Operationalizing the Crown-of-thorns starfish and coral monitoring design

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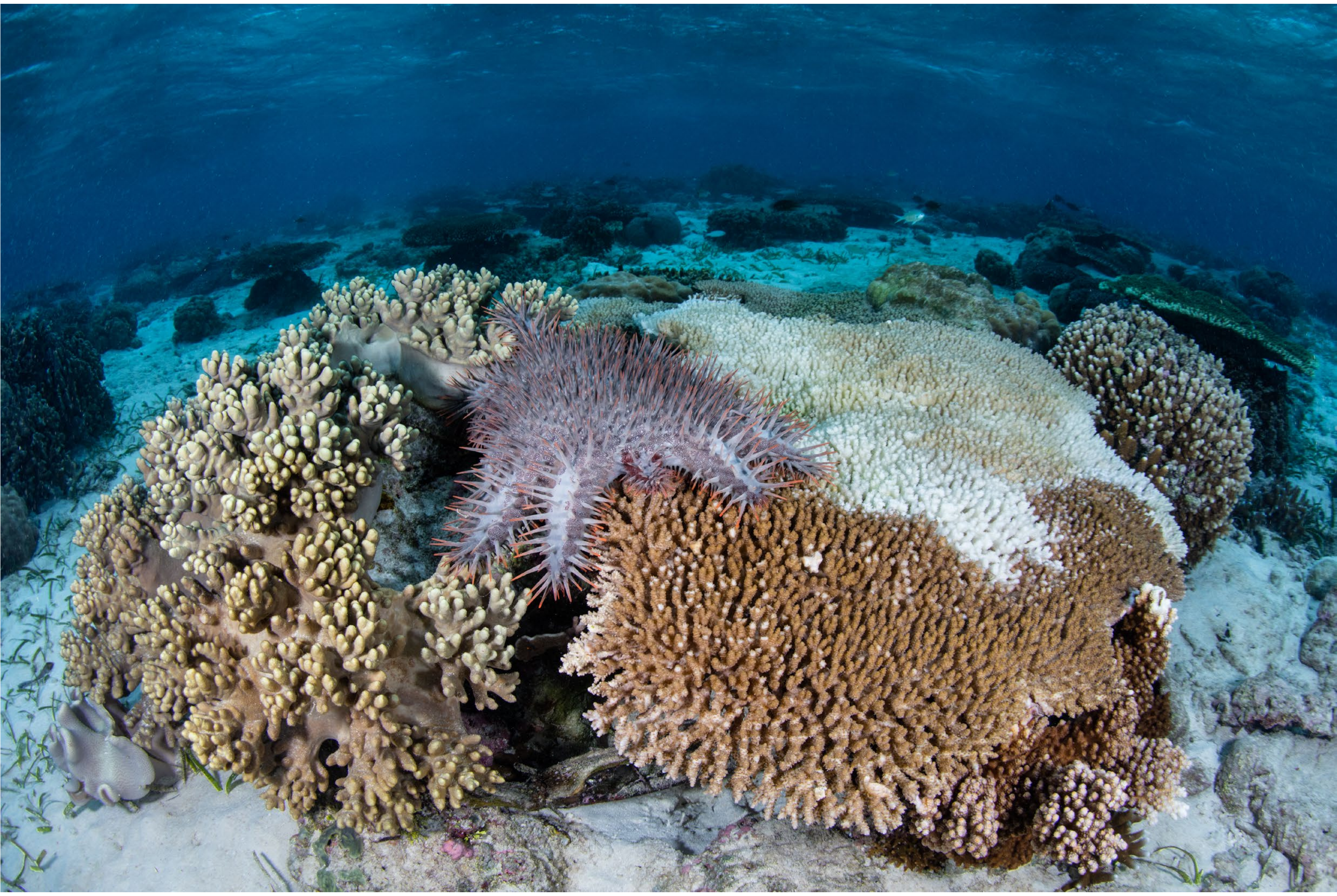

Operationalizing the Crown-of-thorns starfish and coral monitoring design plan

Emma Lawrence[1], Dan Gladish[1], Scott Foster[2], Brano Kusy[3], Arjun Chennu[4]

1. CSIRO Data61, Dutton Park, QLD, 4072
2. CSIRO Data61, Hobart, TAS, 7000
3. CSIRO Data61, Pullenvale, QLD, 4069
4. Australian Institute of Marine Science, Townsville, QLD, 4810

COTS Control Innovation Program | A research and development partnership to better predict, detect and respond to crown-of-thorns starfish outbreaks

Inquiries should be addressed to:

Emma Lawrence
CSIRO
emma.lawrence@data61.csiro.au

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The COTS Control Innovation Program aims to accelerate the development of innovative surveillance and control methods to manage outbreaks of coral-eating starfish on the Great Barrier Reef. The Program is a collaboration between the Great Barrier Reef Foundation, Australian Institute of Marine Science, Commonwealth Scientific and Industrial Research Organisation, James Cook University and The University of Queensland. The Program is funded by the partnership between the Australian Government's Reef Trust and the Great Barrier Reef Foundation.

Traditional Owner Acknowledgement

The COTS Control Innovation Program extends its deepest respect and recognition to all Traditional Owners of the Great Barrier Reef and its Catchments, as First Nations Peoples holding the hopes, dreams, traditions and cultures of the Reef.

Research Translation Project CCIP-RT-01

Contents

List of Figures

List of Tables

Acronyms and Abbreviations

AIMS	Australian Institute of Marine Science
CCIP	Crown-of-thorns starfish Control Innovation Program
COTS	Crown-of-thorns starfish
eDNA	Environmental DNA
GBR	Great Barrier Reef
LIRS	Lizard Island Research Station
LTMP	Long term monitoring program
PCR	Polymerase chain reaction
QPWS	Queensland Parks and Wildlife Service
Reef Authority	Great Barrier Reef Marine Park Authority
RJFMP	Reef Joint Field Management Program
SALAD	Scooter assister large area diver-based

PROJECT SUMMARY

This project successfully translated the project CCIP-D-01 monitoring design framework into an operational, field-tested plan ready for implementation. Through stakeholder engagement and iterative refinement, we developed a comprehensive monitoring program comprising an initial 66 baseline reefs organised into 22 clusters across the Great Barrier Reef (GBR), complemented by up to 29 strategically positioned early warning reefs for outbreak detection.

The baseline monitoring design employs spatially balanced cluster sampling to provide statistically robust, unbiased status and trend data for crown-of-thorns starfish (COTS) and coral at the GBR scale, addressing a critical gap in COTS management capability. For the first time, the COTS Control Program will be able to definitively assess management effectiveness and GBR-wide COTS trends on a routine basis. The early warning component integrates COTS environmental DNA (eDNA) sampling at high-risk reefs to detect emerging outbreaks before they reach damaging densities, enabling preventative intervention rather than reactive response.

Field trials during January-February 2025 successfully demonstrated the operational feasibility of integrating emerging technologies with traditional monitoring methods. Environmental DNA sampling proved highly compatible with existing monitoring protocols, requiring minimal additional vessel time while providing enhanced detection sensitivity. ReefScan technology demonstrated concurrent COTS and coral assessment capabilities, indicating potential for future operational efficiencies.

The stratification of baseline monitoring reefs by Australian Institute of Marine Science (AIMS) Long-Term Monitoring Program (LTMP) sectors ensures adequate geographic representation while complementing and aligning with existing management reporting frameworks. The proposed monitoring program naturally achieves representation across both marine reserve and fished areas, supporting multiple management evaluation objectives. The design also provides implementation flexibility, allowing the program to scale with available resources while maintaining statistical validity.

Critically, the spatially unbiased design ensures monitoring data will support management questions extending well beyond COTS surveillance. Depending on the monitoring conducted, the baseline reefs could provide unbiased estimates on coral bleaching impacts, effectiveness of zoning arrangements, and overall reef health trends across the GBR, representing exceptional value for monitoring investment and positioning reef management agencies to make evidence-based decisions efficiently and cost-effectively for decades to come.

CONTEXT & OBJECTIVES

Background

Outbreaks of crown-of-thorns starfish (COTS) are one of the primary drivers of coral decline on the Great Barrier Reef (GBR), compounding the effects of other stressors such as cyclones, bleaching, and flooding (Great Barrier Reef Marine Park Authority 2024). Unlike other major causes of coral mortality, COTS outbreaks are amenable to direct management intervention through the COTS Control Program (Fletcher et al. 2021; Matthews et al. 2024), formally established by the Great Barrier Reef Marine Park Authority (Reef Authority) in 2012.

Effective reef monitoring and management depends on distinguishing between long-term monitoring and tactical surveillance. Long-term monitoring provides systematic data to track ecosystem changes and assess management effectiveness over time (Lindenmayer and Likens 2010), whereas surveillance focuses on detecting emerging threats that require rapid response (Gitzen and Millspaugh 2012; Westcott et al. 2021). Both are essential but serve distinct purposes within adaptive management frameworks such as the COTS Control Program (Lawrence et al. 2025a).

Implementing both monitoring and surveillance effectively across the GBR presents major logistical challenges, with over 3,000 reefs spanning 344,440 km². Given resource constraints, comprehensive monitoring of COTS and coral across this vast area has historically been difficult to achieve. The COTS Control Program has necessarily focused data collection on tactical surveillance needs, gathering information to guide immediate control operations (Fletcher et al. 2020). While operationally essential, this emphasis on surveillance over systematic monitoring creates potential for spatial bias in our understanding of outbreak patterns and the effects of management intervention (Boyd et al. 2023; Lawrence et al. 2025a).

Understanding the spatial and temporal patterns of COTS outbreaks remains a key challenge for effective management. Research has documented four major outbreak waves on the GBR since the 1960s, typically occurring at intervals of 15-20 years (Pratchett et al. 2014). Early hypotheses suggested these outbreaks consistently originated in a northern mid-shelf region between Lizard Island and Cairns, termed the "initiation box" (Fabricius et al. 2010). More recent analyses have questioned this pattern, with evidence that elevated COTS densities can appear in far northern areas substantially before detection in the previously identified initiation zone (Vanhatalo et al. 2017; Chandler et al. 2023; Emslie et al. 2024). These findings suggest outbreak origins and larval dispersal patterns may be more complex than previously understood (Pratchett et al. 2025) and emphasise the need for systematic monitoring.

Despite decades of research, significant gaps persist in understanding outbreak initiation and spread. While the Control Program draws on data from sources including the Long-Term Monitoring Program (LTMP) and Reef Joint Field Management Program (RJFMP) activities (Matthews et al. 2024), these existing monitoring and surveillance programs were not designed to provide the spatial representation and statistical framework required for systematic baseline monitoring of COTS, their impact on corals and the effectiveness of management intervention.

The CCIP Detection Subprogram

The COTS Control Innovation Program (CCIP) Detection Subprogram addressed the challenge of designing a comprehensive long-term monitoring design for the COTS Control

Program through project *CCIP-D-01: Crown-of-thorns starfish monitoring design: sample design for science and management decisions* (Lawrence et al. 2025a). This foundational work provided critical insights into monitoring purposes, evaluated different monitoring tools and statistical designs, and delivered key recommendations for implementation.

Key findings from CCIP-D-01 included:

- **Current approaches have significant limitations beyond tactical management.** While existing monitoring and surveillance effectively support day-to-day operational decisions, they do not provide adequate data to address strategic planning questions or assess management outcomes at the GBR scale.
- **Three distinct monitoring and surveillance approaches are needed.** The COTS Control Program requires: (1) routine surveillance at priority reefs for tactical decisions, (2) baseline monitoring using a spatially balanced cluster design for strategic planning and effectiveness assessment, and (3) early warning monitoring at high-risk reefs to detect emerging outbreaks.
- **A statistically robust baseline monitoring design is feasible and achievable.** Contrary to initial expectations that baseline monitoring of the vast GBR would require enormous resources, simulation studies demonstrated that 16-20 clusters of 3-4 reefs (60-80 reefs total) monitored annually can provide statistically robust trend data at the GBR level. The clustered approach minimises vessel travel costs while maintaining statistical rigour. Importantly, the spatially balanced design ensures data can be used in an unbiased way to report on broader GBR management priorities beyond COTS, including coral bleaching responses, effectiveness of zoning arrangements, and overall reef health trends (provided relevant data is collected at the specified reefs).
- **Implement early warning monitoring at strategically selected high-value and high-risk reefs** using eDNA and Scooter-assisted large area diver-based (SALAD) surveys to detect emerging outbreaks before they reach damaging densities. Data from early warning monitoring should be analysed separately from baseline monitoring due to inherent spatial bias in site selection.
- **Emerging technologies offer improvements.** Environmental DNA sampling can detect COTS at concentrations below visual survey detection limits. ReefScan technology promises semi-automated, concurrent assessment of both COTS and coral. SALAD surveys provide detailed COTS size structure data and can effectively estimate COTS at lower densities than manta tow. These emerging technologies provide solutions to current limitations in the accuracy and effectiveness of COTS and coral monitoring conducted as part of the COTS Control Program.

CCIP Research Translation

This Research Translation project (*CCIP-RT-01: Operationalise monitoring design plan*) represents the critical bridge between the theoretical framework developed during CCIP-D-01 and an operational, field-tested monitoring system. The project builds upon the foundational monitoring design work to develop a monitoring program that can be implemented alongside existing COTS and coral monitoring and surveillance activities, primarily to enhance the ability of the COTS Control Program to answer strategic and management effectiveness monitoring objectives.

The project operationalises the key CCIP-D-01 monitoring design recommendations, which combine statistically designed baseline reef monitoring with early-warning reef monitoring. It also integrates findings from other CCIP projects, particularly CCIP-D-03 (*Operationalising eDNA monitoring* (Uthicke et al. 2025)) and CCIP-P-04 (*Pre-outbreak monitoring* (Pratchett et al. 2025)), to inform early-warning reef selection and refine monitoring strategies.

The specific objectives of this project are to:

1. Select the reefs that will become part of baseline monitoring and early warning monitoring, to be measured on an annual basis.
2. Identify the reefs that could be monitored to supplement those in objective 1, following the same sample design process.
3. Specify the monitoring tools to be used at each reef (including any relevant supplementary monitoring such as water quality).
4. Pilot monitoring activities at reefs during the January and February 2025 RJFMP field trips and analyse data collected.
5. Refine and adjust the monitoring plan based on field experiences and stakeholder feedback.
6. Analyse the options for resourcing the monitoring plan, including the balance of effort between RJFMP and COTS Control Program.
7. Develop a fully operational monitoring plan.

The outcomes of the project will be:

1. A tested and refined COTS and coral monitoring program that incorporates both statistically designed baseline reef monitoring and targeted early-warning reef surveillance.
2. Improved early detection capabilities for COTS outbreaks.
3. Enhanced collaboration among various stakeholders in reef monitoring and management.
4. A comprehensive, operational monitoring plan ready for full implementation.

This project serves as a crucial step in translating CCIP's scientific innovations into practical, operational improvements for COTS management on the GBR. By implementing a monitoring program that addresses both tactical and strategic information needs, the COTS Control Program will be better positioned to protect coral across the GBR, benefiting Traditional Owners, the tourism industry, and the broader community through enhanced reef resilience and ecosystem health.

APPROACH

This project operationalises the CCIP-D-01 monitoring design recommendations (Lawrence et al. 2025a) through a multi-phase approach. We implemented the recommended monitoring program by: (1) selecting baseline monitoring clusters using a spatially balanced cluster design algorithm to provide statistically robust, GBR-scale trend data; (2) identifying early warning reefs through expert consultation and integration of CCIP-D-03 (Uthicke et al. 2025) and CCIP-P-04 (Pratchett et al. 2025) findings to detect emerging outbreaks at high-risk locations; and (3) specifying appropriate monitoring tools for each reef type. The approach was validated through pilot field trials during the January-February 2025 RJFMP trips, with results informing refinements to protocols and resourcing recommendations.

We consider the direction of effort towards routine surveillance that the COTS Control Program undertakes at priority reefs for tactical decisions to be a complementary but separate process and so this type of surveillance does not form part of this project or the proposed monitoring plan.

Baseline monitoring design development

The development of the baseline monitoring design involved refining the CCIP-D-01 recommendations into a practical, implementable plan. The foundational principle was to establish spatially balanced cluster monitoring (Foster et al. 2024; Lawrence et al. 2025a) with 16-20 clusters of 3-4 reefs monitored annually to provide statistically robust trend data at the GBR level. However, translating this theoretical framework into an operational plan required addressing practical considerations. Discussions with operational staff confirmed that three reefs per cluster within a 25 km cluster radius is achievable in most circumstances, and that monitoring three clusters (nine reefs) is typically feasible within a standard RJFMP COTS voyage. For the purposes of this design, a standard RJFMP COTS voyage is assumed to comprise a multi-day (typically 10-12 days) vessel-based field trip operating within a defined sector of the GBR, with daily dive-based surveys and supplementary monitoring and surveillance (e.g. eDNA monitoring) conducted across multiple reefs. Additionally, while the design needs to be statistically robust, some areas of the GBR cannot currently be monitored due to safety concerns or practical constraints (excessive distance offshore, depth limitations, crocodile risk, tidal restrictions). While some reefs may never be able to be surveyed, others may become feasible as tools or operational constraints evolve.

To address these considerations, we adopted a master sample approach, creating a long list of monitoring clusters distributed across the entire GBR and assigned a predefined selection order based on a spatially balanced design. Each year, clusters are selected for monitoring by progressing through this ordered list, subject to operational feasibility. This ordered structure ensures that any cluster surveyed—whether as part of the core annual program or through opportunistic monitoring—can be incorporated into GBR-wide estimates without introducing bias, provided the predefined order is retained.

Clusters may be temporarily excluded due to logistical or safety constraints without compromising the statistical integrity of the design, monitoring effort can be increased over time by progressing further through the master list, and the full list enables early stakeholder review of practical feasibility prior to finalising annual survey plans.

Early warning reef selection

The early warning reef list was developed by integrating findings from projects CCIP-D-03 (*Operationalising eDNA monitoring*) and CCIP-P-04 (*Pre-outbreak monitoring*). During those projects, an expert-based approach was used to identify high-risk reefs where early detection of emerging outbreaks would provide maximum benefit for outbreak prevention. Twenty-six reefs were recommended for annual early-warning monitoring in CCIP-D-03. It is not currently possible to survey all of these reefs each year with the available budget so we looked at the duration for which the data had been collected and cost-effective ways for collecting eDNA samples which could form the basis of decisions around which early warning reefs may be best sampled each year. We also looked at the Southern GBR where early-warning monitoring has not previously been a focus and recommended some reefs for monitoring in that region.

Monitoring tools and resourcing

Tool recommendation and deployment strategies were guided by the comprehensive tool evaluations and feasibility analyses completed under CCIP-D-01 and CCIP-D-02 (Lawrence et al. 2025b). This foundational work assessed the performance characteristics, operational requirements, and cost-effectiveness of available monitoring technologies, providing an evidence base for matching tools to monitoring objectives.

For baseline reefs, the monitoring strategy (Table 1) draws directly on CCIP-D-01 findings demonstrating that eDNA sampling can detect COTS at concentrations below visual survey detection limits, making it an important tool for establishing baseline presence/absence across all sites. Manta tow surveys should also be deployed at baseline reefs, leveraging their operational efficiency for immediate density estimates and maintaining continuity with historical data. As recommended in CCIP-D-01, ReefScan technology (Bainbridge et al. 2025) should be progressively integrated as it matures operationally, offering semi-automated, concurrent assessment of both COTS and coral cover. Where possible, deploying ReefScan Surface (previously called ReefScan Transom) concurrently with manta tow will allow the integration of this new technology with the advantage of providing a stream of data to update COTS and coral calibration models (Lawrence et al. 2025b). ReefScan-Deep represents a higher overhead option for integration, as the towed camera system requires additional vessel considerations and field teams have expressed greater risk aversion to towing equipment over reef structures.

Early warning reef monitoring should utilise the tiered response framework developed in CCIP-D-01, which maximises detection capability while managing resource constraints. Primary monitoring uses eDNA sampling to detect COTS presence at low densities. CCIP-D-03 (Uthicke et al. 2025) established trigger thresholds whereby eDNA results indicating potential outbreak development prompt follow-up surveys using manta tow or SALAD surveys to quantify COTS density and size structure, or cull surveys if the COTS densities observed in follow-up in-water surveys trigger this. This adaptive framework allocates intensive survey effort only where needed.

Resource allocation decisions similarly built upon the CCIP-D-01 resourcing analysis, which considered the effort requirements for different monitoring configurations and evaluated the capacity of existing programs to absorb additional monitoring responsibilities.

Culling at Monitored Reefs

The purpose of baseline monitoring is to provide spatially representative, statistically robust estimates of COTS density and coral condition across the GBR. This includes reefs that may be culled under normal IPM processes as well as those that are not. To maintain the integrity of this design, decisions regarding culling at baseline reefs must continue to be guided solely by the established reef prioritisation and IPM processes, rather than by a reef's inclusion in the monitoring sample. To be clear, if a reef is a target reef (due to ecological, cultural, economic reasons determined independently of being in the baseline sample), then culling should occur if it is above the ecological threshold; if it is not a target reef, it should not be culled. Either way, it should continue to undergo annual monitoring.

Baseline reefs are therefore not all designated as "no-cull" reefs, nor should they receive special consideration or de-prioritisation in operational planning. Treating baseline reefs differently would diminish their representativeness. Instead, baseline reefs continue to be monitored consistently through time to establish long-term trajectories of both COTS density and coral condition. Maintaining a clear separation between the monitoring design and operational prioritisation preserves the statistical properties of the baseline sample, ensures defensible estimation of long-term trends, and strengthens the program's ability to demonstrate measurable coral outcomes attributable to COTS control. In 25/26, eight of the baseline reefs were target reefs, should the number of target reefs in the baseline monitoring increase by 50% in the future i.e. twelve or more reefs, it will be important to reassess and consider substituting reefs or adding more reefs into the baseline monitoring to ensure that the program can collect adequate data to meet management needs.

Early warning reefs can be monitored without compromising the baseline design because they serve a different purpose i.e. targeted, risk-based surveillance for outbreak detection, and their data are analysed separately from the spatially representative baseline dataset, ensuring they do not influence or bias GBR-wide trend estimation.

Table 1 Summary of monitoring tools, frequency, and response protocols for baseline and early warning reefs.

Reef Type	Primary Methods	Frequency	Follow-up Actions
Baseline Reefs	• Manta tow surveys • eDNA sampling • ReefScan Surface (concurrent with manta tow) • ReefScan Deep (progressive integration)	Annual	• Annual monitoring continues regardless of COTS presence or culling • If reef falls in the priority reef category, then follow IPM process

Early Warning Reefs	• eDNA sampling	Annual	• If eDNA proportion positive > 0.4: Manta tow or SALAD survey to quantify density and size structure • Culling should be based on results of above follow up survey

Pilot field trials

Two deployments were conducted to pilot and test the monitoring design recommendations developed under CCIP-D-01 (Figure 1). While ideally, we would have first selected baseline reef clusters and then piloted monitoring at those locations, the timing and approximate location of the RJFMP field trips had been previously set for January-February 2025. Therefore, we piloted monitoring activities within operational constraints: the Reef Authority had already identified target reefs based on operational priorities for COTS surveillance rather than through the statistical sampling design. To approximate the proposed baseline design as closely as possible, we worked with the Reef Authority and RJFMP to identify three clusters of three reefs in each of two regions (Swain Reefs in January and Mackay region in February), mirroring the key recommendation from CCIP-D-01 for spatially balanced cluster sampling.

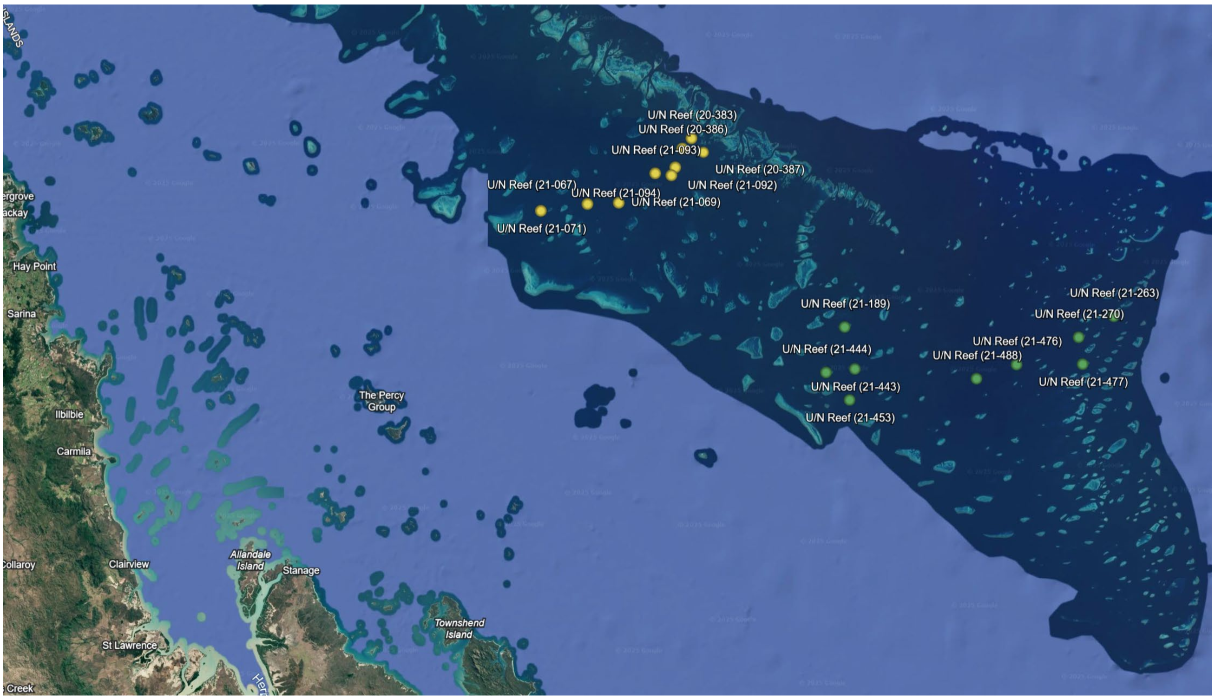

Figure 1 Location of the 18 reefs surveyed as part of the two pilot monitoring trips to the Swain reefs and Mackay areas.

At each cluster, manta tow surveys around the reef edge were conducted along with standard RJFMP operations. To pilot the integration of emerging technologies, Queensland Parks and Wildlife Services (QPWS) undertook eDNA sampling at each reef using the sampling regime stipulated under CCIP-D-03, and the ReefScan Surface unit was deployed on the tender for most manta tows, providing concurrent image-based data collection. Where operationally feasible, ReefScan Deep transects (approximately 1-2 nautical miles) were conducted to demonstrate the technology's capabilities. We coordinated closely with the project team operationalising eDNA monitoring (CCIP-RT-02, Uthicke et al. 2026) to maximise overlap between projects, ensuring efficient use of vessel time and resources.

Manta tow data were summarised at the reef level by aggregating all tows within each reef. Metrics calculated included total COTS observed, counts of each feeding scar category, proportion of tows with feeding scars (either present or common), and proportion of tows with COTS and/or feeding scars. For hard coral cover, estimates recorded using standard manta tow categories (Miller and Müller 1999) were converted to midpoint values at the individual tow level, and average hard coral cover per reef was calculated as the mean across all tows.

ReefScan data were processed using the automated COTS detection system (Bainbridge et al. 2025), which employs machine learning models trained on underwater imagery to infer COTS in the survey images. The system groups consecutive detections into sequences to reduce false positives. We extracted high-confidence sequences (median confidence ≥ 0.75, length ≥ 5 images) and validated them manually to ensure no false positives were detected. As ReefScan Deep units have two cameras that currently operate independently, we used only COTS detections from a single camera to remove any duplicate COTS identifications. Hard coral cover was calculated from benthic image analysis using the ReefCloud platform (www.reefcloud.ai).

Environmental DNA metrics were used as provided by project CCIP-RT-02 (Uthicke et al. 2026), including the proportion of samples testing positive and average copy number per site, aggregated by taking the mean of the sites at the reef to allow comparison with other monitoring tools.

Stakeholder engagement

Stakeholder engagement was central to ensuring the monitoring program would meet operational needs and integrate effectively with existing programs. An initial workshop in June 2025 brought together key stakeholders from the Reef Authority, QPWS and Australian Institute of Marine Science (AIMS) to review the proposed monitoring design and gather input on practical implementation considerations. This was followed by a series of meetings from July to November 2025 to refine specific aspects of the design and build support for implementation across stakeholders.

OUTCOMES & MANAGEMENT IMPACT

This project has successfully translated the CCIP-D-01 monitoring design framework into an operational, field-tested monitoring program ready for implementation. Through stakeholder engagement, pilot field trials, and iterative refinement, we have developed a practical monitoring program that maintains statistical rigor while addressing operational constraints and safety considerations.

Baseline monitoring design refinement

The initial spatially balanced cluster design, balanced at the GBR-wide level, is statistically optimal for estimating long-term trends but can present practical challenges for operational implementation. In a spatially balanced master sample, clusters are assigned a predefined selection order generated through a probabilistic, spatially balanced algorithm (Lawrence et al. 2025a). Progressing through this order ensures that each additional cluster incrementally improves spatial coverage in a statistically unbiased manner. Deviating from this order, for example by preferentially selecting clusters in specific regions would distort the underlying inclusion probabilities and introduce bias into GBR-wide estimates.

When clusters are selected strictly in their predefined order, the resulting pattern can concentrate sampling in regions of high reef density, leaving larger geographic gaps elsewhere along the coastline. While this configuration maintains statistical efficiency and minimises uncertainty in GBR-wide estimates, it can reduce sensitivity to emerging outbreaks in under-represented areas and limit the ability to support regionally framed reporting aligned with existing management boundaries.

To address this, the master sample framework was implemented with controlled operational flexibility. Clusters may be temporarily deferred or supplemented with additional monitoring in priority regions to meet surveillance and management needs, while retaining the predefined selection order for inclusion in GBR-wide trend estimation. This approach preserves the statistical validity of GBR-scale estimates while allowing adaptive responses to emerging risks and regional information requirements.

A stakeholder workshop with representatives from the Reef Authority, QPWS, and AIMS researchers addressed these challenges and identified solutions that would maintain statistical validity while improving operational feasibility. The workshop participants agreed to adopt a stratified approach based on AIMS LTMP sectors when selecting reef clusters. By ensuring at least one cluster per AIMS sector, the updated design will maintain adequate geographic spread while preserving the statistical principles of the spatially balanced approach. This stratification also aligns with existing reporting frameworks used across GBR monitoring programs, enhancing compatibility and integration of baseline monitoring data with other reef monitoring initiatives. Instead of the recommended 16 clusters of three reefs across the entire GBR, the entire span of the GBR was split amongst 11 sectors with the aim of selecting one to two clusters of three reefs in each sector. We then created an oversample of clusters of reefs and reefs in a cluster to create the master list, ensuring enough reefs were selected that could logistically be monitored. This led to some duplicate reefs (reefs selected in multiple clusters), so the duplicates were removed.

Substantial discussion also centred on the importance of representing both Green or Preservation Zones (no-take marine reserves) and other zoning categories where fishing is permitted, within the monitoring program. This balance was recognised as critical for management evaluation, providing value for multi-program planning, and supporting ongoing

COTS predation research. The project team initially considered adjusting the monitoring design reef selection inclusion probabilities (Lawrence et al. 2025a) to ensure equal selection of reefs from both zoning categories within clusters. However, this approach was rejected because it may substantially complicate the statistical analysis and interpretation of future monitoring data and create challenges if reefs were rezoned. The AIMS sector stratification approach provided an elegant solution, naturally achieving representation of both zoning categories without requiring complex probability adjustments.

Iterative refinement with stakeholders

Following the workshop, the project team initiated an iterative review process with participants to evaluate the feasibility of each cluster identified through the stratified spatially balanced cluster design. This process systematically examined each cluster and individual reefs within it, with COTS Control Program, RJFMP and AIMS staff providing detailed operational assessments based on their program management and extensive field experience.

Feasibility assessments identified potential constraints including:

- **Safety considerations:** Crocodile risk assessments (ranging from low to high risk), depth constraints preventing safe manta tow operations, strong tidal streams creating hazardous conditions,
- **Weather dependencies:** Reefs requiring particularly favourable weather conditions due to exposure to swell or accessibility challenges,
- **Cultural sensitivities:** Areas requiring consultation with Traditional Owners or sites with cultural significance,
- **Physical constraints:** Reefs with very large margins requiring excessive survey time, shallow areas or deep drop-offs preventing standard survey methods, or reefs too deep for safe operations,
- **Temporal constraints:** Reefs that could only be safely surveyed during particular tidal conditions or specific seasons.

Based on these assessments, reefs were either removed from annual monitoring if they posed unacceptable ongoing safety risks or retained with documented conditions for safe implementation. When reefs were removed from a cluster, the next reef on the master sample list within that AIMS sector were evaluated as potential replacements, maintaining the cluster structure and geographic representation. Reefs flagged for First Nations sensitivity were retained with commitment to undertake appropriate consultation with Traditional Owners prior to scheduling monitoring activities. The iterative review resulted in several rounds of feedback and adjustment. In some cases, a reef within a cluster was replaced, while other times it was necessary to replace an entire cluster with the next on the master list i.e. when suitable reefs were unavailable.

Final baseline monitoring design

The iterative stakeholder review process resulted in a refined baseline monitoring design comprising 66 reefs organised into 22 clusters across the 11 AIMS LTMP sectors (Table 2). The selected clusters maintain the core principles of spatially balanced cluster sampling while addressing operational feasibility and ensuring adequate geographic representation across the GBR. The design includes two clusters of three reefs per sector, achieving the target range of 60-80 reefs recommended in CCIP-D-01 for statistically robust trend estimation at the GBR scale. There are 29 reefs within Green or Preservation Zones and 37 reefs in other zoning categories, demonstrating fairly balanced representation of Marine Park zones across the 66 selected reefs at the whole of GBR level.

Table 2 Baseline monitoring clusters selected across the GBR showing two clusters per AIMS sector with three reefs per cluster, operational dependencies, zoning status (Green or Preservation Zones vs other zoning categories) and historical monitoring data availability.

Sector	Cluster	Reef	Reef Name	Dependencies	Green or Preservation Zone	Past cull dives	Past manta tow	Programs for which manta tow data is available
1	3	1	U/N Reef (11-074)	Weather dependent	YES	NO	NO	
1	3	2	U/N Reef (11-076)	Weather dependent	YES	NO	NO	
1	3	3	U/N Reef (11-088)	Weather dependent	YES	NO	NO	
1	7	1	Douglas Islet Reef (11-038)	Monitor crocodile risk	YES	NO	NO	
1	7	2	U/N Reef (11-041a)	Monitor crocodile risk	NO	NO	NO	
1	7	3	U/N Reef (11-047)	Monitor crocodile risk	YES	NO	NO	
2	1	1	Ogilvie Reef (13-076)	Monitor crocodile risk	YES	YES	YES	AIMS LTMP, Control Program, RJFMP
2	1	2	U/N Reef (13-077)	Monitor crocodile risk	YES	YES	YES	Control Program, RJFMP
2	1	3	Noddy Reef (No 3) (13-079c)	Monitor crocodile risk	NO	NO	NO	
2	3	1	Lytton Reef (13-088)	Monitor crocodile risk + Reef extent large	NO	YES	YES	Control Program
2	3	2	U/N Reef (13-093a)	Monitor crocodile risk	NO	NO	NO	
2	3	3	Kestrel Reef (13-104)	Monitor crocodile risk	NO	NO	NO	
3	1	1	North Warden Reef (14-039)		YES	NO	NO	
3	1	2	South Warden Reef (14-051)	Reef extent large	YES	NO	YES	Control Program
3	1	3	U/N Reef (14-053)	Monitor crocodile risk	YES	NO	YES	Control Program

3	3	1	Williamson Reefs (15-039)		YES	NO	YES	RJFMP
3	3	2	U/N Reef (15-043)		NO	YES	YES	AIMS LTMP, Control Program, RJFMP
3	3	3	U/N Reef (15-045)		NO	YES	YES	RJFMP
4	4	1	Agincourt Reefs (No 2a) (15-099b)		YES	YES	YES	Control Program
4	4	2	U/N Reef (16-013a)		YES	YES	YES	AIMS LTMP, Control Program, RJFMP
4	4	4	Undine Reef (East) (16-020b)		NO	YES	YES	Control Program, RJFMP
4	5	1	Pearl Reef (15-087)		NO	NO	YES	Control Program
4	5	2	Andersen Reef (15-090)		NO	YES	YES	AIMS LTMP, Control Program
4	5	3	Rachel Carson Reef (15-092)		NO	NO	YES	AIMS LTMP, Control Program
5	1	2	Noggin Reef (17-008)		NO	NO	YES	AIMS LTMP, Control Program, RJFMP
5	1	3	Gibson Reef (17-017)		NO	YES	YES	Control Program, RJFMP
5	1	4	U/N Reef (17-025)	Weather dependent + Deep reef	NO	NO	YES	Control Program, RJFMP
5	2	1	Milln Reef (16-067)	Weather dependent	YES	YES	YES	AIMS LTMP, Control Program, RJFMP
5	2	2	Pellowe Reef (16-070)	Weather dependent	NO	YES	YES	Control Program, RJFMP
5	2	3	North West Reef (16-072)	Weather dependent	YES	NO	YES	RJFMP
6	1	1	Little Kelso Reef (18-031)		YES	YES	YES	AIMS LTMP, Control Program
6	1	2	Rib Reef (18-032)		NO	YES	YES	AIMS LTMP, Control Program, RJFMP
6	1	3	Roxburgh Reef (18-042)		NO	NO	YES	AIMS LTMP, Control

								Program, RJFMP
6	2	1	Dip Reef (18-039)		YES	YES	YES	AIMS LTMP, RJFMP
6	2	2	Faraday Reef (18-041)		YES	NO	YES	AIMS LTMP
6	2	3	Coil Reef (18-046)	Weather dependent	YES	NO	YES	AIMS LTMP
7	1	1	Prawn Reef (19-024)	Weather dependent	NO	YES	YES	AIMS LTMP, Control Program, RJFMP
7	1	2	Shell Reef (19-028)	Weather dependent	NO	NO	YES	AIMS LTMP, Control Program, RJFMP
7	1	3	U/N Reef (19-032)	Weather dependent	NO	NO	NO	
7	2	1	Kangaroo Reef (East) (19-063a)	Reef extent large	YES	NO	YES	AIMS LTMP, Control Program, RJFMP
7	2	2	Kangaroo Reef (West) (19-063b)		YES	NO	YES	AIMS LTMP, RJFMP
7	2	3	U/N Reef (19-065)		YES	NO	YES	RJFMP
8	1	1	U/N Reef (19-131a)	Weather dependent + Restriction tidal streams	NO	YES	YES	AIMS LTMP, Control Program, RJFMP
8	1	2	Hook Reef (19-136a)	Weather dependent + Restriction tidal streams	NO	YES	YES	Control Program, RJFMP
8	1	3	Barb Reef (19-136b)		NO	NO	YES	Control Program, RJFMP
8	4	1	U/N Reef (19-161)	Weather dependent	NO	NO	NO	
8	4	2	Gargoyle Reef (19-180)	Weather dependent	NO	NO	NO	
8	4	3	U/N Reef (19-190)	Weather dependent	NO	NO	NO	
9	1	1	Wyatt Earp Reef (19-214)	Weather dependent	NO	NO	NO	
9	1	3	Williams Reef (19-218)	Weather dependent	NO	NO	YES	RJFMP
9	1	4	White Tip Reef (19-220)	Weather dependent	NO	NO	NO	
9	2	1	U/N Reef (20-192)	Restriction tidal streams	NO	NO	YES	RJFMP
9	2	2	U/N Reef (20-193)	Restriction tidal streams	NO	NO	NO	
9	2	3	U/N Reef (20-197)	Restriction tidal streams	NO	NO	NO	
10	1	1	Mystery Reef (21-258)		NO	NO	NO	

10	1	2	U/N Reef (21-259)		NO	NO	NO	
10	1	3	U/N Reef (21-266)		NO	NO	NO	
10	2	1	U/N Reef (21-507)		YES	NO	YES	RJFMP
10	2	2	U/N Reef (21-520)		YES	NO	YES	Control Program, RJFMP
10	2	3	Houdini Reef (21-524)		YES	YES	YES	RJFMP
11	3	1	Wreck Island Reef (23-051)	Restriction Sea state/Swell	YES	NO	YES	AIMS LTMP, RJFMP
11	3	2	One Tree Island Reef (23-055a)	Restriction Sea state/Swell	YES	YES	YES	AIMS LTMP, Control Program, RJFMP
11	3	3	Lamont Reef (23-076)	Restriction Sea state/Swell	NO	YES	YES	Control Program, RJFMP
11	4	1	Erskine Reef (23-068)		YES	YES	YES	AIMS LTMP, Control Program, RJFMP
11	4	3	Polmaise Reef (23-071)		YES	YES	YES	Control Program, RJFMP
11	4	4	Rock Cod Shoal (23-072)		NO	NO	NO	

The cluster numbers shown in Table 1 reflect the master sample approach, where clusters were selected sequentially from the spatially balanced design until two operationally feasible clusters were identified in each sector. In some sectors, such as Sector 1 where clusters 3 and 7 were selected, several earlier clusters in the sequence required removal due to safety concerns or operational constraints. In contrast, other sectors had fewer logistical constraints, with clusters 1 and 2 proving suitable for monitoring. This variation demonstrates the importance of the master sample approach. The ordered list of backup clusters and reefs ensures the monitoring program can adapt to changing operational conditions while maintaining statistical validity.

Behind the 22 clusters presented here lies a comprehensive master list containing backup reefs for each cluster and additional backup clusters for each sector. While desktop feasibility assessments have identified potential constraints, actual monitoring experience may reveal additional challenges requiring further substitution of reefs or clusters from the master list. A key requirement of a spatially balanced master sample is that the integrity of each cluster must be maintained. Reefs within a cluster are selected as a set because, in combination, they provide the spatial configuration needed to uphold the design’s probabilistic balance. Mixing reefs from different clusters (e.g. substituting a reef from one cluster into another) would disrupt this balance and introduce spatial bias, undermining the statistical properties that enable unbiased GBR-wide and sector-level estimation. For this reason, clusters cannot be ‘mixed and matched,’ and substitutions must follow the predefined order of reefs within the same cluster.

Critically, the order of reefs within each cluster is also important, if individual reefs need to be replaced, they must be substituted with the next sequential reef from the master list for that cluster to preserve the spatial balance properties. The sequential nature of the master sample ensures that any such substitutions maintain the spatial balance and statistical properties of the design. The full master list, including backup reefs and clusters in their predefined sequence, is provided to field teams prior to deployment to guide any required in-field adjustments. This ensures that substitutions are made transparently and consistently, rather than on an ad hoc basis, preserving the integrity and comparability of the monitoring program over time.

Importantly, while clusters must remain intact as statistical units, they do not need to be completed within a single field trip. If weather or logistics prevent all reefs in a cluster from being surveyed during one voyage, the remaining reefs can be completed later in the same annual cycle without affecting statistical validity. What matters is that all reefs in the cluster are surveyed within the year, unless substitutions follow the prescribed sequence—not that they are visited during the same deployment. This provides operational flexibility while preserving statistical rigor.

Importantly, to maintain statistical validity, any expansion of the monitoring program must proceed sequentially through the master list within each AIMS sector. Selecting clusters out of order would undermine the spatially balanced properties that enable unbiased GBR-wide estimation. The master list has been designed so that monitoring effort can be scaled up from the 66 reefs as resources permit, with each incremental addition maintaining the statistical rigor of the overall design.

Approximately 77% of the selected baseline reefs (51 of 66 reefs) have existing manta tow survey data from previous programs, with many also having been targeted for COTS control operations. This extensive historical baseline means the baseline monitoring will immediately provide valuable temporal context, allowing assessment of trends from the commencement of monitoring rather than requiring multiple years of data before meaningful temporal analysis becomes possible.

Coordination with the AIMS LTMP would promote efficient use of monitoring resources when implementing this design. One baseline monitoring cluster (Sector 4, Cluster 4) includes St Crispin Reef (16-013a), which is monitored annually by AIMS LTMP. To avoid duplication of effort while maintaining the three-reef cluster structure recommended in CCIP-D-01, this cluster was expanded to include a fourth reef. The AIMS monitoring data for St Crispin Reef can be directly incorporated into the future baseline monitoring analyses. This integration demonstrates how the baseline monitoring design can work synergistically with existing programs to maximise the information gained from GBR monitoring investments.

The operationally focused nature of this design, particularly its alignment with RJFMP field operations, enhances the feasibility of implementation within existing resource allocations. Many selected reefs are accessible during standard RJFMP voyages, and the clustered approach of monitoring three reefs in geographic proximity aligns well with typical voyage planning. Weather-dependent reefs and those with tidal restrictions have been documented

(Table 2), allowing voyage planning to account for these constraints. Reefs requiring consultation with Traditional Owners prior to monitoring have been retained in the design with the commitment to undertake appropriate engagement, ensuring the program respects cultural protocols while maintaining geographic representation.

Early warning reef monitoring design

The early warning reefs complement the baseline program by targeting high-risk reefs where early detection of increasing COTS densities provides the greatest potential for management intervention before outbreaks reach damaging levels. The early warning reef list integrates findings from CCIP-D-03 (Uthicke et al. 2025) and CCIP-P-04 (Pratchett et al. 2025), refined through expert consultation and stakeholder review.

Project CCIP-D-03 initially recommended 26 reefs for annual early-warning monitoring based on outbreak risk analysis and reef connectivity patterns. Given current budget constraints, we reviewed temporal patterns of existing eDNA data collection (ranging from 3-7 years across different reefs) and identified cost-effective approaches for ongoing sample collection. Three of the early-warning reefs were also selected in the baseline monitoring reefs and so could serve both purposes. The stakeholder review process also identified a potential monitoring gap in the far southern GBR, where early warning capacity has historically been limited. Three additional reefs (U/N 22-141, U/N 22-143, and U/N 22-144) have been added to address this gap, bringing the total early warning list to 29 reefs (Table 3).

A key consideration for implementing this network cost-effectively is the diversity of existing access opportunities across the selected reefs. Many early warning reefs could be monitored through existing programs and infrastructure, reducing the marginal cost of sample collection. These opportunities include: baseline monitoring (three reefs), integration with AIMS LTMP voyages (nine reefs), access through the Lizard Island Research Station and associated field operations (four reefs), partnerships with commercial dive operators (four reefs), opportunistic sampling through research station activities at Green Island, Orpheus Island, and Reef Magic pontoons (three reefs) and other AIMS field work/vessel time. The remaining nine reefs would require dedicated RJFMP or COTS Control Program vessel time.

Early warning eDNA monitoring is designed to operate during the pre-outbreak phase when COTS densities are low and difficult to detect visually. Once outbreak densities are confirmed through manta tow or SALAD surveys, the region transitions into the tactical response phase, and the early warning function is no longer required. Early warning monitoring at reefs within an active outbreak zone may therefore be paused until the region returns to non-outbreak status. This ensures that sampling effort is allocated where it provides the most value, while maintaining the long-term continuity of the early warning network for future outbreak detection.

Table 3 Early warning reefs selected for ongoing monitoring to enable early detection of COTS outbreaks. Previous years of eDNA samples indicates existing temporal baseline, and sampling options identify cost-effective access opportunities through existing programs and infrastructure.

Reef Name	**Years of eDNA sampling**	**Sampling options**
McSweeney Reef	4	LTMP
Monsoon Reef	3	LTMP
U/N 11-049	4	LTMP
U/N 11-160	3	
U/N 13-093a	3	Baseline reef monitoring
U/N 13-124	4	LTMP
Corbett Reef	4	LTMP
Davie Reef	3	LTMP
Yonge Reef	5	Access through LIRS (weather dependent) or LTMP
Lizard Island	7	Access through LIRS
Eyrie Reef	6	Access through LIRS
North Direction Island	6	Access through LIRS
Ribbon Reef 9	3	Dive operators
Ribbon Reef 5	3	Dive operators
Osterlund Reef	4	
Cairns Reef	4	
Undine Reef	4	Dive operators Pt Douglas, Baseline reef monitoring
Rudder Reef	4	Dive operators Pt Douglas
Tongue Reef	4	
Batt Reef	4	
Green Island	4	Opportunities through Cairns
Thetford Reef	5	LTMP
Moore Reef	5	Reef Magic
Rib Reef	3	May be possible from Orpheus Island RS, Baseline reef monitoring
Davies Reef	7	LTMP
Bowden Reef	7	
U/N 22-141	0	
U/N 22-143	0	
U/N 22-144	0	

Combined monitoring design

The comprehensive monitoring framework integrates 66 baseline reefs across 22 clusters with 29 early warning reefs to provide GBR-wide COTS surveillance (Figure 2 and Figure 3). Baseline reefs deliver spatially balanced, statistically robust trend estimation at the GBR scale, while early warning reefs target high-risk locations where early detection enables timely management intervention to prevent outbreak escalation.

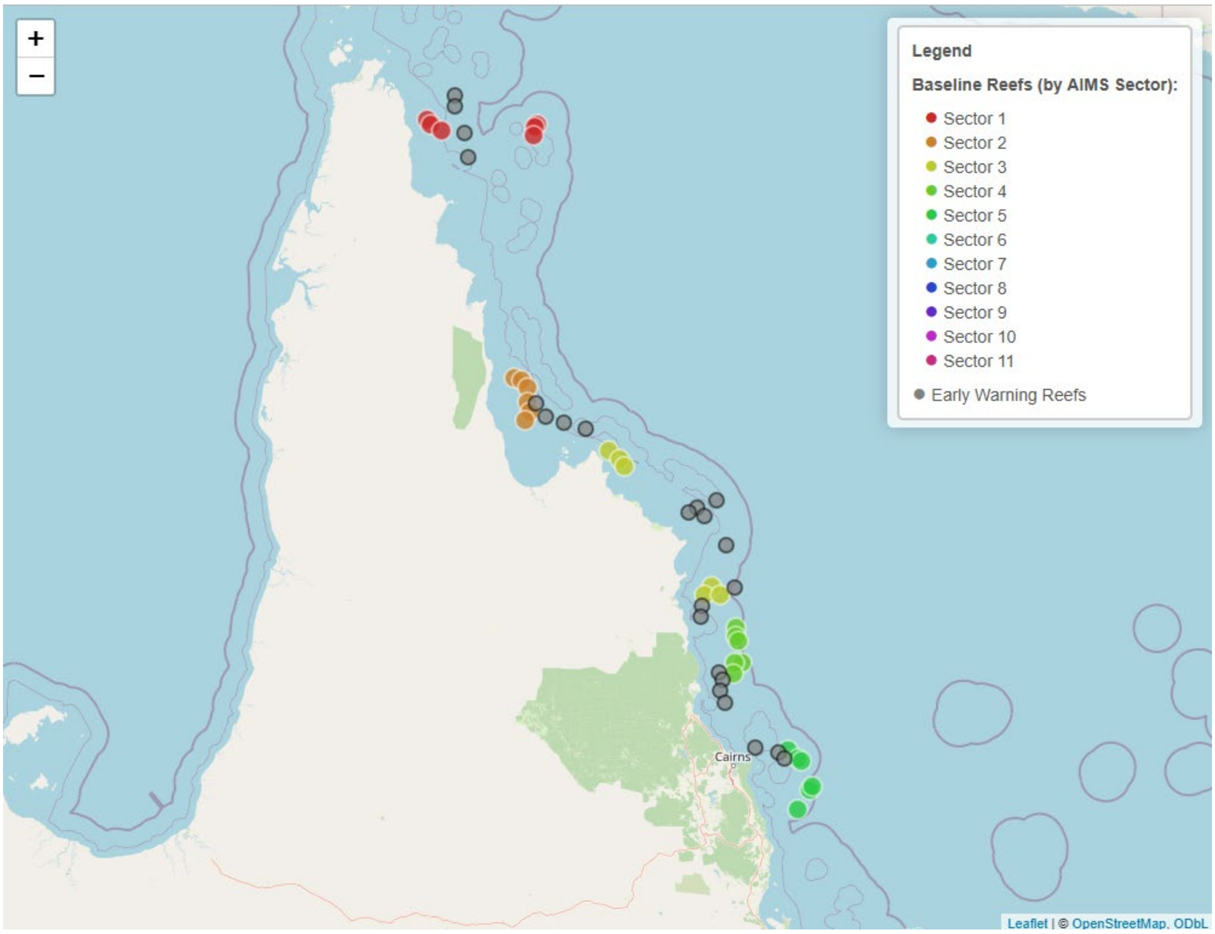

Figure 2 Map of the proposed baseline and early warning reefs in AIMS Sectors 1-5. The baseline reefs are numbered by the AIMS Sector that they fall in.

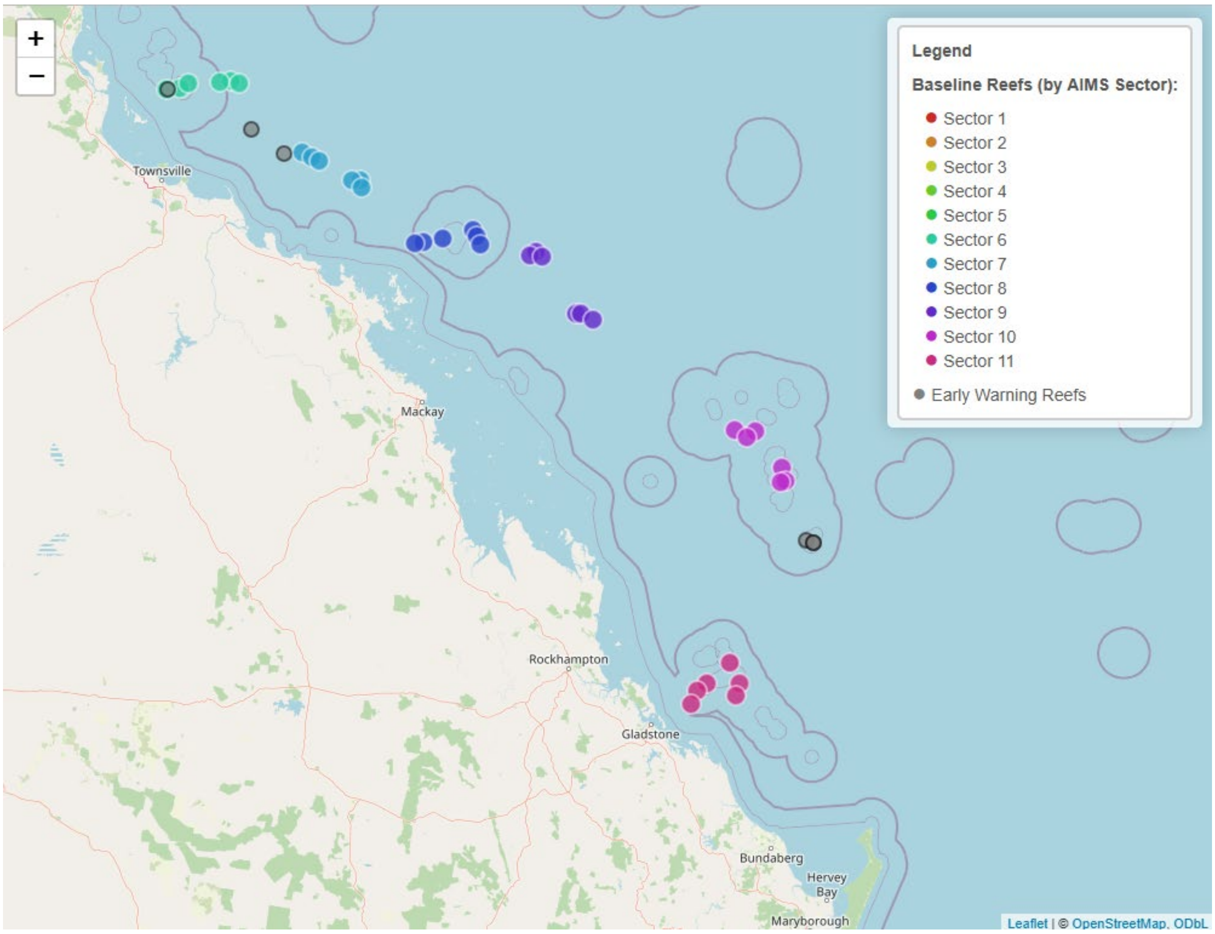

Figure 3 Map of the proposed baseline and early warning reefs in AIMS Sectors 6-11. The baseline reefs are numbered by the AIMS Sector that they fall in.

Pilot field trial outcomes

January 2025 Deployment – Swain Reefs

The first deployment focused on the northern sector of the Swain Reefs complex (cross-latitude 21 degrees south) aboard the QPWS vessel *Reef Resilience*. The deployment successfully completed 366 individual broad-scale manta tows, surveying approximately 70 km (703,871 m²) of reef margin across nine clustered target reef locations.

The ReefScan Surface system was deployed simultaneously with the manta tow and captured 162,783 images (540 GB). The towed ReefScan Deep unit (with dual cameras) collected 206,248 images (460 GB). The ReefScan Deep unit was towed for varying proportions of the reef perimeters (usually 1-2 nautical miles). AIMS technicians provided comprehensive training to QPWS crew members on equipment operation and data download protocols, advancing the research translation and technological capabilities of reef monitoring efforts.

To support early warning COTS detection research by AIMS, the deployment collected 216 eDNA samples (plus controls) at the nine reef locations and 48 plankton samples for COTS larvae analysis at 16 reef locations.

February 2025 Deployment – Mackay Region

Following a one-day weather delay, the second deployment targeted clustered reefs offshore Mackay (north of latitude 20 degrees south). The team completed 247 individual broad-scale manta tows under moderate-to-heavy monsoonal weather conditions, surveying approximately 47 km (474,977 m²) of reef margin across nine clustered target reef locations.

Despite challenging weather conditions, the deployment successfully demonstrated the operational resilience of emerging technologies. The ReefScan Surface unit collected 110,091 images (335 GB), again being deployed simultaneously with the manta tows. The towed ReefScan Deep was also deployed across all target reefs. The system operated for 432 minutes (7.2 hours) of active recording, capturing 155,722 images (378 GB), with 19 confirmed COTS detected by the real-time detection system. For small reefs (21-067, 21-071, 21-094) the ReefScan Deep was towed for the entire reef perimeter, while for larger reefs (all remaining reefs) varying proportions of the reef perimeters were towed (usually 1-2 nautical miles).

The team also collected 216 eDNA samples (plus controls) at nine reef locations and 49 plankton samples for COTS larvae analysis at 13 reef locations, maintaining the early detection research focus despite adverse weather.

Analysis of data from field trials

The pilot field trials provided the first opportunity to compare COTS detection and coral cover assessment across multiple monitoring tools deployed concurrently at the same reefs. Data were collected using manta tow surveys, eDNA sampling, and ReefScan technology (both Surface and Deep configurations) across 18 reefs in the Swain and Mackay regions during January-February 2025.

COTS detection across monitoring tools

The four monitoring approaches showed varying sensitivity in detecting COTS presence across the surveyed reefs (Figure 4). Environmental DNA detected a COTS signal (proportion positive >0) at all 18 reefs surveyed, while manta tow surveys detected COTS at four reefs (22%) and COTS or scars at five reefs (28%), ReefScan-Surface identified COTS at six reefs (33%), and ReefScan-Deep identified COTS at eight reefs (44%). The interpretation of eDNA results requires consideration of the density thresholds established in Uthicke et al. 2026. Two-thirds of the 18 reefs had proportion positive values less than 0.4, corresponding to very low COTS density estimates equivalent to less than three COTS per hectare. At these low densities, Uthicke et al. 2026 recommend no follow-up action is required, as COTS are present at background levels that do not threaten coral communities. The other six reefs showed eDNA values above this threshold, potentially indicating COTS densities warranting closer monitoring or follow-up surveys. Details of the eDNA monitoring results for these reefs and their recommended interpretation for COTS management are provided in the final report for translation project CCIP-RT-02 (Uthicke et al. 2026).

At reefs where visual methods (i.e. manta tow, ReefScan) detected COTS or feeding activity, eDNA values were generally higher, showing concordance between methods at reefs with elevated COTS densities.The enhanced sensitivity of eDNA at low densities makes it particularly valuable for early warning monitoring, where the objective is to detect increasing populations before they reach outbreak densities.

Several reefs with eDNA values above the 0.4 proportion positive threshold showed no COTS detection via manta tow or either ReefScan platform (e.g., UN Reef 21-093, UN Reef 21-444). ReefScan-Deep detected COTS at several reefs (e.g. 21-443) where ReefScan-Surface did not, even though the Reef-Scan Deep transects were substantially shorter than the distance covered by the Reefscan-Surface at some reef. As the tracks were not the same for the two units it is difficult to ascertain the cause of these differences, though it is possible the COTS detected by the ReefScan Deep were located at depths the Surface could not effectively survey. There have been few side by side comparisons of the two ReefScan units to date, so it will be important to validate this result by collecting and analysing future data. These patterns also highlight the complementary nature of the different detection methods and the importance of using multiple approaches to build a comprehensive understanding of COTS distribution and abundance.

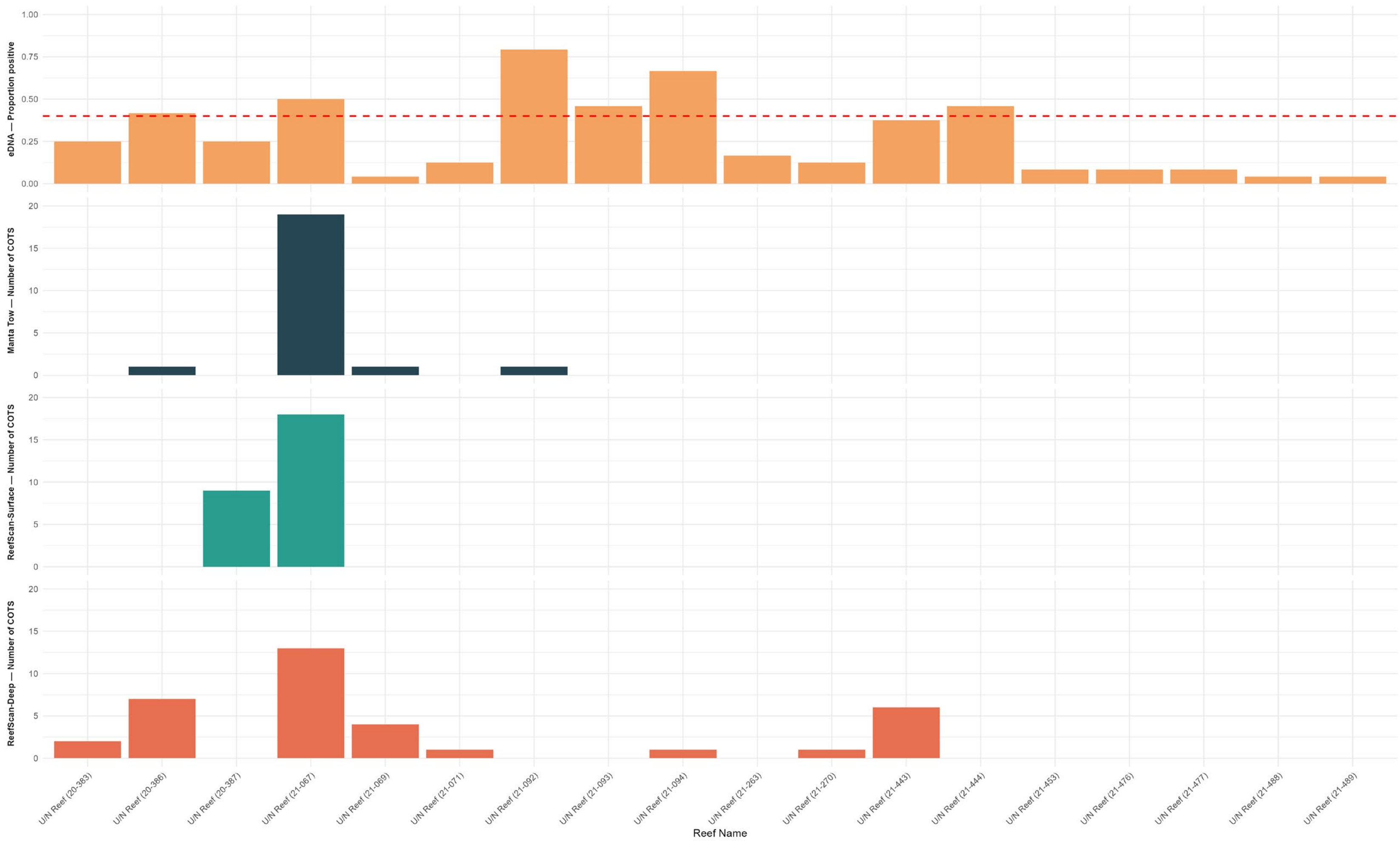

Figure 4 Comparison of COTS detection across monitoring tools at 18 reefs surveyed during January-February 2025 pilot field trials. Environmental DNA (eDNA) proportion positive values are shown alongside the number of COTS detected from manta tow surveys and ReefScan automated detection. The dashed horizontal line at 0.4 proportion positive eDNA samples indicates the threshold recommended in Uthicke et al. 2026 below which COTS densities are estimated at less than 3 COTS per hectare and no follow-up action is recommended. Missing bars indicate no COTS were detected. The ReefScan-Deep towed the entire perimeter of 21-067, 21-071 and 21-094 and varying proportions of the remaining reefs.

Coral cover assessment

Coral cover estimates from the three survey methods showed varying levels of correspondence across the 18 surveyed reefs (Figure 5). As expected, manta tow and ReefScan-Surface estimates showed closer agreement, as both methods were deployed concurrently from the same tender vessels, sampling the same reef areas at the same time. The manta tow hard coral cover estimates were consistently higher than the equivalent ReefScan-Surface estimates from ReefCloud's model.

ReefScan-Deep estimates showed greater deviations from both other methods, although coral cover was almost always lower than on manta tow. These differences reflect several factors: ReefScan-Deep was towed on separate transects covering only a subset of the reef perimeter (compared to full perimeter coverage by manta tow), operates at greater depths, and may be capturing different benthic communities. Additionally, manta tow provides categorical assessments (e.g., 0-10%, 10-30% cover categories converted to midpoints), while both ReefScan platforms use automated pixel-level classification of benthic imagery, a heuristically different approach to assess areal coverage of the reef floor.

These results are preliminary, and AIMS is currently working to validate and improve the assessments of benthic cover that can be derived from ReefScan imagery. Despite current methodological differences and ongoing analytical refinements, the general agreement in trend between manta tow and ReefScan-Surface demonstrates that co-deployed methods can produce comparable results. The concurrent assessment of both COTS and coral from the same imagery represents a significant management advantage. As deployment protocols and classification algorithms are refined, ReefScan is expected to provide increasingly valuable contributions to baseline monitoring of the GBR.

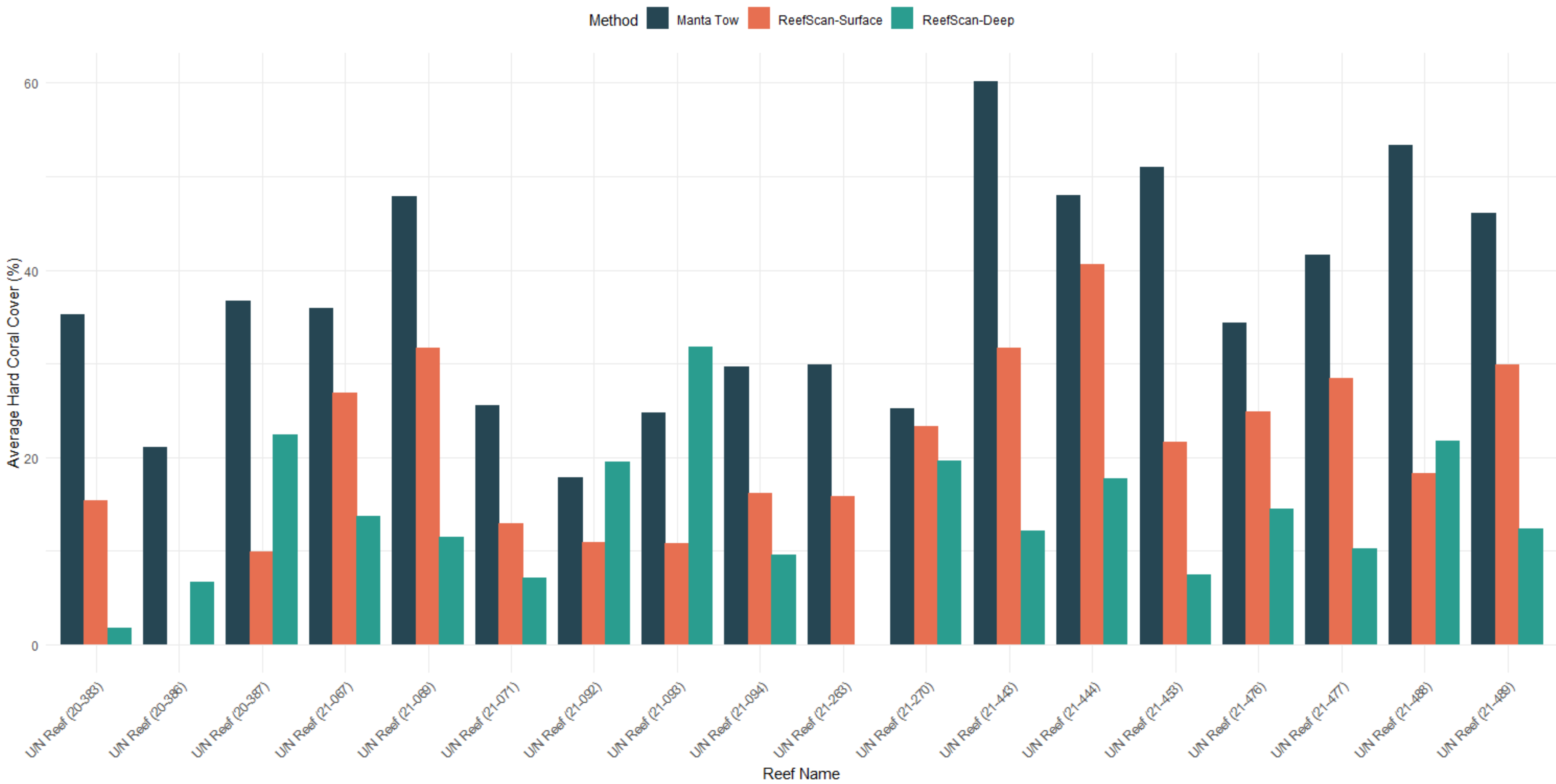

Figure 5 Comparison of coral cover estimates from manta tow surveys, ReefScan-Surface, and ReefScan-Deep across 18 reefs surveyed during January-February 2025 pilot field trials. Manta tow and ReefScan-Surface were conducted concurrently from the same tender vessels. ReefScan-Deep was towed on separate transects sampling a subset of the reef perimeter. Missing bars indicate observations not recorded for that method. Results are preliminary; AIMS is conducting ongoing work to validate and improve automated classification accuracy.

Operational considerations and resourcing

The field trials demonstrated that all three monitoring approaches can be successfully integrated into RJFMP operations. eDNA sampling proved highly compatible with existing field protocols, requiring minimal additional vessel time beyond the standard deployment for manta tow surveys. QPWS staff quickly became proficient in eDNA collection procedures through the training provided during the deployments via CCIP-RT-02, with sampling controls demonstrating contamination-free collections (Uthicke et al. 2026).

ReefScan technology showed operational promise but requires further refinement of data collection and transfer to reduce the time needed to retrieve, download and analyse the data. The Surface unit was successfully deployed from the tender vessel during manta tow operations, demonstrating the feasibility of concurrent data collection. The ReefScan Deep unit, towed behind the tender vessel, proved more weather-dependent than manta tow surveys but successfully collected data across extended transects when conditions permitted.

The trials confirmed that the recommended three-reef cluster structure for baseline monitoring is operationally feasible within standard RJFMP voyage schedules. All three reefs in each cluster were successfully surveyed despite weather constraints. The integration of emerging technologies added value without substantially compromising the efficiency of standard monitoring and surveillance operations, supporting the progressive integration approach recommended in CCIP-D-01.

The scalable design of the baseline monitoring program enables flexible implementation that can align with existing vessel schedules and available resources. If half (30 days) of the currently scheduled RJFMP COTS surveillance days were allocated to baseline monitoring, the RJFMP program could potentially cover up to 27 reefs annually (assuming three clusters of three reefs per ten day voyage). Such a phased implementation approach offers a practical pathway to establish the monitoring program. Rather than requiring immediate commitment to all 66 reefs, RJFMP could begin by incorporating baseline clusters located in AIMS sectors already scheduled for surveillance visits. This approach would allow the program to monitor two clusters across more of the scheduled trips (e.g., 1-2 clusters on each of six trips) rather than concentrating effort on fewer voyages (e.g., three clusters on three trips). This distribution would build operational experience across the program while providing broader geographic coverage from the outset. Additional baseline clusters could be incorporated by COTS Control Program vessels if built into their forward operational schedules, creating a collaborative approach to delivering the full monitoring design.

Early warning reef monitoring presents different resourcing considerations. Many of the 29 early warning reefs can be accessed cost-effectively through existing programs and infrastructure, including AIMS LTMP voyages (nine reefs), research station operations at Lizard Island, Orpheus Island, and Green Island (seven reefs), and partnerships with commercial dive operators (four reefs). However, unlike baseline monitoring, where eDNA sampling can be integrated efficiently into RJFMP voyages, the majority of early warning reefs are not expected to be sampled by RJFMP vessles. Early warning sampling is likely to instead rely on opportunistic access through these partner programs and facilities.

While eDNA sample collection at reefs can often be achieved at low marginal cost, the laboratory processing and analysis of eDNA samples requires dedicated funding that is not currently available within existing program budgets. Importantly, this funding requirement applies to both baseline and early warning samples. Securing funding for eDNA sample processing remains a critical requirement for implementing the early warning component of the monitoring design (and the baseline monitoring if this method is to be integrated into the baseline monitoring program as recommended), regardless of the efficiency gains achieved through coordinated sample collection. To undertake eDNA monitoring of both the baseline and early-warning reefs, around 2800 eDNA samples would need to be processed annually using current sampling protocols (six samples at four sites per reef, plus controls).

Impact pathway

This project contributes directly to the overarching outcomes and impacts identified in CCIP's Research Impact Plan:

- **Improved detection and monitoring:** The integration of eDNA sampling with traditional methods provides detection capability at COTS densities below visual survey thresholds. The spatially balanced baseline design ensures representative, unbiased data collection across the GBR. The introduction of ReefScan technology provides the ability to monitor COTS and coral cover simultaneously.
- **More efficient and effective operational response:** The tiered response framework at early warning reefs allocates intensive survey effort only where eDNA results indicate potential outbreak development, maximising detection capability while managing resource constraints. The baseline monitoring data provides spatially representative information to inform prioritisation of control efforts and assessment of management effectiveness, enabling evidence-based resource allocation decisions.
- **COTS outbreaks suppressed and prevented:** Early warning monitoring at high-risk reefs enables detection and intervention before COTS reach densities that cause significant coral mortality. The combination of early detection capability and improved understanding of outbreak dynamics positions management to prevent outbreaks rather than merely responding after coral damage has occurred.
- **Measurement of coral cover protected across the GBR:** The baseline monitoring data will directly inform future updates to the COTS Control Program's tactical and strategic priorities. The ability to assess management effectiveness through statistically robust baseline monitoring enables adaptive management at the GBR scale, ensuring control efforts are optimally allocated to protect coral cover.
- **Traditional Owners, tourism industry and community benefit:** Enhanced reef resilience through effective COTS management protects the ecosystem services that support Traditional Owner cultural connections, tourism industry viability, and broader community wellbeing.

CONCLUSIONS & NEXT STEPS

The project has operationalised the CCIP-D-01 monitoring design recommendations by selecting 66 baseline reefs organised into 22 clusters across 11 AIMS sectors, ensuring both statistical validity and geographic representation. The iterative stakeholder review process successfully identified and addressed operational constraints including safety considerations, weather dependencies, and cultural sensitivities, while maintaining the master sample approach that preserves design flexibility and statistical properties. The integration of 29 early warning reefs, strategically positioned at high-risk locations, provides enhanced capacity to detect emerging outbreaks before they reach damaging densities.

Field trials in the Swain Reefs and Mackay regions demonstrated the operational feasibility of integrating emerging technologies with traditional monitoring methods. eDNA sampling proved highly compatible with existing field protocols, requiring minimal additional vessel time while providing enhanced detection sensitivity at low COTS densities. ReefScan technology successfully demonstrated concurrent COTS and coral assessment capabilities, though further refinement of data handling protocols is needed to maximise operational efficiency. The successful completion of all planned surveys despite weather constraints confirmed that the three-reef cluster structure aligns well with standard RJFMP voyage schedules.

The stratification by AIMS sectors addresses multiple objectives simultaneously: it ensures adequate geographic representation for outbreak detection, aligns with existing management reporting frameworks, and naturally achieves representation of both green zones and fished areas without requiring complex probability adjustments. Early and regular stakeholder engagement identified practical improvements over the theoretical design, which enhance both operational feasibility and management utility.

Next Steps for Implementation

Several critical actions are required to transition from operational readiness to full program implementation:

- Begin monitoring baseline clusters, initially in AIMS sectors that already have upcoming scheduled RJFMP surveillance. There are two trips scheduled for early 2026.

- While it is possible to utilise existing vessel resourcing for collecting eDNA samples for many reefs, the baseline and early warning monitoring components cannot be implemented without dedicated funding for laboratory analysis of eDNA samples.

- The data flow from field collection using ReefScan through to analysis and reporting, including quality assurance procedures, data storage systems, and integration pathways with Reef Authority systems is currently an impediment to maximising this technology to its full utility. Future work being undertaken in CCIP will benefit from and contribute to this data pipeline.

- Formalise protocols for incorporating AIMS LTMP monitoring data into baseline monitoring analyses where it is appropriate to directly substitute, maximising value from existing investments.

- Continue progressive integration of ReefScan technology as operational protocols mature and detection algorithms improve, potentially transitioning toward this as a primary monitoring tool.

- While SALAD surveys were identified as valuable for quantifying COTS size structure at early warning reefs, operational protocols for their deployment in response to eDNA triggers require further development.

- Methods for integrating historical surveillance data with new baseline monitoring data require refinement to maximise the value of decades of existing reef surveys while maintaining statistical rigour.

While operationalising water quality and environmental covariate monitoring was not within the scope of this project, we acknowledge the recommendations from the CCIP-D-01 report regarding the value of collecting environmental data at monitoring sites (Lawrence et al. 2025a). Such data could help identify environmental drivers of COTS outbreaks, improve predictive model accuracy, and disentangle the impacts of multiple stressors. Although operationalising environmental covariate monitoring represents a lower priority relative to establishing the core baseline and early warning monitoring programs and is beyond current funding capacity, future program development should consider incorporating water quality monitoring at some or all baseline sites where it makes sense in terms of time and cost efficiency, potentially leveraging integration with eReefs modelling to maximise value.

Transformational Change in COTS Management

This research translation project represents a fundamental shift in how COTS management operates on the GBR. For the first time, the COTS Control Program will have access to spatially unbiased, statistically robust monitoring data that can definitively answer strategic questions about management effectiveness and GBR-scale trends. Previous approaches, while operationally essential, were inherently biased toward reefs targeted for control operations or included in other programs for different purposes, limiting the ability to draw GBR-wide conclusions or assess whether management intervention is successfully protecting coral cover.

The most significant change in practice is the transition from surveillance-driven data collection to a dual framework that maintains tactical surveillance capability while simultaneously building a statistically designed baseline monitoring program. This transformation enables the COTS Control Program to operate with confidence that management decisions are informed by representative data, that effectiveness can be rigorously assessed, and that emerging outbreaks can be detected through early warning monitoring before they cause widespread coral mortality.

Critically, this change has been achieved not with massive resource expansion, but through strategic integration with existing programs, thoughtful design that aligns with operational realities, and collaborative engagement with stakeholders across multiple organisations. The scalable, flexible design ensures the program can grow as resources permit while delivering value from day one of implementation. By bridging the gap between scientific rigour and operational feasibility, this project has created a pathway for evidence-based adaptive management of COTS at the scale required to protect coral across the GBR.

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DATA ACCESSIBILITY

The master sample list is stored on the CSIRO Data Access Portal https://doi.org/10.25919/2vfs-kn26 and linked to the COTS Information System.

The field work data is stored on the CSIRO Data Access Portal https://data.csiro.au/collection/csiro:72211 and linked to the COTS Information System.

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Emma Lawrence
(emma.lawrence@data61.csiro.au)
CSIRO, Data61
EcoSciences Precinct,
41 Boggo Road, Dutton Park, Qld, 4102.

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