralised, and networked systems under real-world operating conditions, including failure modes and storm impacts;
- **Link exposure to coral reef response:** use empirical studies and modelling to relate discharge levels to nearshore exposure and reef response indicators (building on Section 3.2.3) and identify threshold ranges;
- **Develop benchmark guidance:** translate findings into tiered targets (screening to advanced), specifying when each tier is appropriate and how uncertainty should be reported;
- **Pilot and iterate:** trial benchmarks in case-study catchments to test feasibility, measurability, and interpretation, and refine based on monitoring results.

OUTPUTS AND HOW THEY WILL BE USED:

- Coral reef-relevant sanitation performance benchmarks and discharge target ranges for priority indicators;
- Monitoring and evaluation guidance to support consistent measurement and comparison of interventions;
- A transparent method that can be updated as new evidence emerges and applied across settings;
- Incorporate One Water principles into standards and guidelines, ensuring they reflect environmental, public health and water resource outcomes, not solely sanitation compliance.

FUNDING AND CAPACITY NEEDS:

Funding is needed for synthesis, targeted field studies, and pilot monitoring to parameterise thresholds. Capacity building is required to support consistent sampling, laboratory analysis, and data interpretation in reef-connected regions.

Photo Rickard Abom

Photo Rickard Abom

Case Study Box 1

Wastewater treatment improves coral reef water quality

Context:

Roatán, Honduras, sits at the heart of one of the world's most biodiverse coral reef systems, yet faced a severe sanitation deficit that was releasing untreated sewage — including nutrients, sediments, and pathogens — directly into reef-adjacent waters, threatening both ecosystem health and a tourism industry that attracts over one million visitors annually.

Intervention model:

Following community engagement initiated in 2011, the West End Wastewater Treatment Plant (WWTP) was built through a collaboration between the local government, donors, reef conservation NGO CORAL, and the community, with ongoing donor support expanding coverage to 97% of homes and businesses in West End and enabling treatment of 28 million gallons of wastewater per year. In parallel, CORAL and Mesoamerican Reef Fund supported the establishment of the first and only water quality laboratory in the Honduran insular region, managed by The Bay Islands Conservation Association providing the monitoring data needed to track progress, assess threats, and justify continued investment.

Technology and operations:

The plant, operated by Polo's Water Association Waterboard, provides secondary treatment through digestion, anoxic and aeration tanks, clarification, and chlorine disinfection prior to discharge. In 2020, the installation of 62 solar panels reduced daytime energy consumption by 80%, with cost savings reinvested into plant assessments and upgrade planning through to 2040 — a financial sustainability model built around strict revenue reinvestment and transparent community-based governance.

Photo Manlio Martinez

Why it matters for coral reefs:

By intercepting and treating wastewater that would otherwise discharge nutrients, pathogens, and sediments directly into reef-adjacent waters, the WWTP directly addresses one of the most acute and proximate drivers of coral reef degradation in densely populated island and coastal tourism settings. The co-location of a water quality monitoring laboratory further strengthens the reef protection value of this intervention by generating the evidence needed to detect pollution threats, enforce standards, and build the case for sustained sanitation investment.

R&D implications for proposal development:

This case study demonstrates that community-based sanitation management models can achieve high coverage, long-term operational sustainability, and measurable reef water quality benefits when financial planning, participatory governance, and monitoring infrastructure are built in from the outset. Key lessons for R&D and proposal development include the importance of embedding a management model that includes financial sustainability mechanisms, including revenue reinvestment and energy cost reduction, alongside the technical intervention and the critical role of locally operated water quality data systems in sustaining stakeholder engagement, regulatory enforcement, and investor confidence over the long term.

Source:

CORAL Reef Alliance

4 Priority area 2
Best practice management of agriculture and integrated land-sea systems

4.1 Sources, pathways, and receptors of pollution

4.1.1 Sources

Agriculture and integrated land-use systems (i.e., crops, livestock, forestry) remain some of the dominant sources of nutrient, sediment, and contaminant loads entering rivers, wetlands, lagoons, and coastal zones (Kaushal *et al.*, 2014; Sahavacharin *et al.*, 2022; Mir *et al.*, 2025). Runoff containing nitrogen and phosphorus contributes to eutrophication and algal blooms (Devlin *et al.*, 2012; Brodie *et al.*, 2013; Devlin & Brodie, 2023), while soil erosion from poorly protected slopes and degraded riparian zones increases turbidity and sedimentation in downstream ecosystems (Hairsine, 2017; Sahavacharin *et al.*, 2022). For coral reefs, these land-based loads reduce light availability, promote macroalgal dominance, oxygen depletion, and increase sediment stress that can smother corals, limit recruitment, and slow post-disturbance recovery (Brodie *et al.*, 2011; Wenger *et al.*, 2015; Johnson *et al.*, 2021; Pezner *et al.*, 2023).

4.1.2 Pathways

Surface runoff is one of the most significant pathways through which landscapes deliver nutrients and contaminants to coral reefs (Carlson *et al.*, 2019; Devlin *et al.*, 2023). When inorganic and organic fertilisers like manure are applied in amounts that exceed crop uptake or at the wrong time relative to rainfall, dissolved nitrogen and phosphorus accumulate on the soil surface and in shallow soil layers. Intense rainfall events, common in tropical and subtropical climates, mobilise these dissolved nutrients and rapidly transport them into rivers, wetlands, and coastal lagoons. Poor soil infiltration, compacted ground, and limited vegetation cover further increase the proportion of rainfall that becomes nutrient-laden runoff. In many catchments, these nutrient pulses drive eutrophication, harmful algal blooms, oxygen depletion, and long-term declines in water clarity and aquatic ecosystem health (Wurtsbaugh *et al.*, 2019; Brush *et al.*, 2020; Johnson *et al.*, 2021; Pezner *et al.*, 2023).

4.1.3 Receptors

Erosion processes increase the delivery of fine sediments and particulate-bound nutrients to nearshore coral reefs, particularly where gully formation, hillslope erosion, and streambank collapse accelerate following land clearing, overgrazing, and the removal of riparian vegetation (Brodie *et al.*, 2013; Bainbridge *et al.*, 2024). The mobilised soils carry particulate-bound nutrients into waterways, where they accumulate in riverbeds, estuaries, and lagoon floors. These deposited sediments act as “legacy nutrient stores,” slowly releasing phosphorus under low-oxygen or disturbed conditions and prolonging water quality problems even when upstream fertiliser inputs are reduced (Howarth *et al.*, 2011; Devlin & Brodie, 2023). Transported fine sediments also increase turbidity, smother seagrass and coral habitats, and deliver additional contaminants (e.g., pesticides or heavy metals) to these ecosystems (Jones *et al.*, 2019). This erosion-driven nutrient loading is especially acute in tropical catchments where high-intensity rainfall and steep terrain accelerate soil loss.

These pollution pathways are amplified by structural challenges across many rural and coastal landscapes. Farmers can lack reliable access to best-practice knowledge, extension services, and access to soil and water testing, which limits their ability to implement precision nutrient management or erosion-control measures. Financial constraints and weak market incentives can discourage investment in sustainable land management, improved feed systems, or better waste-handling infrastructure. At the same time, fragmented land use, limited enforcement capacity, limited ability to implement best practice management, and the absence of integrated catchment planning create barriers to coordinating actions across farms, villages, and industry operators.

As climate pressures intensify, through more intense rainfall, prolonged dry seasons, or saltwater intrusion, these watersheds and associated coral reef ecosystems become even more vulnerable (McLaughlin *et al.*, 2003; D'Olivo *et al.*, 2013; Bricheno *et al.*, 2023). Extreme weather events can increase runoff volumes, overwhelm erosion controls, and mobilise stored nutrients and contaminants into the downstream coral reef environments. Without targeted support, coordinated planning, and improved technical options, the contribution of agriculture and integrated systems to downstream water quality degradation is likely to grow, undermining both agricultural productivity and ecosystem resilience.

4.1.4 Monitoring and indicators

Monitoring should connect farm and catchment changes to reef exposure, tracking nutrient loads (nitrogen and phosphorus), suspended sediments/turbidity, and relevant contaminants (e.g., pesticides) alongside reef response metrics such as water clarity at reefs, benthic algal cover, coral recruitment, coral disease incidence, and post-disturbance recovery.

4.2 Responses & enabling actions: Identified R&D priorities

Research and innovation are needed to better understand parts of the system, support solutions already being utilised, develop more cost-effective tools for monitoring and evaluation, and improve collaboration and capacity building between stakeholders. Priority areas include defining thresholds for pollutant loads, identifying hotspots for pollution, and advancing research regarding pollutant impacts on ecosystem sensitivity and resilience. For coral reefs, this includes quantifying how nutrient enrichment, turbidity, sediment deposition, and contaminant mixtures translate into reef condition and recovery outcomes (e.g., benthic algal cover, coral recruitment, disease prevalence, and bleaching recovery trajectories). The development of low-cost monitoring and data collection technology would also enable the evaluation of solution effectiveness and impact, including tracking both catchment indicators and reef-facing endpoints at priority receiving reefs.

A strong R&D agenda must also integrate social, economic, and health dimensions along with ecological aspects. One Health studies linking pollution with human health outcomes and socio-economic impacts will provide powerful evidence to support policy change and investment, particularly where communities depend on reef fisheries, tourism, and coastal protection services. Research into human behavioural drivers, incentive programs, and the effectiveness of certification and supply-chain interventions will help scale best practices more rapidly. Collaboration, knowledge transfer, and capacity building between all actors in the system will be critical to the success of future implementation and uptake for any identified solutions. Together, these R&D priorities will enable countries to support robust, adaptive, and future-proof production systems that protect both livelihoods and coral reef ecosystems downstream. The priorities are intended to support a practical progression from diagnosing the system, to testing interventions, monitoring outcomes, incentivising adoption, and scaling approaches that can be replicated across catchment-to-reef settings. Farmer adoption is central to this progression, because agricultural water quality solutions will only deliver sustained reef benefits where they are economically viable, locally acceptable, supported by extension systems, and linked to incentives that reduce risk and reward long-term practice change.

Consultations during and after the workshop have identified the following R&D priorities for the best practice management of agriculture and integrated land-sea systems (Table 3).

Table 3. Summary table of R&D priorities and rankings identified for the Best Practice Management of Agriculture and Integrated Land-sea Systems priority area.

		Assessment factor		
Evidence gaps	**R&D priorities addressing gaps**	**Feasibility**	**Impact**	**Cost-effectiveness**
Theme: Understanding the system – Reef exposure pathways and hotspots (agriculture→ coast→ reefs)				
Critical gaps remain in the spatial resolution and comprehensiveness of pollutant source attribution, limiting the ability to target interventions where they will deliver the greatest water quality gains.	High-resolution hotspot mapping and load apportionment (nutrients, sediments, pesticides) using integrated field data, remote sensing, and models to prioritise reefs and sub-catchments for action.	High	High	High
	Coral reef-facing exposure and response links: quantify how land-based loads and plume metrics translate into reef thresholds and outcomes (water clarity, algal cover, coral recruitment, coral disease risk, recovery). Innovation in delivery pathway modelling (storm pulses, groundwater, legacy stores) to predict when/where pollutants reach coral reefs and the time-lags to improvement.	High	High	Medium
Theme: Successful solutions – Reef-protective innovations in farm practice and land management				
Evidence on the real-world performance, cost efficiency, and broader co-benefits of water quality interventions remains fragmented and inconsistent, undermining the ability to compare and prioritise investment across management options.	Develop, pilot, and scale precision agriculture and runoff-reduction technologies (e.g., variable-rate nutrient application, smart irrigation, manure treatment/containment, erosion controls) with measurable coral reef benefits. Performance and cost-effectiveness evidence: evaluate intervention portfolios (technology + practice + NbS) using robust designs that link catchment change to reef outcomes.	Medium	High	High
The behavioural, cultural, and economic barriers that prevent adoption of known effective management practices are insufficiently understood, leaving a persistent gap between what is technically feasible and what is implemented.	Innovation in incentives and adoption systems (certification/supply-chain levers, blended finance) to accelerate uptake and maintenance at scale.	High	Medium	High
There is limited understanding of how interventions interact with one another and how their effects propagate across different spatial scales and time horizons, creating risk of unintended consequences and missed synergies.	Assess interactions and trade-offs across space/time (legacy nutrients, climate extremes) to optimise sequencing and placement for maximum coral reef benefit.	Low	High	Medium

Table 3. Summary table of R&D priorities and rankings identified for the Best Practice Management of Agriculture and Integrated Land-sea Systems priority area. (continued)

Evidence gaps	R&D priorities addressing gaps	Assessment factor: Feasibility	Impact	Cost-effectiveness
Theme: Monitoring and evaluation (including new technologies)				
Existing monitoring networks are too sparse, costly, and slow to provide the resolution and coverage needed to detect change, validate interventions, and support adaptive management in real time.	Develop and validate low-cost sensors, automated samplers and reef-ready monitoring packages for nutrients (N and P), turbidity/sediments, and priority pesticides/contaminants (including storm-event capture). Advance remote sensing/drone methods for sediment and nutrient plume detection, erosion features, land-use risk indicators, and intervention tracking, integrated with ground truthing and coral reef monitoring. Build interoperable data platforms, dashboards and decision-support tools to link farm actions > catchment loads > reef exposure > reef response.	Medium	High	Medium
Systematic evidence on what governance structures, policy instruments, and management programs actually deliver measurable water quality improvements is lacking, limiting the ability to replicate success and reform underperforming approaches.	Innovate in evaluation approaches and uncertainty reporting so programmes can credibly demonstrate coral reef outcomes.	High	Medium	High
Theme: Collaboration, capacity building, and knowledge transfer				
The absence of structured mechanisms for sharing data, methods, and lessons across jurisdictions and disciplines means that knowledge generated in one context is frequently not mobilised to inform practice elsewhere.	Co-design innovation pilots with farmers, communities, Indigenous partners, and agencies, ensuring technologies are usable, affordable, and maintained. Create communities of practice and shared learning networks to accelerate scaling, share failure learning, and harmonise coral reef-facing indicators.	Medium	High	High
Uptake of best-practice approaches is constrained by uneven access to skills, tools, and technical guidance, particularly in under-resourced regions where water quality pressures are often most acute.	Develop toolkits, training, and extension packages (including digital tools) to support adoption of new practices or technologies and consistent monitoring.	High	Medium	High

4.2.1 Understanding the system: Reef exposure pathways and hotspots

WHY THIS IS NEEDED:

Diffuse pollution from agriculture and mixed land uses is spatially variable, episodic (storm-driven), and often poorly attributed. Without robust, spatially explicit evidence on sources, delivery pathways, and reef-facing exposure, investments risk being misdirected and insufficient to protect the most sensitive reefs, particularly under increasing climate variability.

WHAT IS NEEDED:

Integrated approaches that combine catchment monitoring, geospatial analysis, and modelling to (i) quantify nutrient, sediment, and contaminant loads, (ii) identify hotspots and delivery mechanisms to receiving reefs, and (iii) define reef-relevant thresholds and indicators that can be used to target and evaluate interventions.

PRIORITY R&D TOPICS TO UNDERSTAND THE SYSTEM:

- **Hotspot identification and load apportionment:** develop harmonised methods and datasets to quantify loads from crops, livestock, forestry, roads, and mixed land uses, including event-driven pulses and seasonality;
- **Fate, transport, and delivery to reefs:** improve models that link hillslope/gully/streambank erosion and nutrient mobilisation to river export and coastal plume exposure at coral reef sites (including groundwater where relevant);
- **Legacy nutrients and sediments:** quantify storage, remobilisation, and time-lags (e.g., sediment banks/ estuary stores) that delay reef improvements after practice change;
- **Coral reef response and sensitivity:** strengthen empirical links between catchment loads/exposure metrics (nutrients, turbidity/suspended sediments, pesticides/mixtures) and coral reef response indicators (e.g., benthic algal cover, coral recruitment, coral disease prevalence, recovery after coral bleaching), as well as associated environmental conditions such as dissolved oxygen dynamics (including hypoxia and diel oxygen variability), pH, and temperature;
- **Emerging pollutants and mixtures:** evaluate newer pesticides, veterinary pharmaceuticals, and combined-stressor effects relevant to reef-connected agricultural catchments;
- **Climate and extreme event effects:** quantify how changing rainfall intensity, drought-to-flood transitions, and saltwater intrusion alter load generation and delivery, and implications for reef recovery timelines.

OUTPUTS AND HOW THEY WILL BE USED:

- Maps and datasets identifying priority sub-catchments and coastal receiving areas driving reef exposure;
- Scenario tools to test alternative intervention portfolios and predict expected reductions in reef-facing exposure;
- Evidence to support setting reef-relevant thresholds/ targets for nutrients, sediments, and priority contaminants.

FUNDING AND CAPACITY NEEDS:

Sustained investment is needed for multi-season monitoring (including extreme events), analytical capacity (nutrients, sediments, contaminants), maintaining interoperable datasets, and developing prediction models. Capacity building is required so local agencies and partners can run analyses, interpret uncertainty, and apply outputs in catchment planning linked to reef monitoring.

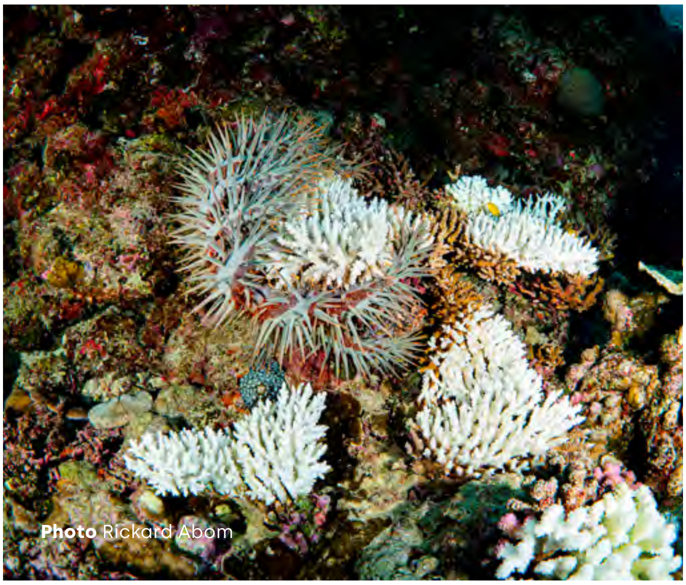
Photo Rickard Abom

4.2.2 Successful solutions: Reef protective innovations in farm practice and land management

WHY THIS IS NEEDED:

A wide range of best management practices and integrated land–sea interventions are promoted, but evidence of performance under real-world conditions is often inconsistent, context-specific, or not linked to reef-facing outcomes. Without defensible evidence on effectiveness, cost, co-benefits, and time-lags, programmes risk investing in measures that do not deliver measurable improvements for coastal water quality and coral reef condition.

WHAT IS NEEDED:

Comparative evaluation of intervention options (single measures and integrated systems) that links (i) changes in land management to (ii) changes in catchment/coastal water quality and (iii) reef response indicators. Research should also address adoption drivers, financing and incentive design, and scale interactions (where/when combinations of interventions deliver the greatest reef benefit).

PRIORITY R&D TOPICS FOR SUCCESSFUL SOLUTIONS:

- **Effectiveness and cost-effectiveness of interventions:** quantify pollutant reductions and reef-facing outcomes for priority practices (e.g., nutrient management and organic fertilizer processing, riparian buffers, erosion controls, gully remediation, managed grazing, pesticide risk reduction), including maintenance requirements and failure modes;
- **Co-benefits and trade-offs:** evaluate effects of interventions on soil health, farm productivity, biodiversity, greenhouse gases, and community wellbeing alongside water-quality and coral reef metrics;
- **Certification and supply-chain levers:** assess whether certification/market mechanisms measurably reduce pollutant losses and under what governance conditions they work;
- **Spatial and temporal interactions:** quantify time-lags and cumulative effects, identify where interventions interact positively/negatively across sub-catchments, and determine optimal sequencing (e.g., source controls vs pathway measures) for reef benefits;
- **Evaluation designs for reef outcomes:** develop practical BACI/paired-catchment designs and monitoring packages that can detect change in reef exposure and response (e.g., turbidity/sedimentation at reefs, benthic algal cover, recruitment, disease signals).

OUTPUTS AND HOW THEY WILL BE USED:

- Decision-support evidence on “what works, where, and at what cost” for reducing reef-facing exposure;
- Guidance on intervention portfolios and sequencing to maximise coral reef benefits under realistic timelines;
- Templates for evaluation and reporting (including uncertainty) to enable comparison across projects and geographies.

FUNDING AND CAPACITY NEEDS:

Long-term field trials and monitoring are needed to capture lag effects and climate variability. Funding is also required for socio-economic research and for building local capability to implement consistent monitoring, collect adoption data, and translate findings into incentive programmes and catchment planning.

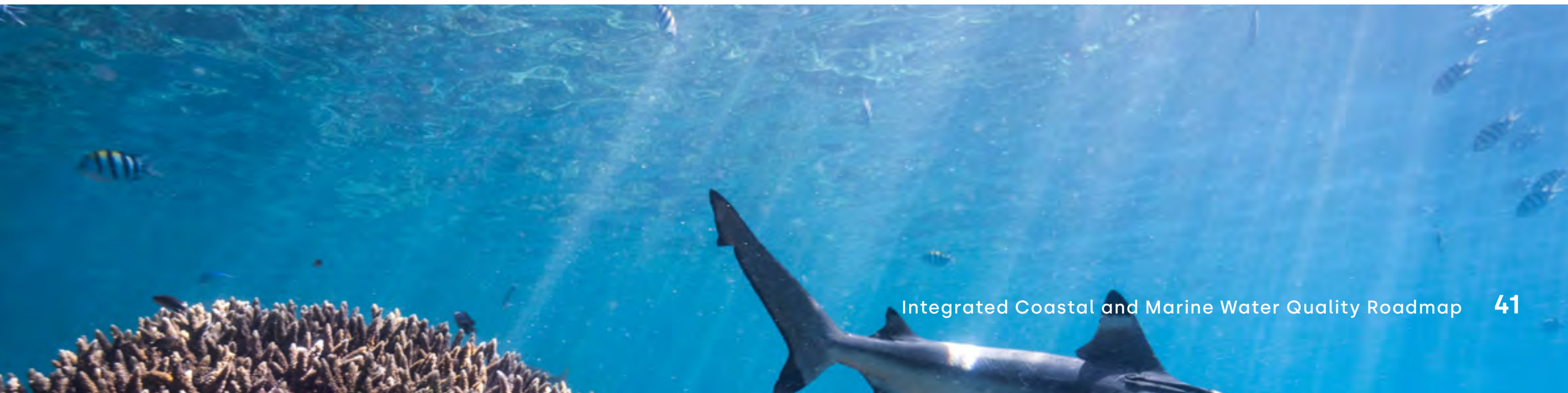


Photo Tom Vierus / Ocean Image Bank

4.2.3 Monitoring and evaluation (including new technologies)

WHY THIS IS NEEDED:

Agricultural and diffuse pollution is highly variable in space and time, yet monitoring is often too sparse, expensive, or technically demanding to support adaptive management. Without accessible monitoring and evaluation approaches, it is difficult to attribute sources, track progress, demonstrate intervention effectiveness, or link catchment actions to reef-facing exposure and reef response.

WHAT IS NEEDED:

Fit-for-purpose monitoring systems that combine low-cost *in situ* sensors, targeted sampling, remote sensing, AI-assisted data analysis, and modelling to measure nutrients, suspended sediments/turbidity, and priority contaminants, alongside reef response indicators. These systems should feed into decision-support tools that enable hotspot identification, intervention targeting, and before-after evaluation.

PRIORITY R&D TOPICS FOR MONITORING AND EVALUATION:

- **Low-cost sensor and sampling packages:** develop and validate robust field methods for turbidity/suspended sediments, N and P forms, and priority pesticides/contaminants, suitable for local agencies and community partners;
- **Remote sensing and plume detection:** advance satellite/drone approaches to detect sediment and nutrient plumes, erosion features, and land-use risk indicators, and integrate with ground-truthing and AI support;
- **Data platforms and interoperability:** create shared, open (where possible) data standards, workflows, and dashboards that combine land management, hydrology, and water quality with reef monitoring outputs;
- **Evaluation and attribution designs:** develop practical designs (paired catchments, BACI where feasible) and statistical approaches that quantify uncertainty and detect change under climate variability;
- **Policy and programme evaluation:** assess how incentive schemes, compliance approaches, and governance arrangements influence adoption and measurable water-quality/reef outcomes.

OUTPUTS AND HOW THEY WILL BE USED:

- Monitoring toolkits and protocols that can be deployed at farm/sub-catchment and coastal receiving scales;
- Integrated dashboards/maps supporting hotspot targeting and tracking progress toward reef-relevant thresholds;
- Comparable evaluation evidence on intervention performance (including uncertainty) to inform investment and policy.

FUNDING AND CAPACITY NEEDS:

Investment is needed for validation studies, equipment procurement and maintenance, training, and long-term data stewardship. Capacity building should include laboratory techniques, field skills, quality assurance/quality control, data management, and interpretation so monitoring outputs reliably inform adaptive management and reef protection decisions.

4.2.4 Collaboration, capacity building, and knowledge transfer

WHY THIS IS NEEDED:

Improving agricultural and diffuse-source pollution requires coordinated action across landholders, communities, agencies, and supply chains. Evidence and tools often remain siloed, and limited extension and training capacity can prevent proven approaches from being adopted and maintained long enough to deliver reef benefits.

WHAT IS NEEDED:

Co-produced research and learning systems that translate evidence into practice — through extension materials, training, peer-to-peer networks, and decision-support products — aligned to local contexts and institutional roles. Knowledge transfer should explicitly connect catchment actions to reef-facing indicators so stakeholders can see and track progress.

PRIORITY R&D TOPICS FOR COLLABORATION, CAPACITY BUILDING, AND KNOWLEDGE TRANSFER:

- **Co-design and co-production models:** test approaches that embed farmers, communities, Indigenous partners, and agencies in project design, monitoring, and interpretation;
- **Extension and training effectiveness:** evaluate which communication, training, and advisory models deliver sustained adoption and measurable outcomes;
- **Knowledge products that support action:** develop practical guidance, decision trees, and implementation toolkits for priority practices, tailored for different user groups;
- **Learning networks and benchmarking:** create mechanisms for sharing lessons across catchments/countries (including failure learning), with consistent metrics for comparison;
- **Impact assessment:** evaluate effectiveness of means of dissemination and communication.

OUTPUTS AND HOW THEY WILL BE USED:

- Capacity-building packages (training modules, field guides, implementation checklists) for land managers and local agencies;
- Knowledge-sharing mechanisms (communities of practice, peer learning, regional exchanges) linked to comparable indicators;
- Practical materials that enable scaling of effective interventions and improve consistency of implementation and monitoring.

FUNDING AND CAPACITY NEEDS:

Dedicated funding is required for extension delivery, facilitation, translation/adaptation of materials, and sustained engagement with communities and landholders. Resourcing should also cover long-term support for monitoring and data use, so collaboration efforts translate into measurable water-quality and reef outcomes.

Photo Jona Uluinaceva

Case Study Box 2
Malawi Deep Bed Farming innovation

Context:

In Malawi, chronic soil erosion, declining crop yields, and widespread runoff from smallholder rain-fed farms were contributing to degraded catchments, reduced groundwater recharge, and declining downstream water quality. Conventional ridge farming was estimated to cause the loss of approximately 29 tonnes of topsoil per hectare per year, along with nutrients and rainfall that would otherwise infiltrate soils. These conditions exacerbated food insecurity and vulnerability to climate extremes such as droughts and cyclones, creating an urgent need for interventions that simultaneously addressed livelihoods and watershed health.

Intervention model:

Deep Bed Farming was developed and implemented by the Malawian NGO Tiyeni, with strong farmer participation, alignment with Food and Agriculture Organization of the UN recommendations on breaking soil compaction, and sustained engagement with government agencies. The approach scaled rapidly through farmer-to-farmer learning and district-level adoption. Multi-year government-led trials across agroecological zones confirmed improvements in crop yields, soil moisture retention, and water infiltration, leading to formal government approval and integration into national agricultural extension services.

Technology and operations:

Deep Bed Farming consists of rows of crops separated by deep boxed furrows aligned along contours, which capture rainwater and allow it to infiltrate de-compacted soil rather than running off planting beds or evaporating (Figure 5). Once established, the permanent contour-aligned beds require less labour over time and continuously improve soil structure. The system is low-cost and low-technology, requiring no specialised inputs beyond farmer knowledge and initial labour investment, making it highly replicable across other rain-fed agricultural systems in similar agroecological contexts.

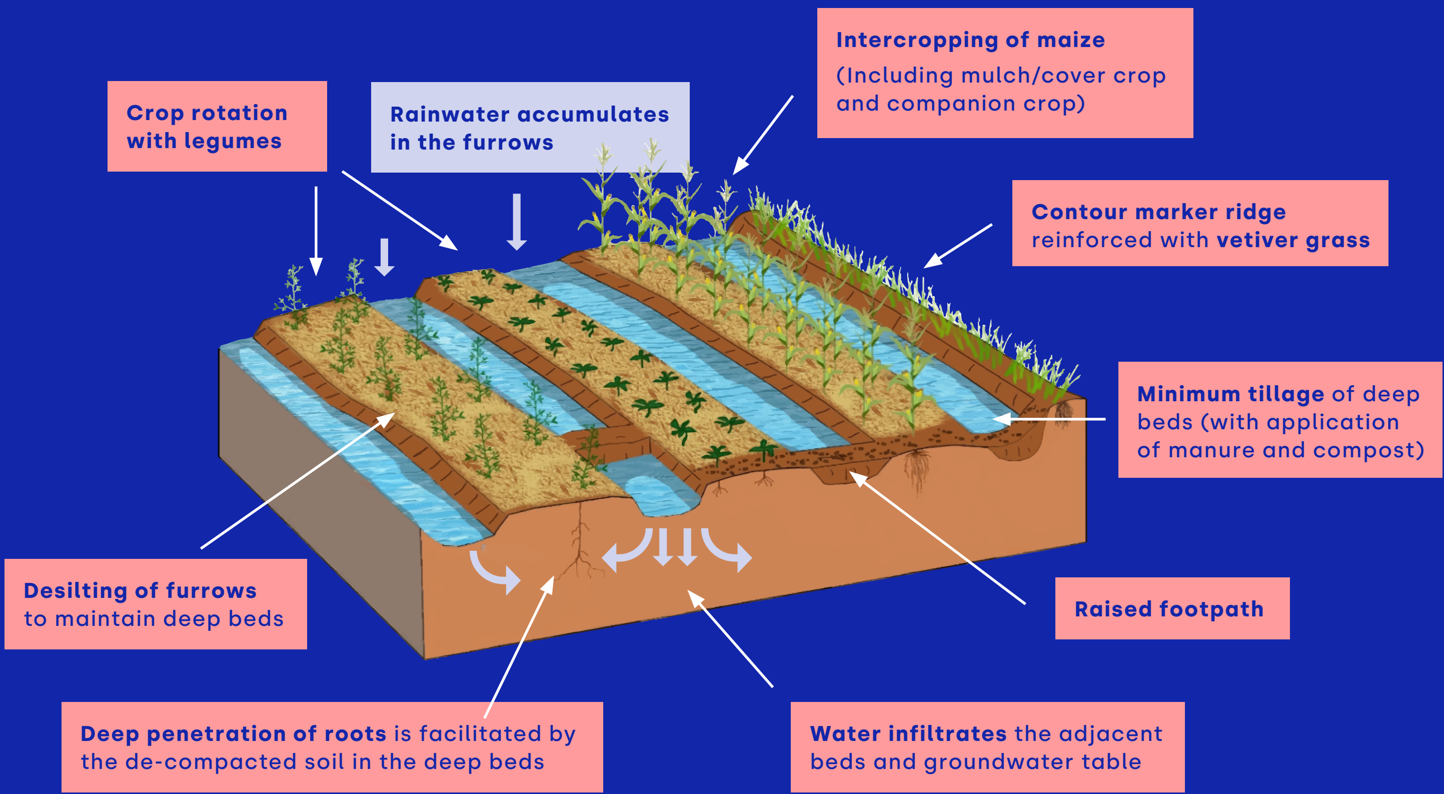

Figure 5. Diagram illustrating the Deep Bed Farming technique. Image credits: Tyeni.

Why it matters for coral reefs:

Even though Malawi has no marine coral reefs, the approach is relevant for marine system protection. By dramatically reducing topsoil loss and surface runoff, deep bed farming directly addresses one of the primary terrestrial drivers of downstream water quality degradation (e.g., sediment and nutrient loading) that smothers coral reefs, reduces light penetration, and drives algal overgrowth in coastal marine environments. Interventions that retain water and nutrients within the soil profile at the catchment scale reduce the volume and concentration of pollutant loads entering waterways and ultimately reaching reef systems, demonstrating that agricultural NbS can deliver water quality benefits well beyond the farm boundary. Further, the approach can be implemented on a large scale in mechanised systems.

R&D implications for proposal development:

This case study illustrates the importance of integrating food security, economic, and water quality co-benefits into the framing of agricultural NbS, as this alignment was critical to achieving government validation and large-scale adoption. Key lessons for R&D proposal development include the value of participatory demonstration models, the role of government validation in enabling scaling up solutions, and the need to quantify downstream water quality outcomes alongside on-farm productivity gains.

Source:

Tiyeni

Photo Tiyeni

5

Priority area 3
Effective Nature-based Solutions to improve coral reef water quality

5.1 Context and drivers for NbS to protect coral reefs

Nature-based Solutions (NbS) are increasingly central to improving water quality for coral reefs because they use living systems to intercept, retain, and transform pollutants before they reach reef habitats (Morais *et al.*, 2020; Jordan & Fröhle, 2022; Ribas, 2024). In reef-connected catchments and coastal zones, NbS can reduce nutrient enrichment, fine sediment delivery, turbidity, and contaminant exposure — stressors that suppress coral recruitment, increase disease risk, oxygen depletion, and slow recovery after bleaching (Moazzem, 2024; Curtis, 2026; Morelato *et al.*, 2026). Reef-relevant NbS include restored or constructed wetlands and riparian buffers that trap sediments and take up nutrients, mangroves and seagrass meadows that stabilise sediments and attenuate plumes, and oyster reefs, seaweed and microalgae systems that filter water and assimilate nutrients in targeted coastal receiving areas (Jordan & Fröhle, 2022; Ribas, 2024; May, 2025; Kasprzyk, 2025).

For coral reef settings, NbS are most effective when designed as reef-protective infrastructure — sited and sized to reduce reef-facing exposure during both baseline conditions and storm-driven pollution pulses. They can complement or, in some contexts, substitute for coastal infrastructure by providing multiple services at once: improved water quality, shoreline protection, biodiversity and blue-carbon benefits, fisheries, and livelihood options (Paxton *et al.*, 2024; de Magalhães *et al.*, 2026). However, reef programmes often struggle to scale NbS because performance is not consistently quantified against reef-relevant endpoints (e.g., water clarity at reefs, plume duration, benthic algal cover, coral disease incidence, recruitment and recovery). Uncertainty around long-term effectiveness, maintenance requirements, and performance under extreme events can also limit investment and constrain innovation (Pontee *et al.*, 2016; Paxton *et al.*, 2023).

Updating the NbS evidence base for coral reefs, therefore requires targeted R&D and enabling conditions that make these approaches deployable, measurable, and fundable. The first priority is to test which NbS interventions work in reef-connected settings—through field trials and demonstration projects that quantify pollutant interception and clarify feasibility, cost, maintenance needs, co-benefits, and potential trade-offs under local hydrology and extreme events. Building on this, priorities include: (i) practical siting and optimisation tools that link catchment loads and coastal circulation to reef receiving areas; (ii) standardised monitoring packages that demonstrate pollutant removal and reef response; and (iii) governance and financing pathways that support long-term stewardship (including hybrid grey-green designs where needed). Demonstration sites co-designed with communities, Indigenous partners, and practitioners are critical for building confidence, testing innovations, and generating transferable lessons, so NbS can be scaled as a core part of catchment-to-reef water quality programmes.

In this roadmap, the success of NbS interventions is defined by their ability to reduce reef exposure to land-based pollution and to support measurable improvements in coral reef condition and resilience.

Nutrient and sediment runoff from agriculture, settlement expansion, and poorly managed land-use continue to place significant direct pressure on coral reefs (and associated seagrass and mangrove systems) (Brodie *et al.*, 2013; Carlson *et al.*, 2019). Excess nitrogen and phosphorus fuel algal overgrowth, reduce water clarity, and weaken the competitive balance between corals and nuisance algae, undermining coral recruitment and recovery after bleaching events, and increasing the risk of disease (Haapkylä *et al.*, 2011; Thompson *et al.*, 2014; Wenger *et al.*, 2016). Interruptions to the lifecycles of key fauna (e.g. herbivorous fish, turtles) due to coastal habitat degradation, create indirect pressures that exacerbate impacts, but could be alleviated by NbS (Rogers & Mumby, 2019).

These pressures are compounded by gaps in planning, design, and investment that limit the deployment of NbS. Despite their potential to stabilise coastlines, trap sediments, and attenuate nutrient flows, NbS are often not fully integrated into engineering standards, coastal hazard planning, or climate adaptation finance pipelines. Many projects default to hard infrastructure, even where ecological options could provide greater long-term resilience and lower life-cycle costs. The absence of standardised design tools, performance benchmarks, and valuation methods restricts broader uptake of wetlands, mangroves, oyster reefs, and hybrid grey-green systems. As a result, opportunities to restore natural processes, enhance ecological resilience, and reduce pollution at its source remain underutilised. For nature-based solutions, monitoring should demonstrate both pollutant interception (e.g., nutrient and sediment reduction, plume extent and duration) and reef response (e.g., improved water clarity at reefs, reduced benthic algal cover, lower coral disease incidence, and improved recruitment and recovery after bleaching).

Photo Srikanth Mannepuri / Ocean Image Bank

5.2 Responses and enabling actions: Identified R&D priorities

The NbS R&D priorities identified in the workshop are framed around a single test of success: do NbS measurably improve reef water quality and coral reef health? This requires moving beyond generic “habitat restoration” toward reef-protective designs that can be deployed, compared, and scaled. The first priority is therefore to identify and field-test the NbS interventions that work best for reefs (and in which settings), quantifying both pollutant interception (nutrients, sediments/turbidity, pathogens, and priority contaminants) and reef response (e.g., water clarity at reefs, benthic algal cover, coral disease incidence, recruitment, and post-bleaching recovery). Trials should explicitly consider storm-pulse performance, maintenance requirements, and feasibility constraints so that “what works” is defined in practical, investable terms.

A second priority is innovation in NbS design for reef-connected hydrodynamics — understanding how different systems (e.g., mangroves, seagrass, salt marshes, oyster/biogenic reefs, seaweed farms, wetlands) change sediment and nutrient plume pathways, mixing, resuspension, and light climate in lagoons and nearshore reef areas. R&D should develop and validate eco-hydrodynamic and biogeochemical models that can predict where NbS will reduce reef exposure most (including during cyclones, king tides, and flood pulses), and test hybrid grey-green concepts (e.g., sediment traps and living shorelines; engineered wetlands and permeable barriers) that deliver reliable performance when ecological systems alone are insufficient.

A third priority is reef-ready monitoring, reporting, and verification (MRV) to demonstrate outcomes and de-risk investment. Innovation is needed in low-cost, low-maintenance sensor networks (nutrient species, turbidity/suspended sediments, dissolved oxygen, chlorophyll-a, microbial indicators) and remote sensing/AI tools to detect plumes, map NbS condition, and track reef response (e.g., coral cover, benthic algae, bleaching impact and recovery signals). Critically, R&D should standardise reef-facing performance metrics that link NbS function with reduced exposure (plume extent/duration, clarity) with improved reef condition, enabling comparable evaluation across sites and faster learning about what can be scaled.

Photo Envato

Finally, NbS innovation must be paired with reef-specific safeguards and long-term performance evidence. R&D should assess ecological and operational risks (e.g., invasive potential of macroalgae, altered hydrodynamics that increase reef sediment resuspension, unintended nutrient release during extremes, greenhouse-gas trade-offs in wetlands, changes in microbial communities and disease dynamics).

Consultations during and after the workshop have identified the following table of R&D priorities for effective NbS for coral reef water quality (Table 4).

A fourth priority is to quantify how NbS support coral reef resilience, not only through nutrient and sediment reduction but through mechanisms that influence reef recovery capacity. Research should test whether NbS interventions measurably improve light availability, reduce algal dominance, alter microbial and disease risk, support herbivore biomass and fish communities, enhance larval connectivity, and provide local pH/oxygen buffering in reef-adjacent waters. This is an area for genuine innovation — particularly for biogenic filtration systems (oyster/biogenic reefs), seaweed/microalgae biofilters (including harvestable biomass pathways), and co-designed living shoreline approaches that deliver multiple reef-relevant benefits and financeable co-products (blue carbon, livelihoods, circular bioeconomy options).

A fifth priority is developing reef-targeted siting and optimisation tools that tell practitioners where NbS will deliver the greatest reef benefit per unit investment. These tools should integrate catchment loads, hydrodynamics/circulation, reef vulnerability and value (e.g., nursery reefs, tourism reefs, restoration sites), land/sea tenure constraints, and future climate risk. Outputs should support practical questions such as: which reefs are most exposed? Which interception points matter most? And what portfolio of NbS (and hybrids) reduces exposure fastest? Co-location opportunities, such as NbS integrated with wastewater outfalls, tourism infrastructure, or farm drainage, should be evaluated explicitly for scalability, maintenance burden, and reef-health outcomes.

Photo Rickard Abom

Table 4. Summary table of R&D priorities and rankings identified for the effective NbS to improve coral reef water quality priority area.

Evidence gaps	R&D priorities addressing gaps	Assessment factor		
		Feasibility	**Impact**	**Cost-effectiveness**
Theme: Demonstrate what works: Reef-protective NbS trials				
Investigate the potential to increase coral reef resilience through the co-location with NbS. There is also limited information regarding the longevity of restored habitats and the maintenance costs associated with regenerated habitats. This information would be critical to the establishment of efficient adaptive management frameworks.	Field-test and compare NbS for reef-facing pollutant interception and reef response (clarity, algal cover, recruitment, disease signals).	Medium	High	Medium
	Quantify feasibility/maintenance and storm-pulse performance.	Medium	High	Medium
	Produce transferable reef-protective design specifications for scaling.	High	High	High
Theme: Reef thresholds & cumulative impact modelling				
Lack of understanding regarding the nutrient and contaminant levels that create stress in coral ecosystems. Regulations cannot protect these ecosystems without an understanding of the thresholds that should be allowed.	Define reef-relevant thresholds/targets for nutrients, turbidity/sediment, and priority contaminants (including pulse exposure).	Low	Medium	High
	Model pollution × warming/bleaching/disease interactions to predict recovery benefits of NbS.	Medium	High	Medium
	Translate thresholds into decision tools for NbS sizing or placement.	Medium	Medium	Medium
Theme: Coastal NbS & co-location to protect priority reefs (blue-green infrastructure)				
Investigate the potential to increase coral reef resilience through the co-location with other marine ecosystems and NbS. The spatial conditions required for restoration to deliver the greatest and most durable ecosystem service benefits remain unclear, constraining the design of restoration programmes for maximum reef protection outcomes.	Optimise living shorelines to reduce sediment resuspension, improve light, and reduce plume exposure.	High	High	Low
	Test co-location with point sources (outfalls/stormwater), including seaweed/microalgae biofilters and hybrids.	Low	High	Low
	Assess ecological safety and operations and maintenance (O&M) pathways.	Medium	Medium	Medium

Table 4. Summary table of R&D priorities and rankings identified for the effective NbS to improve coral reef water quality priority area. (continued)

Evidence gaps	R&D priorities addressing gaps	Assessment factor		
		Feasibility	**Impact**	**Cost-effectiveness**
Theme: Reef-ready MRV technologies				
A fundamental constraint on the effective design, placement, and evaluation of NbS is the lack of affordable, high-resolution, real-time monitoring systems capable of detecting pollution events and tracking how NbS perform as conditions change.	Develop low-cost sensors and remote sensing/AI to measure exposure reduction and reef response.	Low	High	Low
	Standardised reef-facing indicators and MRV protocols for comparability. Dashboards linking NbS condition > exposure reduction > coral health.	High	Medium	Medium
Theme: Valuation frameworks for reef outcomes				
There is currently no standardised framework for comparing the economic performance of NbS interventions across the full range of scales and implementation contexts, leaving policymakers and investors without the evidence base needed to confidently prioritise and fund NbS over conventional water quality management approaches.	Quantify economic and One Health benefits from improved reef water quality and coral health (tourism, fisheries, coastal protection, health risk reduction) to support investment cases.	High	High	High

5.2.1 Understanding the system: Reef exposure pathways and hotspots

WHY THIS IS NEEDED:

NbS are widely promoted, but in reef-connected settings there is still limited, comparable evidence on which NbS interventions reduce reef exposure and deliver measurable improvements in coral reef health. Without field-tested performance evidence (including under storm pulses and climate variability), programmes risk investing in interventions that are not feasible to maintain, are poorly targeted, or do not generate detectable reef benefits.

WHAT IS NEEDED:

A coordinated portfolio of field trials and demonstration projects that compare NbS types and designs across representative reef settings (e.g., fringing reefs, lagoons, atolls; tourism and mixed-use coasts). Trials must quantify (i) pollutant interception (nutrients, turbidity/sediment, pathogens/priority contaminants where relevant) and (ii) reef response (e.g., water clarity at reefs, benthic algal cover, coral disease signals, recruitment, and post-bleaching recovery), with clear feasibility and maintenance requirements.

PRIORITY R&D TOPICS TO DEMONSTRATE WHAT WORKS:

- **Comparative NbS trials**: test wetlands, riparian buffers, mangroves, seagrass, oyster/biogenic reefs, seaweed/microalgae biofilters, floating treatment wetlands, and hybrid grey–green designs, using comparable metrics;
- **Storm-pulse performance:** measure NbS effectiveness during extreme rainfall/flood events and quantify how performance changes with disturbance, sediment remobilisation and seasonal variability;
- **Feasibility and maintenance:** define operations and maintenance (O&M) requirements, failure modes, longevity, and cost profiles, including community/agency capacity needs;
- **Reef-health endpoints:** test which reef indicators respond most reliably to reduced exposure, and over what timeframes, to support practical evaluation designs.

OUTPUTS AND HOW THEY WILL BE USED:

- Evidence on "what works, where, and under what conditions" for improving reef water quality and coral health;
- Transferable reef-protective design specifications (siting, sizing, maintenance, safeguards) that can be used to scale successful NbS;
- Comparable datasets to support investment prioritisation and to inform standards, MRV, and adaptive management.

FUNDING AND CAPACITY NEEDS:

Funding is required for multi-year trials, event-based monitoring, and long-term stewardship. Capacity building is needed for local partners to implement, maintain, and monitor NbS and to interpret results for reef management decisions.


Photo Envato

5.2.2 Understanding the system: Reef exposure pathways and hotspots

WHY THIS IS NEEDED:

NbS cannot be optimally designed or evaluated without knowing how much exposure reduction is needed to protect reefs. Reef response depends on both chronic conditions and short-term pulses, and pollution interacts with warming, bleaching, and disease. Without reef-relevant thresholds and models of cumulative stress, targets remain unclear and NbS performance cannot be linked confidently to expected coral health outcomes.

WHAT IS NEEDED:

Reef-specific water-quality targets and modelling tools that (i) define thresholds for nutrients, turbidity/sedimentation and priority contaminants, including pulse exposure; (ii) quantify how pollution interacts with climate stressors; and (iii) translate targets into NbS sizing, placement, and expected reef benefit.

PRIORITY R&D TOPICS FOR REEF THRESHOLDS AND CUMULATIVE IMPACT MODELLING:

- **Reef-relevant thresholds:** establish target ranges for nutrient enrichment, turbidity/sediment deposition and (where relevant) pathogen/contaminant exposure that relate to coral recruitment, algal dominance, and disease risk;
- **Cumulative stressor modelling:** model pollution × warming/bleaching/disease interactions to predict recovery trajectories and the added value of NbS under different climate futures;
- **Pulses and time-lags:** incorporate storm-driven plume dynamics and legacy stores (sediment/nutrient reservoirs) to reflect realistic improvement timelines;
- **Decision translation:** develop practical tools that convert thresholds into NbS design parameters and prioritisation rules for protecting high-value or highly exposed reefs.

OUTPUTS AND HOW THEY WILL BE USED:

- Defensible reef-facing targets to guide NbS and hybrid design and to support programme accountability;
- Scenario tools that estimate expected reef benefits from alternative NbS portfolios and placements;
- Guidance on timelines, uncertainty, and detectability of reef response to reduced exposure.

FUNDING AND CAPACITY NEEDS:

Investment is needed for integrated monitoring-modelling programmes, access to long-term reef datasets, and skills to run/interpret models locally. Collaboration between modellers, reef ecologists, and practitioners is essential.

5.2.3 Coastal NbS and co-location to protect priority reefs (blue-green infrastructure)

WHY THIS IS NEEDED:

Many reef impacts are driven by what happens in coastal receiving areas — where plumes mix, sediments resuspend, and nutrient-rich waters persist near reefs. Coastal NbS (living shorelines, seagrass/mangrove/oyster systems) and co-location approaches (NbS placed at point sources/outfalls) may offer some of the most direct and innovative ways to reduce reef exposure, but their design must account for reef-connected hydrodynamics and operational constraints.

WHAT IS NEEDED:

Reef-protective coastal NbS designs that explicitly target plume attenuation, sediment stabilisation, filtration, and nutrient uptake in the places that matter most for reef exposure, including hybrid grey-green solutions where ecological systems alone are insufficient.

PRIORITY R&D TOPICS FOR COASTAL NBS AND CO-LOCATION TO PROTECT PRIORITY REEFS:

- **Living shoreline optimisation:** test and optimise mangroves, seagrass, and oyster/biogenic reefs to reduce sediment resuspension, improve light climate, and shorten plume duration at priority reefs**;**
- **Co-location at point sources:** evaluate seaweed/microalgae biofilters, floating wetlands, constructed wetlands and hybrid systems sited at stormwater drains and wastewater outfalls to intercept loads before reef exposure;
- **Eco-hydrodynamic design:** develop design rules for different lagoon/fringing reef settings (currents, wave climate, residence time), including performance during storms and high tides;
- **Safeguards and ecological safety:** assess invasive risk, habitat trade-offs, and unintended hydrodynamic effects that could increase turbidity or stress at reefs.

OUTPUTS AND HOW THEY WILL BE USED:

- Design guidance and siting rules for reef-protective coastal NbS and co-location interventions;
- Evidence for when hybrid grey-green approaches are required to meet reef targets;
- Demonstration lessons to support scaling in tourism hubs, mixed-use coasts, and small-island settings;

FUNDING AND CAPACITY NEEDS:

Funding is needed for coastal engineering–ecology co-design, permitting support, and long-term O&M planning. Capacity building should include local construction/maintenance skills and monitoring partnerships linked to reefs.

Photo Envato

5.2.4 Reef-ready MRV technologies

WHY THIS IS NEEDED:

NbS investment and scaling depend on credible evidence that interventions reduce reef exposure and improve coral health. Current monitoring is often too expensive, inconsistent, or not linked to reef response, making it hard to compare projects, learn quickly, or unlock performance-based finance.

WHAT IS NEEDED:

Reef-ready MRV packages that measure (i) NbS condition and functioning, (ii) changes in water quality and plume exposure, and (iii) reef response indicators and ecosystem service outcomes using affordable, maintainable technologies and standardised protocols.

PRIORITY R&D TOPICS FOR REEF-READY MRV TECHNOLOGIES:

- **Low-cost sensor networks:** develop/validate sensors and automated samplers for nutrient species, turbidity/suspended sediments, microbial indicators, dissolved oxygen, and chlorophyll-a (including event capture);
- **Remote sensing and AI:** improve satellite/drone methods to detect plumes, map coastal habitats/ NbS condition, and track reef response signals (e.g., coral cover/bleaching, benthic algae proxies) with ground-truthing;
- **Standardised reef-facing indicators:** define minimum indicator sets that link NbS performance to reef exposure reduction and the resulting reef health and ecosystem services outcomes, with uncertainty reporting;
- **Data platforms and dashboards:** interoperable data workflows that allow managers to see NbS status, water-quality change and reef response in one place for adaptive management.

OUTPUTS AND HOW THEY WILL BE USED:

- Comparable MRV protocols that enable cross-site learning and transparent reporting to funders and regulators;
- Decision dashboards supporting adaptive management and rapid identification of underperforming interventions;
- Evidence packages suitable for performance-based finance and stewardship agreements tied to reef outcomes.

FUNDING AND CAPACITY NEEDS:

Investment is needed for equipment, calibration/quality assurance and control, data stewardship, and training. Capacity building should support local laboratories/field teams and long-term data management to sustain MRV beyond project cycles.

5.2.5 Valuation frameworks for reef outcomes

WHY THIS IS NEEDED:

Even effective NbS can fail to scale if benefits for coral reefs are not valued and adequately funded. Reef benefits (tourism, fisheries, coastal protection, One Health) are often externalised, while NbS require ongoing maintenance and governance. Without fit-for-purpose finance and stewardship models, projects remain short-lived pilots. Valuation frameworks are an important first step in this process.

WHAT IS NEEDED:

Valuation approaches that connect NbS performance to reef services and reward verified outcomes that keep NbS functioning over time. Frameworks should translate environmental outcomes into economic, health, climate resilience, and development metrics used by governments, investors, and funding institutions, enabling reef benefits to be incorporated into investment decisions and long-term stewardship mechanisms.

PRIORITY R&D TOPICS FOR REEF-READY MRV TECHNOLOGIES:

Quantify economic and One Health benefits from improved reef water quality and coral health. In this context, One Health benefits refer to the linked gains for people, ecosystems, and local economies that arise when pollution is reduced, including lower exposure to waterborne pathogens and harmful algal blooms, safer fisheries and recreation, healthier reef and coastal habitats, more resilient livelihoods from tourism and fisheries, and reduced public health and climate-related risks. These benefits should be valued alongside tourism, fisheries, coastal protection, health risk reduction, climate resilience, and livelihood outcomes, and evaluated for how they can be incorporated into public investment decisions, finance mechanisms, and long-term stewardship models.

OUTPUTS AND HOW THEY WILL BE USED:

Investment-ready business cases and decision-support frameworks that translate reef benefits into metrics relevant to government, investor and funding decisions.

FUNDING AND CAPACITY NEEDS:

Funding is required to develop valuation baselines and establish connections to finance and stewardship mechanisms. Capacity is needed to integrate ecological, social, health, and economic data, and translate valuation outcomes into investment cases and decision-support frameworks that support planning, financing, and long-term stewardship.

Photo Renata Romeo / Ocean Image Bank

Case Study Box 3

Bioreactor gardens reduce wastewater nutrient input to reefs

Context:

Across tropical island communities, failing septic systems and direct discharge to sandy or high-water table soils allow nutrients, pathogens, and contaminants to rapidly reach reef-adjacent waterways, threatening ecosystem health as well as the food security and livelihoods of coral reef communities.

Intervention model:

Ridge to Reefs developed the bioreactor garden approach by combining denitrifying bioreactors with planted aerobic filtration layers, working closely with local partners, governments, and communities, with grant-based financing co-developed with local institutions and sustainable development banks supporting initial installations in Palau, Costa Rica, and the USA.

Technology and operations:

Bioreactor gardens treat septic wastewater through a layered bed of wood chips or coconut fibre, biochar, and sand planted with vetiver grass or locally appropriate species, achieving nutrient removal rates often approaching or exceeding 90%. Systems require minimal maintenance, are designed to last decades, and in some Palau installations incorporate food-producing crops irrigated by treated effluent at no additional cost.

Why it matters for coral reefs:

By intercepting and treating wastewater at source before it reaches coastal waterways, bioreactor gardens directly reduce the nutrient, and pathogen loads that drive algal overgrowth and reef degradation in island settings where non-sewered sanitation failure can be prevalent.

R&D implications for proposal development:

For the success of these projects, early regulator engagement and multi-benefit framing—connecting wastewater treatment to food security, ecosystem health, and community resilience—were critical to overcoming regulatory hesitancy and securing uptake across multiple jurisdictions. To further build the regulatory evidence base, long-term performance monitoring across diverse island geographies remains a key research need.

Source:

Ridge to Reefs

Photo Ridge to Reefs

6 Financing & governance for coral reef water quality solutions

Improving water quality across catchment-to-reef systems at the scale and pace required to tackle water pollution demands not only scientific innovation and management action, but policy frameworks, governance structures, and financial pathways that enable countries to prioritise, fund, and implement solutions. Across many coral reef geographies, particularly Small Island Developing States (SIDS), the primary constraint is not the absence of solutions, but the lack of pathways to translate planning, evidence, and pilot interventions into sustained investment at scale. To ensure the right interventions reach the right places, resources and institutional support must endure beyond individual project cycles and countries must have clear pathways to prioritize, fund, and implement solutions beyond pilot stages. Recommendations on the R&D priorities for governance and funding for all three priority areas are discussed below.

6.1 Finance and governance to support Priority Area 1: Improved sanitation to reduce domestic wastewater pollution

WHY THIS IS NEEDED:

Even well-designed sanitation technologies can fail to deliver water-quality or reef benefits if they are not adopted, maintained, or trusted. Social norms, service models, institutional capacity, and governance arrangements strongly influence whether sanitation interventions are implemented at sufficient scale and sustained long enough to reduce reef-facing pollution.

However, in many reef geographies, a more fundamental constraint is that sanitation is not prioritised or financed at the national level. Without policy anchoring, access to finance, and pathways to translate plans into investment, sanitation solutions often remain fragmented, underfunded, or limited to pilot-scale interventions.

WHAT IS NEEDED:

Build an evidence base on the factors that enable uptake and long-term performance of sanitation solutions in reef-connected settings, including equity and inclusion considerations, behavioural drivers, service delivery models, and institutional roles. The aim is to generate transferable insights that improve intervention design and implementation pathways (not to prescribe policy).

In addition, there is a need to address systemic constraints that limit prioritisation and investment in sanitation. These include weak integration into national policy frameworks, limited access to climate and development finance, fragmented institutional mandates, and insufficient capacity to develop bankable, investment-ready projects.

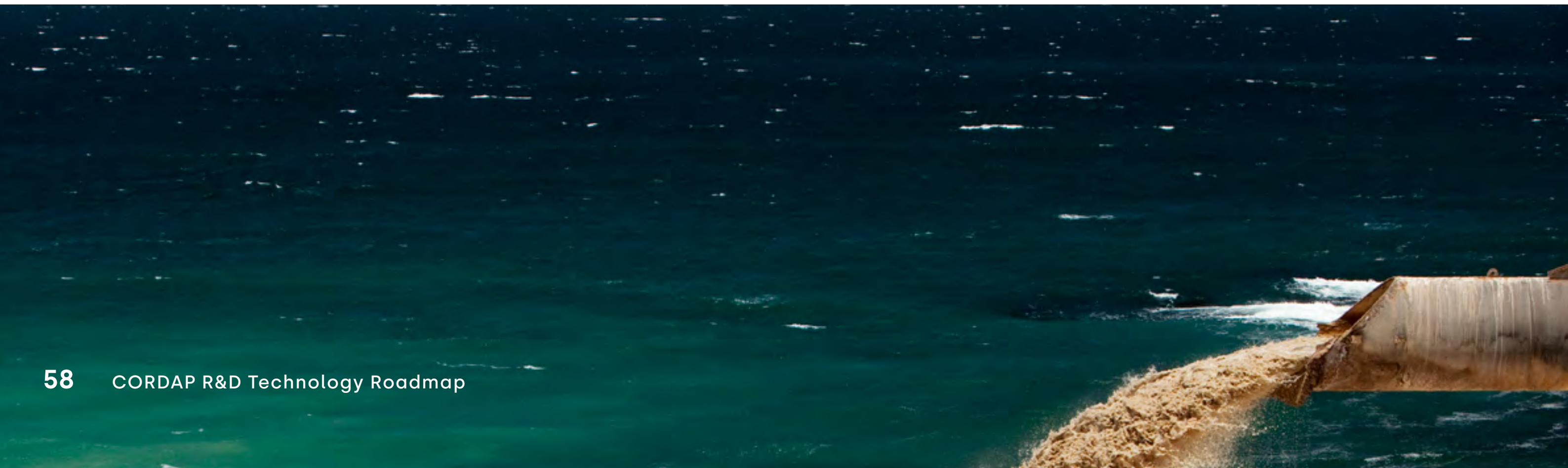

Photo CM Turkmen

PRIORITY R&D TOPICS TO IMPROVE OUR UNDERSTANDING OF THE SOCIAL, CULTURAL, OR GOVERNANCE FACTORS REQUIRED TO SUPPORT SANITATION SOLUTIONS:

A. Enabling adoption, delivery, and long-term performance

- **Map stakeholder and service contexts:** document who owns/operates systems, how services are financed and delivered, and where responsibilities sit across institutions;
- **Assess behavioural and cultural drivers:** identify motivations and barriers to adoption (risk perception, preferences, norms, trust) and test communication/engagement approaches;
- **Evaluate service models:** compare models such as scheduled desludging, community-managed systems, and public-private delivery, focusing on reliability, affordability, and maintenance performance;
- **Integrate with technical and monitoring evidence:** link social findings to measured performance and reef-facing indicators to understand which enabling conditions are associated with successful outcomes;
- **Iterate and generalise:** synthesise across case studies to produce practical design principles and implementation checklists that can be adapted across regions.

B. Strengthening policy, finance, and investment pathways

- **Policy prioritisation and integration:** assess how sanitation is integrated into national policy frameworks (e.g., NDCs, NAPs, National Biodiversity Strategy and Action Plans (NBSAPs), water sector strategies) and identify pathways to strengthen prioritisation and alignment with climate, biodiversity and development agendas;
- **Access to climate and development finance:** identify barriers and opportunities to accessing climate, biodiversity, and development finance (e.g., Green Climate Fund, Global Environment Facility, Multilateral Development Banks) including how sanitation investments can be aligned with adaptation, ecosystem resilience, and reef protection outcomes;
- **Project preparation and pipeline development:** evaluate models for project preparation, technical assistance, and investment structuring that support the development of bankable, investment ready sanitation projects;
- **Economic case and valuation approaches:** assess methods for translating sanitation impacts into economic and asset-risk terms (e.g. tourism, fisheries, coastal protection) including the application of One Water valuation frameworks to capture system-wide co-benefits;

- **Governance and institutional coordination:** assess institutional and governance constraints that limit coordination across utilities, environment, health, and finance actors, and identify models that support integrated, cross-sectoral decision making;
- **Pathways from planning to finance implementation**: identify mechanisms to ensure that national plans, monitoring efforts and source to sea/ridge to reef strategies are translated into funded implementation at scale;
- **Monitoring, reporting, and accountability frameworks:** assess approaches for tracking wastewater flows, treatment performance, and reef-facing outcomes, including how monitoring systems can support national reporting, international comparability, and accountability mechanisms;
- **Regional Standards Gap:** evaluate the absence of regionally appropriate wastewater standards and define research requirements to adapt or develop context-specific frameworks, including comparative analysis of existing instruments (e.g., the Cartagena Convention);
- **Regulatory and standards pathways:** assess how wastewater standards and water quality targets can be translated into enforceable policies, permitting systems, and compliance mechanisms;
- **Global and regional financing mechanisms:** assess models for scaling finance across countries, including pooled financing, concessional mechanisms, and approaches that ensure equitable access for SIDS and low-capacity contexts.

OUTPUTS AND HOW THEY WILL BE USED:

- Evidence on adoption, maintenance, and service factors linked to successful water-quality and reef outcomes;
- Transferable principles for co-design, equity-aware delivery, and long-term system performance;
- Tools such as interview guides, monitoring-integration templates, and implementation checklists for practitioners;
- Evidence and tools to support policy integration, investment justification, and access to climate and biodiversity finance for sanitation;
- Evidence and guidance to inform the development and adaptation of regionally appropriate wastewater standards.

FUNDING AND CAPACITY NEEDS:

Funding is needed for participatory research, multi-site case studies, and long-term engagement. Capacity is required to integrate social research with technical monitoring and to ensure local partners can lead data collection and interpretation. Capacity is also required to support project preparation, financing pathway development and coordination across sectors to move from planning to implementation.

In many regions implementation is further constrained by shortages of trained practitioners, technical assistance providers, contractors, and permitting capacity. Investment is needed in workforce development, certification and apprenticeship pathways, technical assistance mechanisms, and institutional capacity to support the long-term delivery, operation, and maintenance of wastewater solutions.

Photo Envato

Case Study Box 4

Hawai'i's statewide cesspool conversion program: Building the capacity to scale wastewater solution

Context:

Hawai‘i is home to approximately 88,000 cesspools, many of which discharge untreated wastewater to groundwater and coastal environments. Research by the University of Hawai‘i, community monitoring groups, and conservation organizations demonstrated links between cesspool pollution, public health risks, and degradation of coral reef ecosystems. In response, Hawai‘i passed Act 125 in 2017, requiring all cesspools statewide to be replaced by 2050.

Intervention model:

To support implementation, the state established the Cesspool Conversion Working Group (CCWG), bringing together government agencies, researchers, utilities, NGOs, communities, and financing partners to identify barriers and develop recommendations for achieving the statewide conversion goal. Recommendations addressed financing, equity, prioritization, governance, technology approval, community engagement, and cross-sector coordination. Collectively, they recognized that cesspool conversion is not simply an infrastructure challenge, but a long-term environmental, public health, and community resilience effort requiring coordinated action across institutions and communities.

Why it matters for coral reefs:

Hawai‘i demonstrates that successful wastewater transitions require more than scientific evidence, financing, and technology. Even where solutions are known, implementation can be constrained by workforce shortages, contractor availability, permitting capacity, and limited technical assistance. These factors influence the pace at which wastewater pollution reductions and associated reef benefits can be achieved.

R&D implications for proposal development:

The CCWG identified workforce development and implementation capacity as critical components of long-term success. Programs such as the Hawai‘i Rural Water Association's apprenticeship pathways and Wastewater Alternatives & Innovations' Work-4-Water initiative are strengthening the workforce pipeline by connecting recruitment, training, certification, and employment opportunities. The case highlights the need for research on workforce development models, technical assistance mechanisms, and institutional capacity-building approaches that can support implementation of wastewater solutions at scale.

Source:

Hawaii.gov

Hawai'i Rural Water Association

Wastewater Alternatives & Innovations

Photo David Lindbo / Flickr

6.2 Finance and governance for Priority Area 2: Best practice management of agriculture and integrated land-sea systems

WHY THIS IS NEEDED:

Improving agricultural and diffuse-source pollution requires coordinated action across landholders, communities, agencies, and supply chains. Evidence and tools often remain siloed, and limited funding and training capacity can prevent proven approaches from being adopted and maintained long enough to deliver reef benefits.

WHAT IS NEEDED:

Sufficient financial and governance support to ensure local agencies and land managers have the skills and knowledge needed to implement water quality improvements. Support for adequate monitoring and evaluation is also required to alleviate the burden of data collection and management and transition to, or improve, holistic watershed management.

PRIORITY R&D TOPICS FOR FINANCING AND GOVERNANCE TO SUPPORT BEST PRACTICE MANAGEMENT OF AGRICULTURE AND INTEGRATED LAND-SEA SYSTEMS:

- **Institutional arrangements for long-term delivery:** identify governance and resourcing models that sustain monitoring, maintenance, and adaptive management beyond project cycles;
- **Uptake, incentives, and behaviour:** identify economic and behavioural barriers/enablers (risk, knowledge, trust, tenure, credit access) and test incentive and extension models that increase sustained practice adoption at scale.

OUTPUTS AND HOW THEY WILL BE USED:

- Financial and governance support for land managers and local agencies capacity building needs;
- Financial and governance support of knowledge-sharing mechanisms linked to water quality indicators.

FUNDING AND CAPACITY NEEDS:

Dedicated funding is required for extension delivery, facilitation, translation/adaptation of materials, and sustained engagement with communities and landholders. Resourcing should also cover long-term support for monitoring and data use, so collaboration efforts translate into measurable water-quality and reef outcomes.

Photo Envato

6.3 Finance and governance for Priority Area 3: Effective NbS to improve coral reef water quality

WHY THIS IS NEEDED:

Even effective NbS can fail to scale if benefits for coral reefs are not valued and if stewardship is not funded. Reef benefits (e.g., tourism, fisheries, coastal protection, blue carbon, cultural values, and One Health) are often externalised, while NbS require ongoing maintenance and governance. Without fit-for-purpose finance and stewardship models, projects remain short-lived pilots.

WHAT IS NEEDED:

Finance and governance approaches that connect NbS performance to reef services and reward verified outcomes, alongside long-term stewardship arrangements (including community/Indigenous governance) that keep NbS functioning over time. This includes governance, community/Indigenous stewardship pathways, and adaptive management triggers. Building a robust evidence-base including benefits and risks will ensure NbS can be deployed confidently as a core strategy for improving coral reef health.

PRIORITY R&D TOPICS FOR FINANCING, GOVERNANCE, AND LONG-TERM STEWARDSHIP FOR REEF OUTCOMES:

- **Outcome-based finance models:** test blended finance, performance payments, and (where applicable) blue-carbon/co-product pathways that reward verified reef outcomes and long-term function;
- **Stewardship and governance design:** develop durable management arrangements, maintenance plans, and adaptive triggers; clarify roles/ responsibilities and enabling policy conditions;
- **Costing and lifecycle evidence:** build realistic lifecycle cost models (maintenance, monitoring) to compare NbS and hybrid options fairly with grey infrastructure**.**

OUTPUTS AND HOW THEY WILL BE USED:

- Investment-ready business cases for NbS that explicitly articulate reef benefits;
- Templates for performance agreements and stewardship plans linked to MRV and reef targets;
- Guidance for funders and governments on financing pathways that enable scaling beyond pilots.

FUNDING AND CAPACITY NEEDS:

Funding is required to develop valuation baselines, pilot finance mechanisms, and establish stewardship institutions. Capacity building should support local financial/governance partners to manage contracts, monitoring requirements, and adaptive management.

Case Study Box 5

Great Barrier Reef spatial management prioritisation framework to support water quality

Context:

The Great Barrier Reef receives runoff from 35 major catchments draining 424,000 km² of coastal Queensland, where grazing, sugarcane, horticulture, and urban land uses contribute sediment, dissolved inorganic nitrogen, and pesticides that are among the primary drivers of inshore reef and seagrass degradation. Despite over two decades of investment under successive Reef Water Quality Improvement Plans, water quality targets have not been met, highlighting the need for more spatially targeted, evidence-based approaches to directing management effort and investment across this vast and diverse catchment system.

Intervention model:

The Spatial Management Prioritisation (SMP) framework, developed as part of the Reef 2050 Water Quality Improvement Plan (WQIP) Review, provides a four-level decision support system that assigns management response levels to each of the 35 Great Barrier Reef catchments based on landscape condition, pollutant loads, ecosystem hazard, and current management. The framework underpins the new Reef 2050 Catchment Water Quality Strategy — a joint Australian and Queensland Government commitment that supersedes the previous WQIP and sets ecologically relevant, catchment-specific water quality targets to be achieved by 2032.

Technology and operations:

The SMP framework integrates spatial data on pollutant sources and loads, ecosystem condition, and management options to categorise catchments across four response levels, from foundational protection of healthy systems to intensive remediation of the most degraded, enabling project partners and funders to direct investment where it will achieve the greatest water quality and reef ecological outcomes. Progress is tracked through the Paddock to Reef Integrated Monitoring, Modelling and Reporting program, which connects on-farm management practice adoption data to modelled end-of-catchment pollutant loads and observed reef water quality conditions.

Why it matters for coral reefs:

By directing the most intensive management effort to the catchments contributing the greatest pollutant loads, while protecting less-disturbed systems from future degradation, the SMP framework maximises the ecological return on finite management investment across a reef system at World Heritage scale.

R&D implications for proposal development:

Spatially explicit decision support tools grounded in current science and integrated with adaptive monitoring systems are essential for translating reef water quality research into targeted investment decisions with Traditional Owner involvement and regular evidence-based review cycles identified as critical to the framework's credibility and long-term effectiveness.

Transferability:

The transferable lesson is the prioritisation logic – linking pollutant sources, reef exposure, ecological risk, and management response — rather than the full data intensity of the Great Barrier Reef system. In SIDS, LMICs, data-poor settings, and community-managed reef contexts, this approach should be adapted through simpler datasets, participatory mapping, locally relevant indicators, lower-cost monitoring, and governance models that reflect local capacity and stewardship.

Source:

Spatial management prioritisation framework overview

Reef 2050 Water Quality Improvement Plan documents

7 Broader considerations & conclusions

Translating the research priorities outlined in this roadmap into meaningful improvements in coral reef water quality will require more than scientific advances. Reef water quality recovery requires integrated, financed, monitored, locally owned, and adaptive action from catchment to reef. Across all three priority areas, this roadmap identifies governance, social, cultural, institutional, and economic conditions as critical determinants of whether technically sound interventions are adopted, maintained, and scaled. Investment in capacity building, knowledge sharing, and participatory approaches, including the integration of Indigenous ecological knowledge, is therefore not peripheral to the research agenda but central to it. Equally important is the development of robust economic valuation frameworks that capture the full costs of inaction and the co-benefits of intervention, including human health, food security, tourism, and climate resilience benefits, so that decision-makers can build a compelling and defensible case for sustained investment in improving and maintaining water quality in coral reef systems.

Evidence alone is often insufficient to move solutions from research into implementation. Research must also translate environmental, social, health, and economic outcomes into metrics, valuation frameworks, monitoring systems, and decision-support tools that align with the priorities of governments, investors, utilities, development partners, and communities.

Doing so can help ensure that water quality improvements are incorporated into planning, budgeting, financing, regulatory, and policy decisions, bridging the gap between scientific understanding and large-scale implementation of interventions.

Climate change is not a future consideration but a present and accelerating pressure. As thermal stress intensifies, acidification accelerates, and cumulative stressor interactions compound, events such as marine heatwaves, coral bleaching, disease outbreaks, and harmful algal blooms are likely to increase in frequency and severity. In this context, local water quality improvement is one of the few actionable interventions available to reduce cumulative stress and improve reef recovery potential under climate change. The stakes are therefore high, and research and implementation cannot be delayed or under-resourced.

The greatest water quality and ecological gains will not come from any single intervention, but from coordinated action across sectors applied at the catchment-to-reef scale. An integrated intervention might begin with spatial prioritisation of pollutant sources across a catchment to identify where agricultural runoff, poorly managed sanitation, and degraded riparian buffers contribute the highest loads to downstream waterways. Solutions would involve a complementary suite of responses: improved sanitation and wastewater treatment to reduce pathogen and nutrient inputs from communities; evidence-based best management practices across farms and grazing lands to control sediment, nutrient, and pesticide losses; and strategically designed Nature-based Solutions, such as riparian revegetation, constructed wetlands, seagrass and mangrove restoration, or coastal biofilter systems, to intercept and process remaining pollutant loads before they reach sensitive coral reef environments.

The priority now is to move from fragmented pilots to coordinated, evidence-based, finance-ready, and scalable reef water quality solutions. This requires funders, governments, researchers, practitioners, communities, and Indigenous partners to work together to turn the roadmap into targeted investment, comparable trials, standardised monitoring, and locally owned implementation. Improving water quality will not solve climate change, but it remains one of the clearest, most practical, and most immediate actions available to reduce cumulative stress and give coral reefs a better chance to recover.

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