COTS Control Innovation Program TECHNICAL REPORT

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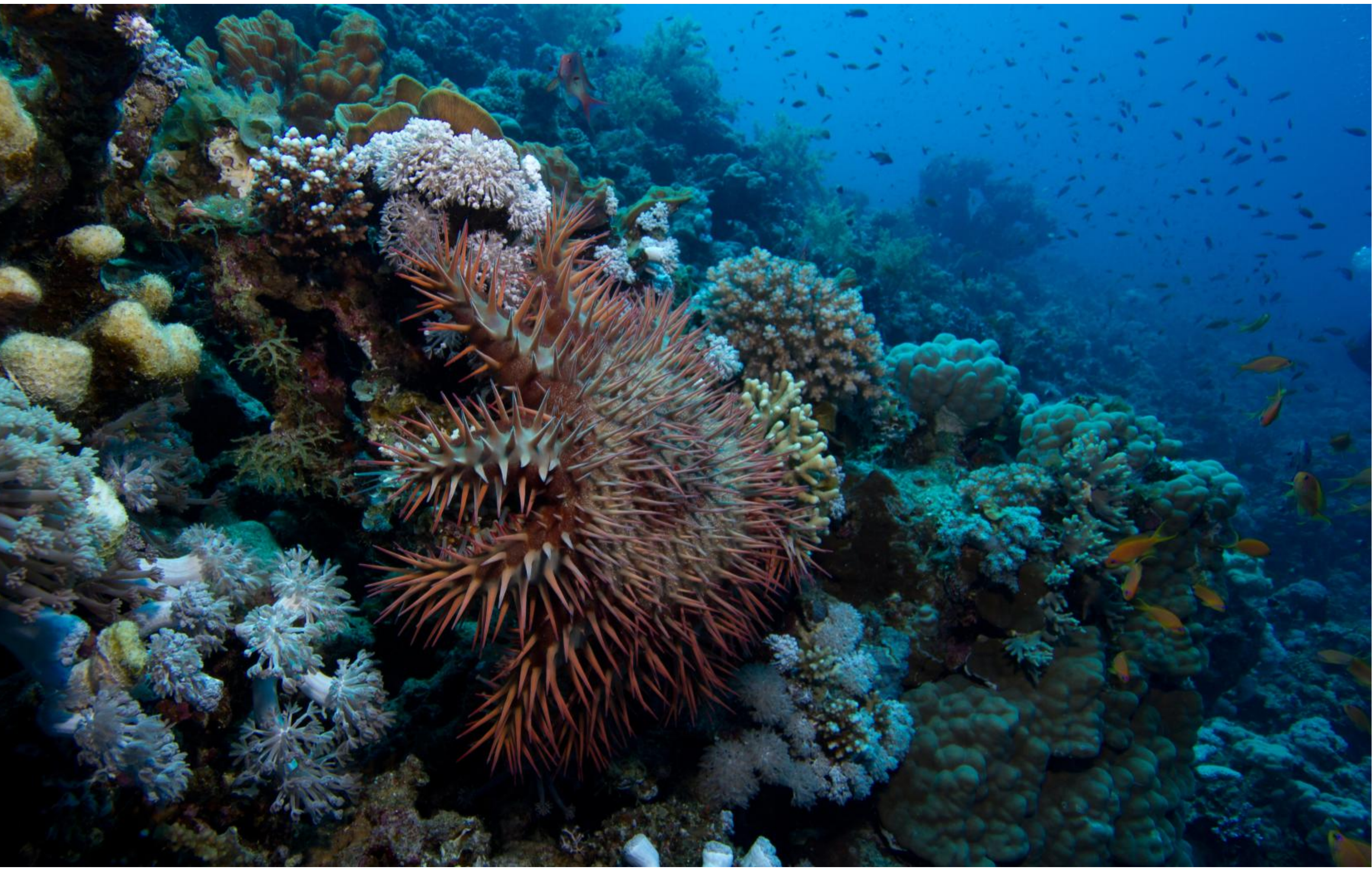

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COTS Control Innovation Program | A research and development partnership to better predict, detect and respond to crown-of-thorns starfish outbreaks

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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.

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Acronyms and Abbreviations

AIMS	Australian Institute of Marine Science
AI	Artificial Intelligence
BPM	Blue Planet Marine
CCIP	Crown-of-thorns starfish Control Innovation Program
COTS	Crown-of-thorns starfish
CPUE	Catch-per-unit-effort
CSIRO	Commonwealth Scientific and Industrial Research Organisation
ddPCR	Droplet Digital Polymerase Chain Reaction
eDNA	Environmental DNA
GBR	Great Barrier Reef
GBRF	Great Barrier Reef Foundation
GLMM	Generalised Linear Mixed Model
GPS	Global Positioning System
IPM	Integrated Pest Management
JCU	James Cook University
JFMP	Joint Field Management Program
LTMP	Long-Term Monitoring Program
ML	Machine Learning
OH&S	Occupational Health and Safety
PCR	Polymerase Chain Reaction
PI	Prediction Interval
PMG	Pacific Marine Group
QPWS	Queensland Parks and Wildlife Service
Reef Authority	Great Barrier Reef Marine Park Authority
RJFMP	Reef Joint Field Management Program
SALAD	Scooter-assisted large area diver-based
SCUBA	Self-Contained Underwater Breathing Apparatus
TO	Traditional Owner

EXECUTIVE SUMMARY

The Pacific crown-of-thorns starfish (COTS) is a coral-eating starfish found across the Indo-Pacific, including Australia's Great Barrier Reef (GBR). COTS are a natural part of reef ecosystems, but populations can undergo outbreaks, during which their intensive coral predation causes rapid and extensive coral loss. Outbreaks of COTS remain one of the leading causes of coral decline on the GBR.

The GBR COTS Control Program (managed by the Great Barrier Reef Marine Park Authority) uses an Integrated Pest Management framework to prioritise and deliver tactical responses to COTS outbreaks. The success of the COTS Control Program depends on monitoring and surveillance data that can be used to assess COTS populations relative to ecological thresholds, currently defined in units of cull diver catch-per-unit-effort (CPUE). However, traditional monitoring tools like manta tow surveys and cull diver surveys (a byproduct of the culling process) have well-documented limitations such as low detectability, large resource requirements, need for divers to be in the water and inability to simultaneously measure COTS and coral accurately.

Emerging tools including environmental DNA (eDNA) sampling, scooter-assisted large area diver-based (SALAD) surveys, and the ReefScan towed camera system offer the potential to address some of these limitations by improving the detection of COTS at low densities, removing the need for divers to be in the water, and expanding spatial coverage. However, before these tools can be integrated into the COTS Control Program's decision-making framework, their outputs must be calibrated against established methods so that observations from different tools can be translated into comparable units.

This study calibrated five monitoring tools deployed side-by-side across reefs with varying COTS densities and coral cover. Three tools measure both COTS abundance and coral cover: manta tow surveys, SALAD surveys and ReefScan underwater camera system. Two tools measure COTS only: cull diver surveys and eDNA sampling. Data from two field trials were used to develop statistical calibration models for each pair of tools. The calibration models enable observations from any one tool to be translated into the units of another, including into the cull diver CPUE units required for threshold-based management decisions.

The results demonstrate promising applications of the novel approaches. eDNA sampling proved effective at detecting COTS presence even at low densities, with eDNA concentrations correlating positively with in-water estimates of COTS density from SALAD surveys and COTS culled CPUE. SALAD surveys outperformed other tools in resolving fine-scale COTS distributions and size metrics. The ReefScan camera systems, which use machine learning to classify benthic images, provided continuous measurements of coral cover and are on a pathway to automate COTS detection as machine learning models are further trained.

The calibration models allow observations from any tool to be expressed as equivalent cull diver CPUE values, directly supporting threshold-based management decisions. For example, at the lower ecological threshold for COTS control (0.04 COTS culled per minute), SALAD surveys would be expected to record approximately 20.6 COTS and scars per hectare, while approximately 54% of eDNA water samples would be expected to test positive. These equivalences enable managers to assess whether COTS densities exceed intervention thresholds regardless of which monitoring tool collected the data. In contrast, manta tow surveys showed consistently low detectability of COTS, a consequence of the cryptic and patchy nature of COTS, substantially underestimating COTS densities compared to other methods like SALAD and cull surveys. The relationship between manta tow and all other methods was highly uncertain across the full range of densities observed. However,

manta tow offers a rapid broad-scale assessment suited for triggering further investigations, which is its primary use in the COTS Control Program.

Three tools (manta tow, SALAD coral transects, and ReefScan) also provide coral cover estimates. ReefScan-derived coral cover showed a positive relationship with manta tow estimates, but the calibration relationship differed substantially between the two field experiments likely reflecting differences in the range of coral cover encountered and the deployment protocol used. The relationship between SALAD coral transects and manta tow was highly uncertain, likely because the short 50 m SALAD transects do not spatially overlap with manta tow transects. Despite these uncertainties, the calibration models provide an initial basis for expressing coral cover estimates from each tool in manta tow-equivalent units, facilitating integration with the long historical record of manta tow data on the GBR. Continued data collection will refine these relationships over time.

Each method exhibited unique strengths and limitations regarding spatial scales, metrics recorded, ease of field implementation, and costs. Integrating multiple complementary tools tailored to specific objectives can significantly enhance and scale up the Program's monitoring capabilities cost-effectively. Critically, statistical calibration models enable translating measurements across tools, allowing diverse data streams to be incorporated consistently into decision-making frameworks. With quantified uncertainties, newly collected data can be contextualised against historical baselines.

The project highlights that integrating traditional methods with novel technologies is an optimal strategy for future monitoring. Coupled with refined decision protocols, this multi-tool approach could help optimise resource allocation for controlling COTS outbreaks and better protect coral cover across the GBR. Key next steps include operationalising ReefScan, updating calibrations with expanded data as it becomes available, developing integrated deployment strategies (see *CCIP-D-01 COTS Monitoring Design*), and consolidating translational protocols to facilitate consistent interpretation of multi-tool monitoring data streams in the COTS Control Program’s decision support systems.

1. INTRODUCTION

The Pacific crown-of-thorns starfish (COTS: *Acanthaster* cf. *solaris*) is a large, predatory sea star found in coral reef ecosystems in the Indo-Pacific region, including the Great Barrier Reef (GBR). While COTS are a natural component of coral reef ecosystems, they can become problematic when their populations surge (termed outbreaks), leading to high densities of large starfish that can devastate coral communities (Pratchett et al. 2014). On the GBR, repeated outbreak events remain one of the major drivers of long-term coral decline, compounding the coral loss caused by other disturbances such as cyclones and bleaching (Bozec et al. 2022; Emslie et al. 2024).

To mitigate the ecological impacts of COTS outbreaks, the Great Barrier Reef Marine Park Authority (Reef Authority) established the COTS Control Program, which is implemented through an Integrated Pest Management (IPM) framework (Fletcher and Westcott 2016; Westcott et al. 2016; Rogers et al. 2023). Since its inception in 2012, the Program has demonstrated that sustained and targeted culling can suppress COTS densities below ecologically damaging levels and contribute to improved coral retention at both reef and regional scales (Matthews et al. 2024). Operational control is delivered by contracted commercial operators, including Pacific Marine Group (PMG) and Blue Planet Marine (BPM), whose trained SCUBA teams locate and inject COTS across large areas of the reef estate. The sustained effort provided by these operators has generated one of the world's most extensive pest-control datasets, forming a critical foundation for understanding outbreak progression and evaluating management outcomes.

Effective management of COTS relies on a robust flow of monitoring and surveillance data that supports strategic prioritisation across the GBR, tactical decisions about where control vessels should allocate their time, and assessment of the ecological outcomes of management interventions (Westcott et al. 2021; Matthews et al. 2024). In practice, initial detection of outbreaks typically occurs through manta tow surveys conducted by PMG, BPM and other partners. These surveys identify the presence of COTS or fresh feeding scars and serve as the primary trigger for deploying cull dive teams to targeted locations. Once deployed, cull divers record catch-per-unit-effort (CPUE; COTS culled per minute), which is used to determine whether ecological thresholds for management intervention have been exceeded (Fletcher et al. 2020; Plagányi et al. 2020). However, cull diving is resource-intensive, spatially constrained, and limited by work health and safety protocols, meaning that CPUE cannot be collected consistently across the more than 3,000 reefs of the GBR. Because most other monitoring tools do not directly generate density-based metrics, their observations must be calibrated against CPUE or density estimates if they are to contribute meaningfully to threshold-based decisions and broader program reporting.

While manta tow surveys and cull dives remain the primary operational tools for surveillance and control, both methods have well-documented limitations, including imperfect detection, observer effects, categorical coral scoring and substantial operational costs (Fernandes et al. 1990; Westcott et al. 2021). Manta tow surveys, although efficient at covering large reef areas, can underestimate true COTS densities due to starfish crypticity, habitat complexity and environmental conditions such as visibility and sea state (Miller et al. 2018). Similarly, coral cover estimates derived from manta tow surveys are limited to coarse categorical bins, reducing their utility for detecting moderate or short-term changes in coral assemblages (Moran and De'ath 1992; Miller et al. 2018). Cull dives, while far more accurate at local scales, require large dive teams, are limited by bottom time, and produce CPUE rather than absolute density unless additional assumptions are made about search area, catchability and diver efficiency (Maunder et al. 2006).

These constraints have spurred substantial investment in the development of new monitoring tools aimed at enhancing detection sensitivity, expanding spatial coverage and improving data quality. Environmental DNA (eDNA) sampling can detect COTS genetic material at densities far below the limits of human visual detection, including in suboptimal visibility or complex habitats (Uthicke et al. 2018; Uthicke et al. 2022; Uthicke et al. 2025). Scooter-Assisted Large Area Diver-based (SALAD) surveys (Chandler et al. 2023; Pratchett et al. 2025) enable divers to rapidly cover much larger areas than traditional SCUBA surveys while simultaneously collecting information on coral composition and benthic context. ReefScan, a towed optical imaging system supported by machine-learning algorithms (Bainbridge and Coleman 2024; Bainbridge et al. 2025), provides the potential for consistent, high-resolution assessments of both coral cover and COTS presence across broad spatial scales. Collectively, these innovations increase data volume, improve sensitivity to both low-density and cryptic COTS populations, and offer the potential for more consistent, automated and scalable monitoring.

However, the diversity of metrics and scales produced by these tools, from eDNA positive sample proportions to SALAD encounter rates means that data from different tools cannot readily be combined or used interchangeably to inform management decisions. Addressing this challenge requires statistical calibration (Osborne 1991), which seeks to identify and quantify sources of variation contributing to differences among measurements produced by different monitoring tools. Calibration enables observations from one monitoring instrument to be translated into the units of another, allowing multiple data streams to contribute to management decisions. The most robust approach for such comparisons is to deploy established and emerging monitoring methods in tandem, enabling direct comparison of their outputs under shared field conditions.

This project, *CCIP-D-02 Tool comparison*, forms part of the COTS Control Innovation Program (CCIP) Detection Subprogram (**Figure 1**). Within this program, Project CCIP-D-02 was designed to characterise the performance and attributes of different monitoring tools and determine how their outputs can be interpreted and integrated within the COTS Control Program. These results are directly incorporated in the *CCIP-D-01 COTS monitoring design* project (Lawrence et al. 2025), ensuring that the emerging COTS and coral monitoring strategy is informed by a rigorous comparison of available tools and their associated measurement uncertainties.

The calibration analyses conducted here also benefit from coordinated research across the broader CCIP program, increasing the ability to incorporate multiple data sources measured with different tools into the decision-making process and thereby reducing uncertainty in management decisions. This calibration project benefited from coordinated research across the Program. The eDNA vs SALAD method comparison (beyond the dedicated field trip data collected during this project) relied on data collected and input from the *CCIP-D-03 Operationalising eDNA monitoring* (Uthicke et al. 2025) and *CCIP-P-04 Pre-outbreak monitoring* (Pratchett et al. 2025) projects. The ReefScan tool, used throughout the fieldwork, was being developed under *CCIP-D-04 The COTS Surveillance System* (Bainbridge et al. 2025). The manta tow vs cull dive method comparison (beyond the dedicated field trip data collected during this project) was performed by the *CCIP-R-02 Empirical Decision Support* (Fletcher et al. 2026) project team and we refer to the results in that report to assist in the inference around these monitoring tools.

Specifically, the aims of project *CCIP-D-02* were to:

1. Develop robust statistical calibration methods for comparing data from different monitoring tools based on a side-by-side comparison study.
2. Compare the calibration study results to previously collected data.
3. Provide a qualitative comparison of the available COTS and coral monitoring tools.

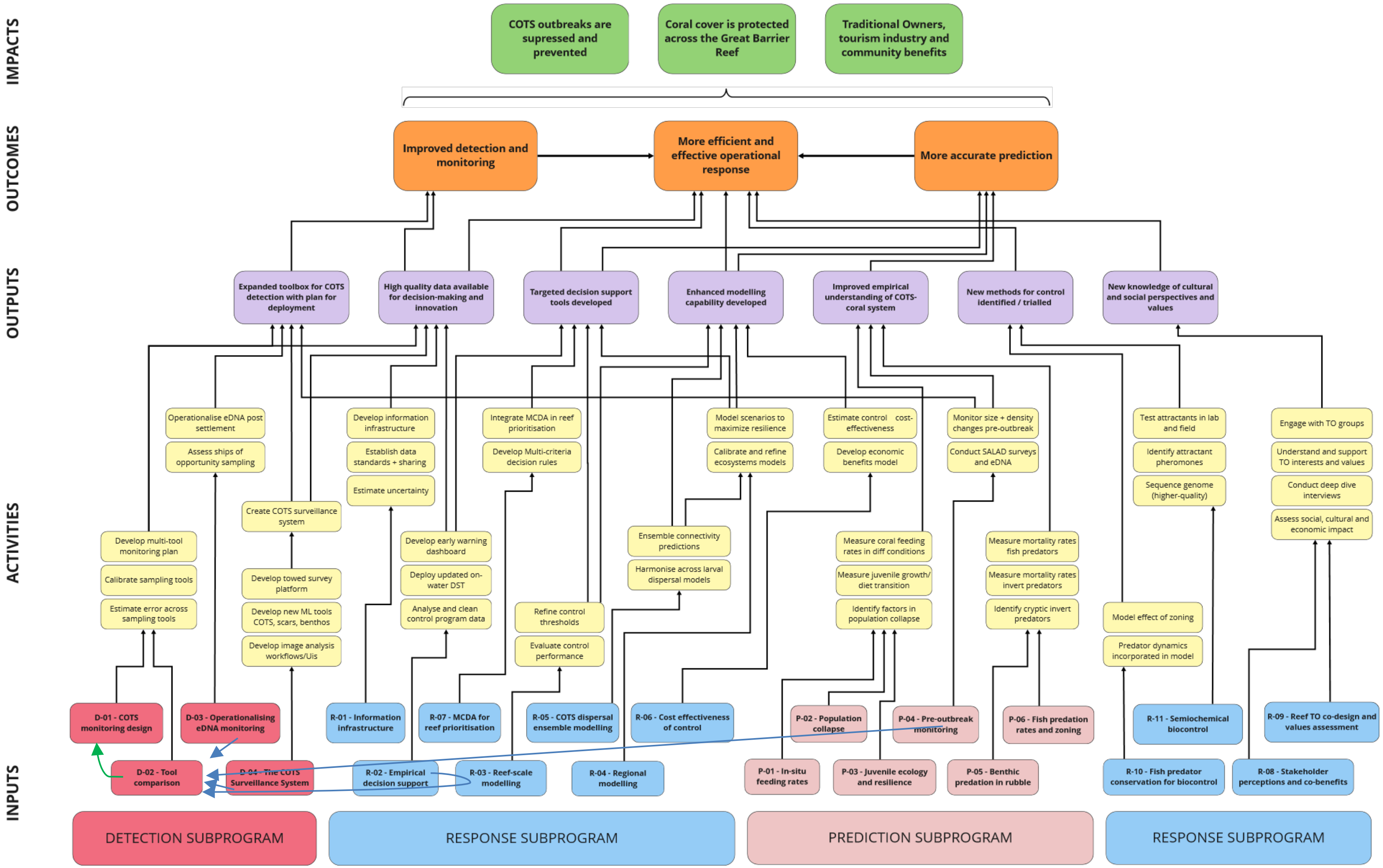

Figure 1. CCIP Program logic. *CCIP-D-02* is an integral part of the Detection Subprogram.

2. METHODS

2.1 Monitoring tools

Five tools were considered as candidates for monitoring COTS and/or coral cover in this project. These are grouped below into established tools (those already in operational use in the COTS Control Program) and novel tools currently under development or evaluation. Brief descriptions of each tool are provided. Full technical details for the emerging methods are given in the relevant CCIP project reports.

2.1.1 Manta tow

Manta tow is a survey method that is widely used for rapid broadscale assessment of coral reefs (Miller et al. 2018) and is the standard surveillance technique used in the COTS Control Program (Fletcher et al. 2020; Matthews et al. 2024). Manta tow surveys involve towing a snorkel diver (observer) at a constant speed behind a boat. The observer holds onto a 'manta board' attached to a suitable vessel by a length of rope. The observer makes a visual assessment of specific variables during each manta tow (two minutes duration) and records these data on a data sheet attached to the manta board at the conclusion of each tow. Each two-minute tow covers approximately 200 m, with a GPS track recorded for each tow to allow the distance covered to be calculated. The effective belt width surveyed is assumed to be approximately 10 m (5 m either side of the tow path), though this varies with sea conditions such as underwater visibility and sea state. The live hard coral cover, soft coral cover and recently dead coral cover are recorded using categories (0%, 1–5%, 6–10%, 11–20%, 21–30%, 31–40%, 41–50%, 51–62%, 63–75%, 76–87%, 88–90%). The total number of COTS observed are counted and COTS scars are recorded as: ABSENT (0 COTS scars observed), PRESENT (1–10 COTS scars observed) and COMMON (more than 10 scars observed).

2.1.2 Culling surveys

Culling surveys are the current standard technique used in the COTS Control Program to estimate COTS density and size distributions at the site scale (Fletcher et al. 2020). Although their primary purpose is culling, the data generated through that process is informative for monitoring. Control dives are performed by dedicated vessels crewed by specially trained and experienced snorkel/SCUBA divers. Divers search defined cull sites, often referred to as cull zones (approximately 10 hectares), and lethally inject all sighted COTS. Cull divers record information on the number and size of starfish culled and the duration spent searching, which is used to calculate a catch-per-unit-effort (CPUE), where effort is measured in time (minutes dived). No coral data is collected during culling surveys.

2.1.3 Scooter-assisted large area diver-based (SALAD) surveys

During each SALAD survey, divers traverse a section of reef looking for COTS and feeding scars within a nominal 5 m wide belt. Divers work in pairs, with each diver covering their own 5 m wide belt (one swimming at a shallower depth than the other), giving a combined effective belt width of approximately 10 m. Both divers tow a GPS so the transect length can be calculated. The divers follow a search protocol: search for scars/COTS and if a scar is seen, carefully inspect to ascertain whether it is caused by recent feeding activity of COTS, if so, then attempt to find the relevant COTS within the area surrounding the most recent feeding scar. If a COTS is found nearby, then the event is recorded as a COTS sighting (not a scar). Where no COTS is located near a scar, the scar is recorded as a distinct feeding event. Importantly, multiple adjacent scars that share a common feeding trajectory or show overlapping edge patterns are assessed by divers as belonging to a single COTS and recorded as one distinct set of scars, equivalent to one inferred COTS. Isolated scars separated in space with no evidence of a shared source are each recorded as a separate distinct set. The total count of COTS sightings plus distinct sets of scars therefore represents the inferred total number of individual COTS present, including those that evaded direct detection (Chandler et al. 2023; Pratchett et al. 2025). The divers also record a range of information about each COTS and scar sighted, including the size and exposure (the proportion of the body visible above the substrate) of each starfish sighted. The approximate location of each COTS and scar can also be ascertained using the towed GPS.

Information on coral cover and habitat structure is also routinely collected during each SALAD survey (Pratchett et al. 2025). Two replicate 50 m point intercept transects are surveyed within the area encompassed by each SALAD survey (one replicate per end; two replicates in total), generally at the start and end of each survey, recording the specific organisms or type of substrate underlying each of 100 uniformly spaced points (50 cm apart) along each transect, following Pratchett et al. (2009). Corals are mostly identified to genus (using contemporary, molecular-based classifications for scleractinian corals), and the underlying substratum is categorised as either sponge, sand/ rubble or carbonate pavement.

2.1.4 COTS Surveillance System monitoring (ReefScan)

The COTS Surveillance System is an integrated technology platform comprising an underwater imaging unit (referred to here as ReefScan), machine learning (ML) algorithms for automated image analysis, and supporting data workflows (Bainbridge and Coleman 2024; Bainbridge et al. 2025). The ReefScan platform collects continuous underwater imagery which is subsequently processed by ML models to identify and quantify COTS and coral cover. The platform can be operated continuously, but the data collected can subsequently be subset to produce the equivalent of shorter transects. The system was under development as part of project *CCIP-D-04* (Bainbridge et al. 2025) during this calibration project, and the deployments in this project were some of the first the platform had undertaken.

There were two related image-capture platforms used during this project: ReefScan-Transom and ReefScan-Deep. ReefScan-Transom is mounted on the transom of the survey tender and captures imagery at a fixed, shallow depth (typically up to 10 m). ReefScan-Deep is a towed vehicle connected to the tender by a tether, allowing operators to control its depth down to approximately 50 m. Because ReefScan-Deep maintains a fixed altitude above the substrate rather than a fixed depth, it can follow the reef profile more consistently in deeper or more topographically complex areas. Both platforms use the same camera design. ReefScan-Deep is expected to produce more geometrically consistent imagery than ReefScan-Transom at sites where the reef extends below the transom system's effective depth range, which should improve the reliability of subsequent ML-based estimates.

2.1.5 Environmental DNA samples

Environmental DNA (eDNA), defined as genetic material obtained directly from environmental samples without any obvious signs of biological source material, involves taking water samples and analysing them via digital droplet PCR (Uthicke et al. 2022). Multiple water samples (typically 12) are taken at each cull site, collected from mid-water depth at locations distributed across the site to capture spatial variation in eDNA signal and each sample is divided into duplicate observations that are measured for the presence of COTS eDNA.

The primary COTS metric used in this report is the proportion of samples at a site that detected COTS. This metric was selected because it is the most robust to the variability inherent in field-collected water samples. Unlike raw copy number concentrations which are sensitive to sample volume, filtration efficiency and inhibition, the proportion positive is a stable binary summary that performs well across the range of COTS densities encountered in this study. Other metrics are possible, including average PCR copy number concentration and the probability of occupancy and their relative merits and limitations are discussed in section 4.3.4.

Prior applications of eDNA for COTS monitoring on the GBR have typically analysed samples at the reef level, rather than at the finer cull site scale, in part because eDNA signal in the water column may integrate over larger areas than a single cull site and spatial resolution within a reef has not always been a primary objective (Uthicke et al. 2022). In this report, however, eDNA data are analysed at the cull site scale. This is necessary to allow direct comparison with the other monitoring tools. The eDNA method is currently being deployed and further refined in project *CCIP-D-03 eDNA monitoring* (Uthicke et al. 2025), and more technical details are given in the report for that project. No coral data is collected during eDNA sampling.

2.2 Field work

2.2.1 Primary side-by-side experiment

To collect data that was fit for purpose for calibration, a side-by-side experiment was planned departing Townsville 24th March 2023 and returning Townsville 3rd April 2023. The field team visited seven mid-shelf reefs: Davies, Lynchs, Banfield North, Shrimp, Prawn, Darley and Faith (**Figure 2**). The weather conditions were excellent, allowing the best possible use of the survey window.

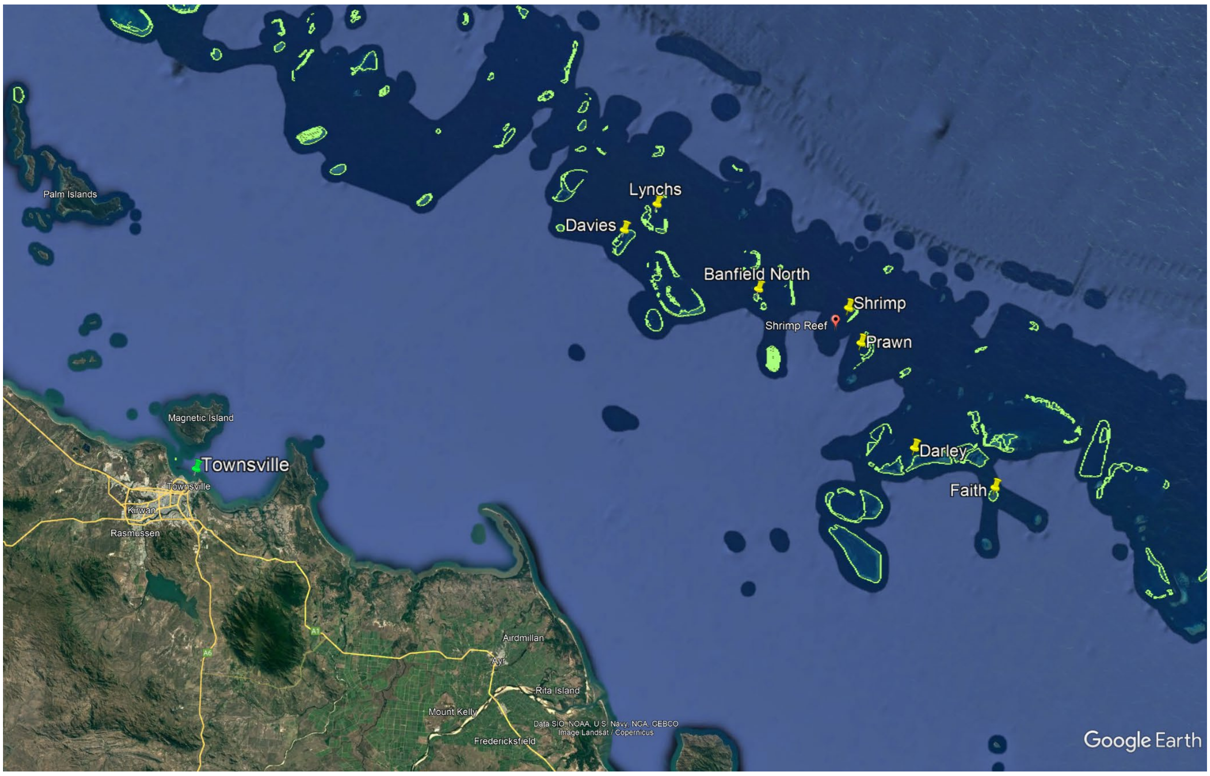

Figure 2. Map of the reefs surveyed on the March to April 2023 field trip.

The experiment was carried out on two main vessels (Queensland Parks and Wildlife Service's (QPWS) *Reef Ranger* and Pacific Marine Group's (PMG) *Odyssey*), and their associated tenders. The Reef Ranger is a 24 m purpose-built vessel with the ability to reach speeds up to 25 knots. The vessel was crewed by a four person QPWS team and seven members of the *CCIP-D-02* project were accommodated for the duration of the trip. The *CCIP-D-02* team performed the ReefScan transects, SALAD surveys and eDNA sampling. The Odyssey is a 24 m vessel with the ability to reach speeds up to 13 knots and has two auxiliary tenders. The vessel was crewed by the PMG team, who are contracted to control COTS as part of the COTS Control Program, and two Reef Authority staff. All manta tows and cull dives were conducted by COTS Control Program divers from PMG, replicating the usual in-field practices. Whilst the primary focus for the Odyssey was this experiment, the PMG team continued some COTS Control Program operations where and when possible. Notably, they were able to perform all research tasks asked of them using their own equipment and expertise.

Determining the level at which to replicate measurements (e.g., reef, site) was a challenging aspect of the experimental design and the most critical to get right. We carefully considered the amount of replication needed to give us adequate power (reduce standard error) to answer the questions at hand. However, replication comes at a cost of generalisation i.e., more replicate sites within each reef location would mean sampling less reefs in total given time constraints, yet each new reef where methods are deployed would allow us to generalise further as it would capture more environmental variability. Generalisation is important so that the results hold in different locations and potentially conditions (e.g. depth, visibility, reef complexity). While some of the monitoring methods are better suited to the whole of reef level (e.g., eDNA), the time available meant that we would not be able to fully sample many reefs using all methods. Therefore, we designed the survey to compare the methods at the cull site scale as we were able to deploy all methods side by side at this scale (**Table 1**). Cull sites are GPS-defined areas of approximately 10 hectares positioned along the outer reef slope, where the culling operations are focused. Within the IPM framework, cull sites are the operational unit at which CPUE is recorded and evaluated against ecological thresholds, making them the natural scale at which to compare monitoring tools whose outputs must ultimately inform those same management decisions.

Table 1. Summary of the area effectively sampled by each monitoring tool and how they relate to a cull site.

Monitoring tool	**Effective area sampled**	**Cull site coverage**
Manta tow	~200 x 10 m (0.2 hectares)	Three or more required to cover the length of a cull site depending on the tow path, but much narrower width than cull site.
Cull dive	~500 m x 200 m (10 hectares)	Diving continues until the whole site is covered.
SALAD	~1 km x 10 m (1 hectare)	Typically crosses two cull sites but much narrower width.
ReefScan Transom & Deep	~200 m x ~8 m (0.16 hectares) (assumes platform scans reef at a distance of 5 m from the bottom, the accuracy of this assumption will vary depending on depth)	Continuous transects were subset to be the approximate length of manta tow but slightly narrower than manta tow and much narrower than cull site.
eDNA	Unknown	12 samples collected per cull site.

Sites were selected across the region using the information available to COTS managers to select sites expected to span a range of COTS densities (as much as the available information would permit). This approach aimed to ensure that the methods were calibrated across a wide range of COTS densities. The design plan was to deploy every method at every cull site (complete block design). There are many types of experimental design but the complexity of field logistics, method comparisons and varying environmental covariates means a fully balanced design i.e., every method at every location, was best suited to the needs of the project. The main advantage of balanced designs is that the factors are independent and so the variance can be decomposed into the individual method contributions without any confounding between method and location.

The standard order of operation at each site consisted of:

1. Manta Tow
2. eDNA
3. ReefScan-Transom
4. SALAD
5. ReefScan-Deep
6. COTS culling

Australian Government Reef Trust Great Barrier Reef Foundation Australian Government Australian Institute of Marine Science CSIRO James Cook University Australia The University of Queensland Australia

This order was chosen for operational reasons. It allowed: 1) culling to proceed last (given that this method impacts COTS numbers and eDNA readings), 2) efficient deployment, 3) increased personal safety, and 4) decreased risk of mistakes i.e., all staff could anticipate what was to happen next. The second point is important as it meant less down-time at each site. We acknowledge that this fixed ordering is not random (a best practice), but we consider the benefits outweigh the negatives. Further, deployment was almost always completed in similar weather conditions (light, wind, tide). The exception was the very last site which was partially measured late on the penultimate afternoon and partially the following morning.

At the start of each sampling day the crew of both vessels met and discussed the sampling plan. Key points were:

- Location of samples
- Sampling plan at each site (path)
- Conditions
- Safety

The project team defined a goal sampling path at each cull site. This maximised the potential of the different methods to be measuring the same environment (overlapping even) at each site. However, the methods all have a different spatial coverage and various challenges in deploying them and so it was never envisaged that the overlap would be perfect. Two neighbouring sites at Darley Reef (**Figure 3**) highlight the range of possible paths. Site Z91 has a transect that all the methods clearly followed. In contrast, Site 98 was more complex and the transect was harder to follow – in this case the manta tow and the ReefScan-Deep transects diverged slightly.

The daily routine was altered for the sites at Lynchs Reef, Banfield Reef, and Faith Reef. This was done to target the higher COTS densities that had been lacking at the other sites. The altered approach was to perform the manta tow surveillance over a wide area *before choosing the sampling sites*. With this approach we had extra information about where on the reef the COTS (if any) were likely to be. This change should not affect calibration using these data (the sample is already known to be preferentially sampled).

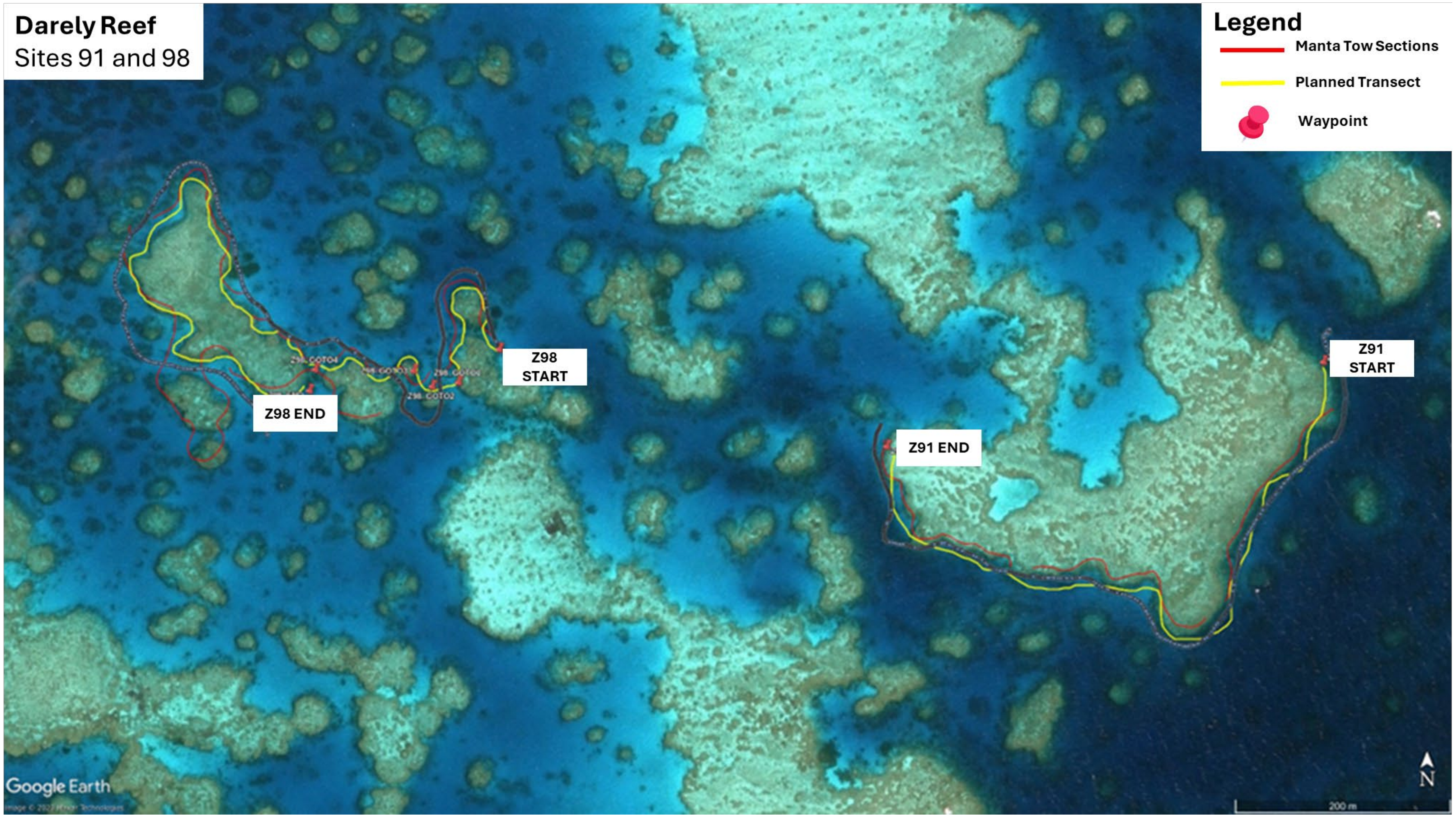

Figure 3. Example of planned transects (yellow lines), with waypoints (red pins). Also shown are the path of the manta tows (red lines) and the ReefScan-Deep photo locations (dark squares). Note that the paths differ in the western site (cull site z98) where the bommie near the end of the transect was circumnavigated by the manta tow but not the Reefscan.

2.2.2 Secondary side-by-side experiment

To provide some complementary data on a subset of the measurement methods, a second experiment was undertaken in January 2024 in the southern part of the Reef, departing from Gladstone. The goal of this experiment was primarily to capture some higher COTS densities using the ReefScan technology as despite planning to measure a range of densities, only low-medium densities were observed in the primary experiment, limiting the ability to calibrate this method.

The measurement tools utilised on this trip were manta tow, ReefScan-Transom, ReefScan-Deep and cull dives. However, the ReefScan-Deep was damaged on the first day of use before meaningful data could be collected. A pending cyclone also impacted on the capacity of the trip to collect cull data. Only three reefs were visited (U/N (21-057), U/N (21-465), U/N (21-551)).

The protocol for the secondary survey was slightly different to that of the primary survey, largely due to the focus on methods with larger spatial coverage (manta tow and ReefScan). In this experiment, a much larger section of the reef was measured with manta tow and ReefScan-transom. The subsequent data were then matched, by visual computer-based inspection, to the nearest cull sites and calibrated at that scale (as was done in the primary experiment). Sometimes a site was measured only once by the manta tow and ReefScan, and other times up to four times.

In the secondary experiment, the focus of the calibration, between manta tow and ReefScan, was in-water (both tools deployed simultaneously from a single tender). This means that variation in the planning aspects to the survey methods were minimised, which was achieved by simultaneous deployment of manta tow and ReefScan. This approach maximises, as far as realistically possible, the common ground measured by both methods. However, this co-deployment approach does not replicate the variation that arises from the tools' independent deployment constraints. In standard operations, the manta tow observer is free to steer toward sightings and adjust their viewing angle, while the ReefScan-Transom is towed at a fixed depth determined by the vessel's transom height regardless of reef topography. When both are deployed simultaneously from a single tender, both are constrained to the same vessel path and speed, which removes these independent sources of variation from the calibration.

2.3 Statistical analysis of field data

The primary objective of the statistical analysis was to establish a calibration framework, essentially a predictive model, between each measurement tool and every other tool used in the study. This entailed constructing multiple regression models to elucidate how observations from one tool correspond to those from others at the site level. For instance, the data collected by cull divers was regressed against measurements obtained from manta tow COTS surveys, SALAD, and eDNA. The specific form of each regression model depended on the nature of the outcome variable and the characteristics of the sampling tool employed. In choosing the response and predictor variables we always chose the count and effort metrics that were directly recorded during the survey rather than any derivatives to minimise error e.g., time spent diving (recorded) over search area (derived; **Table 2**). SALAD surveys are the one exception, with data analysed both as count per unit time (per minute) and count per unit area (per hectare). SALAD area estimates are the most directly grounded of any method used here, for two seasons. First, transect length is calculated from GPS tracks recorded throughout each survey (Chandler et al. 2023; Pratchett et al. 2025) rather than assumed. Second, because divers operate at depth in close proximity to the substrate, the 5 m belt width per diver is more reliably estimated than the nominal 10 m belt width of manta tow surveys, where the observer views the reef obliquely at the surface at angles that vary with depth and visibility (Miller et al. 2018). We acknowledge residual uncertainty in the belt width assumption even for SALAD. Cull dive data were not converted to density as although each cull site has a defined nominal area (~10 hectares), the effective area searched by divers within that boundary is not directly recorded and varies with team size, bottom time and COTS distribution. CPUE per minute is also already the operationally relevant metric relative to ecological thresholds (Fletcher et al. 2020).

Table 2. Variables used in the calibration analysis for each monitoring tool, including the raw count metric, effort measure, and the rate used as the analytical variable in the Generalised Linear Mixed Models (GLMMs). All variables are aggregated to cull site level prior to analysis.

Tool	Raw count metric	Effort metric	Analytical rate (used in GLMM)
Manta tow Manta tow (coral cover)	Proportion of tows with COTS scars+ Ordinal cover category per tow	Number of tows	Proportion of tows with scars Mean of tow midpoints per cull site (%)
Cull dive	COTS culled (count)	Total dive time (minutes)	COTS culled per minute (CPUE)
SALAD SALAD coral transect	COTS + scars counted Points hitting coral (of 100 per transect)	Survey time (minutes); GPS-derived area (ha) Fixed design: 2 × 50 m transects, 100 points each	Count per minute and count per hectare Mean proportional coral cover (%)
ReefScan-Transom and ReefScan-Deep (coral only)	Coral cover per image frame	Transect length (m); assumed width (~8 m)	Mean proportional coral cover (%)
eDNA	Number of positive samples	Total samples collected (typically 12)	Proportion of samples positive (unitless)

+ For manta tow, COTS counts were near-zero across all primary experiment sites; the two tows that recorded COTS also recorded scars. Proportion of tows with COTS scars was therefore used as the sole manta tow-based COTS metric, as it was the only manta tow variable that carried a usable signal across the range of sites.

To illustrate, consider the formulation of a generalised linear mixed model (GLMM) to explain the cull data using SALAD data. The cull data consists of the count of COTS culled at each site and the total time spent at each site, aggregated from individual diver recordings. Similarly, SALAD data were aggregated at the site level. The GLMM included a fixed effect for the log of SALAD count per unit effort (COTS plus scars), a random effect for reef variability, and an offset of log cull dive time. A log link is used, and the sampling variation is assumed to follow a negative binomial distribution. The relationship between the cull data and the SALAD data is log-log, which is curvilinear and quite flexible. The reef random effect allows for reef-to-reef variability and also for possible within-reef correlation. The offset standardised the model for cull catch-per-unit-effort (CPUE).

Bayesian methods were employed for inference, necessitating the specification of priors for each parameter. Vague Gaussian priors were used for fixed effects, a vague log-normal prior for random effect variance, and a vague gamma prior for negative binomial dispersion. The posterior distribution was approximated using a Gibbs sampler in the JAGS software (Plummer et al. 2016). The posterior samples, along with functions predicting all sampling methods from each other, are all available through the R package Rosetta_COTS (Foster et al. 2024). RosettaCOTS provides calibration estimation tools to facilitate conversion of COTS and coral estimates from one monitoring tool to another, together with associated uncertainty quantification. The package is freely available at https://github.com/Scott-Foster/Rosetta_COTS. Similar regression approaches were applied to data from other sampling methods, with differences arising from varying outcome types, link functions, and sampling strategies (negative binomial for counts, binomial for success/failure data, and beta for proportion data).

2.4 Statistical analysis of other relevant data

While the field trips provided the primary data source for this project, there was existing data available where monitoring methods have been deployed concurrently as part of routine COTS Control Program operations or other research projects. The two matching data sets we considered in this project were:

- eDNA vs SALAD from 2019 to 2023, and
- manta tow vs cull from 2018 to 2023.

These data were not collected with the intention to control the spatial and temporal proximity of sampling as closely as our project and so the discrepancies between the data collection in space and time is almost always greater than in our controlled experiments.

The eDNA vs SALAD data were matched at the site level by the teams that undertook the field work. Data were considered a 'match' if they were sampled close enough in space and time to represent the same site at a point in time (usually within days and hundreds of metres). The analysis of these data consisted of two separate analyses at different spatial scales: site and reef. The reef level analysis was performed to side-step any potential issue of spatial and temporal mismatches, and also due to recognition that eDNA may not spatially resolve intra-reef variation. This work was completed with the *CCIP-D-03* project team and so the methods and results are described in detail in that report (Uthicke et al. 2025).

The site-level analysis for SALAD and eDNA data follows that described for the data from the primary field experiment. That is, a GLMM was fitted that describes the variation in SALAD data in terms of the eDNA proportion positives, and vice versa. See Section 2.3.

The manta tow vs cull data comparison was performed as part of *CCIP-R-02* and we refer to that project report for the detailed description of the data and statistical methods (*CCIP-R-02*, Fletcher et al. 2026). Manta tow and cull data collected as part of the IPM work between November 2018 and December 2023 was analysed.

Due to the excessive zeros in the cull density (~23% of cull density was zero), a zero-inflated model was found to be the best to model the relationship between the cull density and information collected from manta tow. If y_{rs} represents the cull density of site s at reef r,

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$$y_{rs} \sim \begin{cases} 0 & with\ probability\ (1-\phi_{rs}) \\ Gamma(\lambda_{rs}) & with\ probability\ \phi_{rs} \end{cases}$$

where ϕ_{rs} is the probability that y_{rs} belonging to negative binomial component of the model, and λ_{rs} is the expected value of Gamma distribution. The probability of belonging to the zero component of the model was modelled using Binomial distribution. The expected value of λ_{rs} and ϕ_{rs} were modelled using the combinations of proportion of tows without a scar, proportion of tows with 1–10 scars, proportion of tows with 10+ scars and tow density. To account for the random variation among reefs, reef was included as the random effect in both intercept and coefficient of tow-density.

2.5 Qualitative tool comparison

We also undertook a qualitative analysis of the existing and emerging COTS and coral monitoring tools. This was to help determine the ability of each tool to address the COTS Control Program monitoring objectives defined in project *CCIP-D-01 COTS monitoring design* (Lawrence et al. 2025*)*. For each tool we looked at and compared the attributes related to:

- Spatial scale
- Monitoring metrics
- Primary utility
- Relative cost.

2.6 Stakeholder engagement

The success of the field trips relied heavily on extensive stakeholder engagement. The primary field trip included participants from CSIRO, the Australian Institute of Marine Science (AIMS), James Cook University (JCU), the Reef Authority, Queensland Parks and Wildlife Service (QPWS) Reef Joint Field Management Program (RJFMP), Pacific Marine Group (PMG) and the Great Barrier Reef Foundation (GBRF) (**Figure 4**). There was a great deal of co-ordination and collaboration required to ensure all participants understood the purpose of the trip, their role and the need to work together towards the intended data collection exercise. The COTS Control Program team were critical in facilitating this work, dedicating one of the RJFMP trips to this project and organising one of the PMG COTS Control vessels to work alongside the QPWS vessel. A factsheet about the field work was shared (via AIMS), with relevant Traditional Owner contacts in the area where the work was carried out (**Appendix A**).

The planning of the second field trip involved engagement with Blue Planet Marine (BPM) who were chartered to complete the culling and manta tow dives and accommodate the AIMS team undertaking the ReefScan monitoring. We also worked closely with the COTS Control Program team at the Reef Authority to ensure the field trip was appropriately planned and maximised the utility of information collected both for our project and the COTS Control Program.

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Figure 4. QPWS, BPM and project team field crew aboard the QPWS vessel Reef Ranger during the primary field trip.

3. RESULTS

3.1 Summary of data collected in the field

During the primary experiment, 16 cull sites were visited and most methods were deployed at every site (**Table 3**). The number of COTS counted by the cull divers ranged between 0 (two sites) and 116 per site. On the other hand, the aggregated manta tow data (3–6 tows per cull site), recorded single COTS at two cull sites and zero at all others. Potential scars were recorded on all but three manta tow transects and so in the analyses that follow we have analysed proportion of tows at each cull site that recorded a COTS scar as the only available manta tow-based indication of COTS density. The recorded density using SALAD data was between 1 and 22 COTS per cull site (and between 2 and 44 based on inferred densities, which include distinct sets of scars). The eDNA data reported a range of concentrations reflecting possible variation in COTS densities. ReefScan only recorded a single COTS on the whole trip and so could not be calibrated in the statistical analysis. At the time of the field work, the machine learning methods deployed on the ReefScan platforms were not yet capable of identifying and counting COTS scars, therefore we were not able to include scars in the statistical analysis. However, ReefScan data was still used in the coral calibration.

Table 3. Summary of deployment at each Site across methods for the **primary** field trip.

Reef	Cull Site	Reef ID	Cull	Manta	SALAD	eDNA	ReefScan Deep	ReefScan Transom
Banfield North	BAN_18-105a_01	18-105a	☑	☑	☑	☑	☑	☑
Banfield North	BAN_18-105a_07	18-105a	☑	☑	☑	☑	☑	☑
Darley Reef	DAR_19-043_58	19-043	☑	☑	X	☑	☑	☑
Darley Reef	DAR_19-043_62	19-043	☑	☑	☑	☑	☑	☑
Darley Reef	DAR_19-043_91	19-043	☑	☑	☑	☑	☑	☑
Darley Reef	DAR_19-043_98	19-043	☑	☑	☑	☑	☑	☑
Davies Reef	DAV_18-096_18	18-096	☑	☑	☑	☑	☑	☑
Davies Reef	DAV_18-096_28	18-096	☑	☑	☑	☑	X	☑

Reef	Cull Site	Reef ID	Cull	Manta	SALAD	eDNA	ReefScan Deep	ReefScan Transom
Faith Reef	FAI_19-044_13	19-044	☑	☑	☑	☑	☑	☑
Lynchs Reef	LYN_18-091_15	18-091	X	☑	☑	☑	☑	☑
Lynchs Reef	LYN_18-091_37	18-091	☑	☑	☑	☑	☑	☑
Lynchs Reef	LYN_18-091_39	18-091	X	☑	☑	☑	☑	☑
Lynchs Reef	LYN_18-091_41	18-091	X	☑	☑	☑	☑	☑
Prawn Reef	PRA_19-024_4	19-024	☑	☑	☑	☑	☑	☑
Prawn Reef	PRA_19-024_11	19-024	☑	☑	☑	☑	☑	☑
Shrimp Reef	SHR_18-118_19	18-118	☑	☑	☑	☑	☑	☑

During the secondary experiment, 44 sites were surveyed with both manta tow and ReefScan-Transom collecting data along the same path from the same tender vessel. The COTS calibration from this experiment is not presented for three reasons. First, only five sites were culled, which is insufficient to reliably fit the hierarchical GLMM structure required (three reefs, five sites is too few observations to estimate reef-level variance). Second, the ReefScan-Deep platform suffered equipment failure early in the trip, limiting deployments; the small number of COTS detected across those deployments could not be validated as confirmed COTS sightings and were therefore excluded. Third, at the time of the secondary experiment, ReefScan-Transom imagery was being used to train the machine learning models rather than as an operational survey tool. For these reasons, only the coral cover calibration is presented for the secondary experiment. Coral cover estimation had been validated on both platforms by this stage, and all 44 manta tow and ReefScan-Transom sites are included in that analysis.

3.2 Tool calibration for COTS and scar count data

The results displayed in **Figure 5** show the relationship between the culling rate of COTS per minute on cull diver surveys and three different detection methods: manta tow, SALAD (both density and count), and eDNA. The black solid line is the estimated relationship, the outer dashed lines indicate the prediction interval, and the inner dashed lines are the confidence

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interval. The confidence interval indicates the uncertainty around the estimated mean relationship, while the prediction interval accounts for the variability of individual observations around the mean. It provides a range of values within which a new individual observation from the same process is likely to fall, with 95% confidence.

Figure 5A shows the SALAD density (COTS + scars counted per hectare) as a function of the culled COTS per minute and **Figure 5B**, the SALAD rate (COTS + scars counted per minute) as a function of the culled COTS per minute. There is a positive relationship between the culling rate and the SALAD detection rate. The estimated relationship shows the encounter rate is typically higher on SALAD, where COTS and scars are both included in the detection rate (**Figure 5B**).

The proportion of manta tow transects with COTS scars (see Section 2.3 for metric rationale) as a function of COTS culled per minute is given in **Figure 5C**. There is a positive relationship between the two measures, but the prediction interval spans almost the full range of possible values (0–1) across the observed range of cull rates. This wide uncertainty is consistent with the known low and variable detectability of COTS on manta tow surveys (Fernandes et al. 1990; Miller et al. 2018) and reflects the fact that scar presence/absence is a coarse, categorical signal that saturates quickly at moderate COTS densities. The manta tow is therefore of limited utility for fine-scale calibration against cull CPUE, though it retains value as a broad-scale trigger for further investigation.

Figure 5D shows the proportion of eDNA samples detecting COTS as a function of the culled COTS per minute. There is a clear positive trend where higher culling rates correspond to higher proportion of eDNA samples detecting COTS eDNA. Note, this analysis is at the site level, so it is promising to see the eDNA correlating to the number of COTS culled even at the site level (current eDNA methods are designed for the reef scale, and technically speaking there is no replication on the site scale with the current method). It is likely that if site scale analysis were required, sampling at several sub sites within site would improve this result. The relationship between eDNA concentration and culled COTS per minute can be found in **Appendix B**. It also shows a positive relationship but with a higher degree of uncertainty.

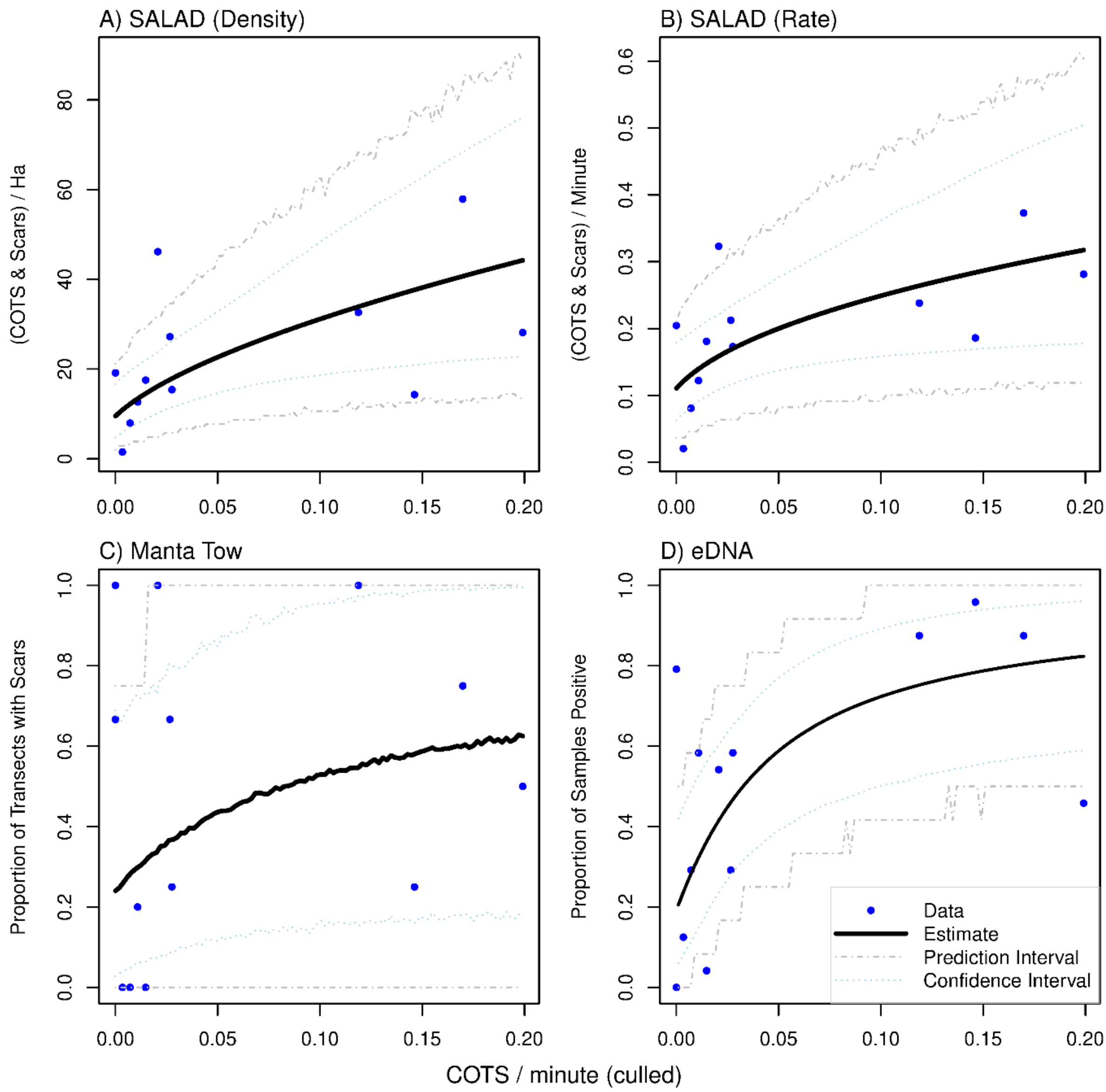

Figure 5. Calibration of COTS monitoring tools against cull diver CPUE (COTS culled per minute). **A)** SALAD surveys (COTS and scars per hectare), **B)** SALAD surveys (COTS and scars per minute), **C)** manta tow (proportion of tows with COTS scars per cull site), and **D)** eDNA (proportion of water samples positive for COTS).The black solid line is the estimated relationship, the grey dashed line is the prediction interval, and the blue dashed line is the confidence interval.

The full set of pairwise COTS calibration models, predicting each method from every other method, is presented in **Appendix B (Figures B1 to B5).** All pairwise relationships were positive, confirming that all tools respond in the same direction to variation in COTS abundance. However, the strength and precision of those relationships varied substantially among tool pairs, and this variation is itself an informative finding about the relative utility of each tool for cross-method translation.

The calibration models allow observations from any tool to be expressed as an equivalent cull diver CPUE (COTS culled per minute), which is the operationally relevant unit for evaluating ecological thresholds. **Table 4** summarises these predicted equivalences across the range of cull rates observed in this study (0–0.20 COTS per minute). At the lower ecological threshold (0.04 COTS per minute), SALAD surveys would be expected to record approximately 20.6 COTS and scars per hectare (prediction interval (PI): 6.6–42.4), while approximately 54% of eDNA water samples would be expected to test positive (PI: 17–92%). The manta tow prediction at this threshold, approximately 40% of tows with scars, carries a prediction interval spanning the full range from 0 to 100%, confirming that manta tow is unreliable as a tool for detecting whether cull CPUE has crossed this threshold at individual sites. At the upper threshold (0.08 COTS per minute), the pattern is similar: SALAD provides a reasonably precise estimate (~28 COTS and scars per hectare) while manta tow remains essentially uninformative at the site scale.

Table 4. Predicted COTS rates for each monitoring tool at selected cull diver CPUE values (COTS culled per minute), with 95% prediction intervals in parentheses. Green rows indicate the lower and upper ecological thresholds for COTS control intervention. Full predictions across the range 0–0.20 COTS per minute are given in the companion paper (Lawrence et al. 2026).

Cull rate (COTS per min)	**SALAD density (COTS & scars per ha)**	**SALAD rate (COTS & scars per min)**	**Manta tow (proportion of tows with scars)**	**eDNA (proportion of samples positive)**
0.00	9.5 (2.7, 22.3)	0.11 (0.02, 0.27)	0.24 (0.00, 1.00)	0.19 (0.00, 0.50)
0.02	16.0 (5.4, 34.6)	0.16 (0.05, 0.34)	0.34 (0.00, 1.00)	0.41 (0.08, 0.75)
0.04 (lower threshold)	20.6 (6.6, 42.4)	0.19 (0.06, 0.38)	0.40 (0.00, 1.00)	0.54 (0.17, 0.92)
0.06	24.5 (8.4, 53.1)	0.21 (0.06, 0.44)	0.46 (0.00, 1.00)	0.63 (0.25, 0.92)
0.08 (upper threshold)	28.0 (9.4, 63.0)	0.23 (0.07, 0.47)	0.50 (0.00, 1.00)	0.68 (0.33, 1.00)
0.10	31.1 (9.6, 71.1)	0.25 (0.07, 0.53)	0.52 (0.00, 1.00)	0.72 (0.33, 1.00)
0.20	44.3 (12.7, 111.9)	0.32 (0.09, 0.69)	0.62 (0.00, 1.00)	0.82 (0.4)

A notable feature of the SALAD results is that at zero cull CPUE, SALAD surveys still predict approximately 9.5 COTS and scars per hectare (PI: 2.7–22.3). This non-zero intercept reflects the fact that SALAD detects both visible COTS and distinct sets of feeding scars and suggests SALAD has higher sensitivity than cull dives at low densities. Conversely, the eDNA relationship shows a strongly increasing trend at low cull rates that begins to flatten at approximately 0.10 COTS per minute, consistent with eDNA approaching detection saturation at higher densities. The **Appendix B** figures also show that the reciprocal calibrations (predicting cull rate from other methods) follow similar patterns, confirming the bidirectionality of the calibration framework. All calibration models and predicted values can be reproduced using the RosettaCOTS R Package (Foster 2024; https://github.com/Scott-Foster/RosettaCOTS).

3.3 Tool calibration for coral cover data

Figure 6 shows the calibration relationships between manta tow coral cover (mean of tow midpoints per cull site) and the three other tools that collect coral data. All relationships are positive, confirming that the tools respond in the same direction to variation in coral cover and coral calibrations show tighter prediction intervals than COTS calibrations for most tool pairs. However, the precision of these relationships varies among tools and the implications for operational use are discussed in Section 4.3.

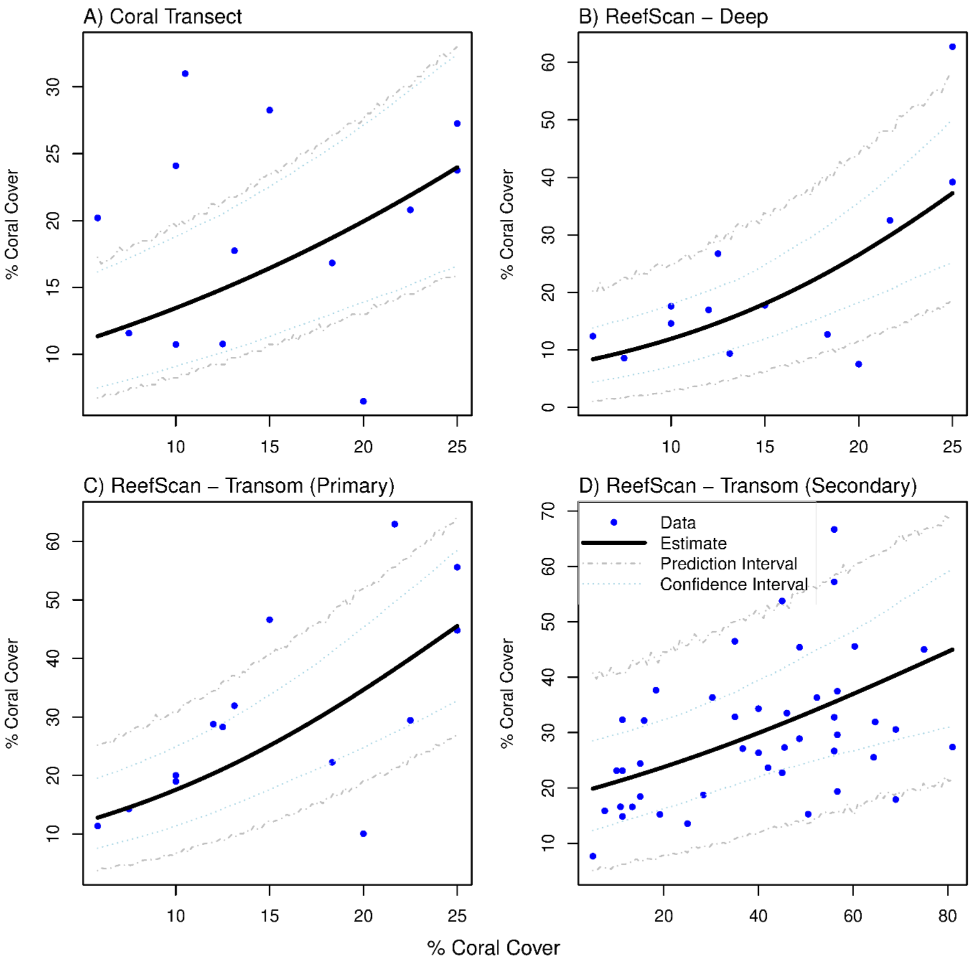

Figure 6. Coral predictions from manta tow. **A)** Coral transect from SALAD, **B)** ReefScan-Deep, **C)** ReefScan – Transom (from the primary experiment), and **D)** ReefScan – Transom (from the secondary experiment). The black solid line is the estimated relationship, the grey dashed line is the prediction interval, and the blue dashed line is the confidence interval.

The relationship between manta tow and SALAD 50 m point intercept coral transects shows a notably close agreement in mean estimates despite the two methods operating at different spatial scales with different measurement approaches (**Figure 6**). At 10% manta tow coral cover, SALAD transects are predicted to record approximately 13.5%, and at 20% manta cover the predicted SALAD value is approximately 19.9%, tracking manta tow estimates closely across the observed range. This convergence is encouraging given that the SALAD transects do not spatially overlap with manta tow transects and each represents a fundamentally different sampling footprint. Prediction intervals are nevertheless wide (7.6–21.4% at 10% manta cover; 12.0–29.8% at 20%), which is expected given the spatial mismatch and the coarse ordinal categories of manta tow coral recording. This site-level uncertainty does not undermine the overall agreement in means, but does limit confidence in translating a single site-level observation from one method to the other.

The manta tow vs ReefScan-Deep relationship is more precise (**Figure 6B**). At coral cover values up to approximately 15%, the two tools produce similar estimates; at 15% manta cover, ReefScan-Deep predicts approximately 18% (PI: 4.7–39.5%). At higher cover values ReefScan-Deep estimates diverge upward, predicting approximately 37% at 25% manta cover (PI: 15.5–61.2%;**Table 5**).

Table 5. Predicted coral cover (%) for each monitoring tool at selected manta tow coral cover values (mean of tow midpoints per cull site), with 95% prediction intervals in parentheses. Full results across all tool pairs are given in Appendix C.

Manta tow (%)	SALAD coral transect (%)	ReefScan-Deep (%)	ReefScan-Transom primary (%)
5	11.0 (5.9, 18.0)	7.8 (0.5, 23.4)	12.0 (2.4, 27.7)
10	13.5 (7.6, 21.4)	11.9 (2.0, 29.8)	17.6 (5.1, 34.5)
15	16.5 (9.5, 25.5)	18.0 (4.7, 39.5)	25.1 (9.7, 44.7)
20	19.9 (12.0, 29.8)	26.5 (9.3, 48.3)	34.6 (16.1, 56.1)
25	24.0 (14.5, 35.5)	37.3 (15.5, 61.2)	45.5 (23.3, 67.8)

ReefScan-Transom results are presented separately for the primary and secondary experiments (**Figure 7C & D**), as the two calibration relationships differ substantially. In the primary experiment, ReefScan-Transom estimates were approximately double manta tow values across the observed range: at 15% manta cover, ReefScan-Transom predicted approximately 25% (PI: 9.7–44.7%). In the secondary experiment the relationship was markedly different, with ReefScan-Transom producing lower estimates than manta tow across much of the observed range. Three features of the experimental design differ between the two trips and may contribute to this discrepancy: the range of coral cover encountered (0–25% in the primary experiment; 0–80% in the secondary), the deployment protocol (sequential in the primary, co-deployed from a single tender in the secondary), and potential variation in manta tow observer teams between trips (Miller et al. 2018). The interpretation of these differences is discussed in Section 4.4.

3.4 Results of eDNA vs SALAD modelling

Figure 7 presents the results for modelling the SALAD and eDNA data at the site scale. The plots show the relationship between SALAD and eDNA from using each measure as the outcome. Like the experimental data (Section 3.2), the relationships are positive but also exhibit more noise than under experimental conditions. This could be due to increased spatial and temporal displacement, or another unknown difference between experimental versus non-experimental conditions. As neither the eDNA nor SALAD tools are designed to measure COTS at the cull site scale, the very uncertain relationship is not surprising. However, it is still valuable to demonstrate the differences between these datasets and the controlled field experiments.

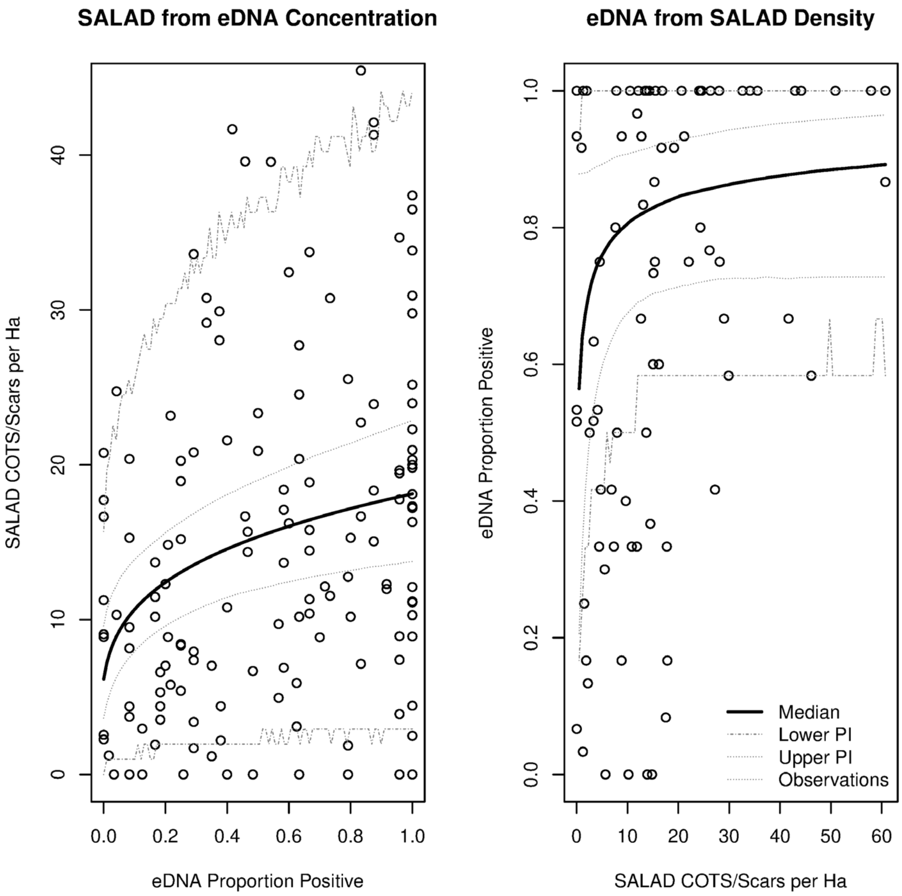

Figure 7. SALAD predictions from eDNA, and vice versa, using data collected through other research projects. The black solid line is the estimated mean relationship, the grey dashed-dotted line is the prediction interval, and the narrow-dotted line is the confidence interval.

Several reef level analyses of SALAD vs eDNA data were conducted as part of *CCIP-D-03 eDNA monitoring* (Uthicke et al. 2025) and we defer to that report for a deeper presentation of results. Here we provide the results of the most comparable model to the site level model applied to the data (**Figure 8**), where average eDNA proportion of samples was used to predict the average density of COTS and scars counted on SALAD surveys. The relationship was less uncertain (than the site level analysis) and has a steeper slope, perhaps indicating an increased potential of eDNA to distinguish between different COTS densities. eDNA might be better at reef level as the current protocol samples the most-mixed part of the water column (surface) rather than the more sedentary bottom water. It is the bottom water that the other methods sample and where the COTS live.

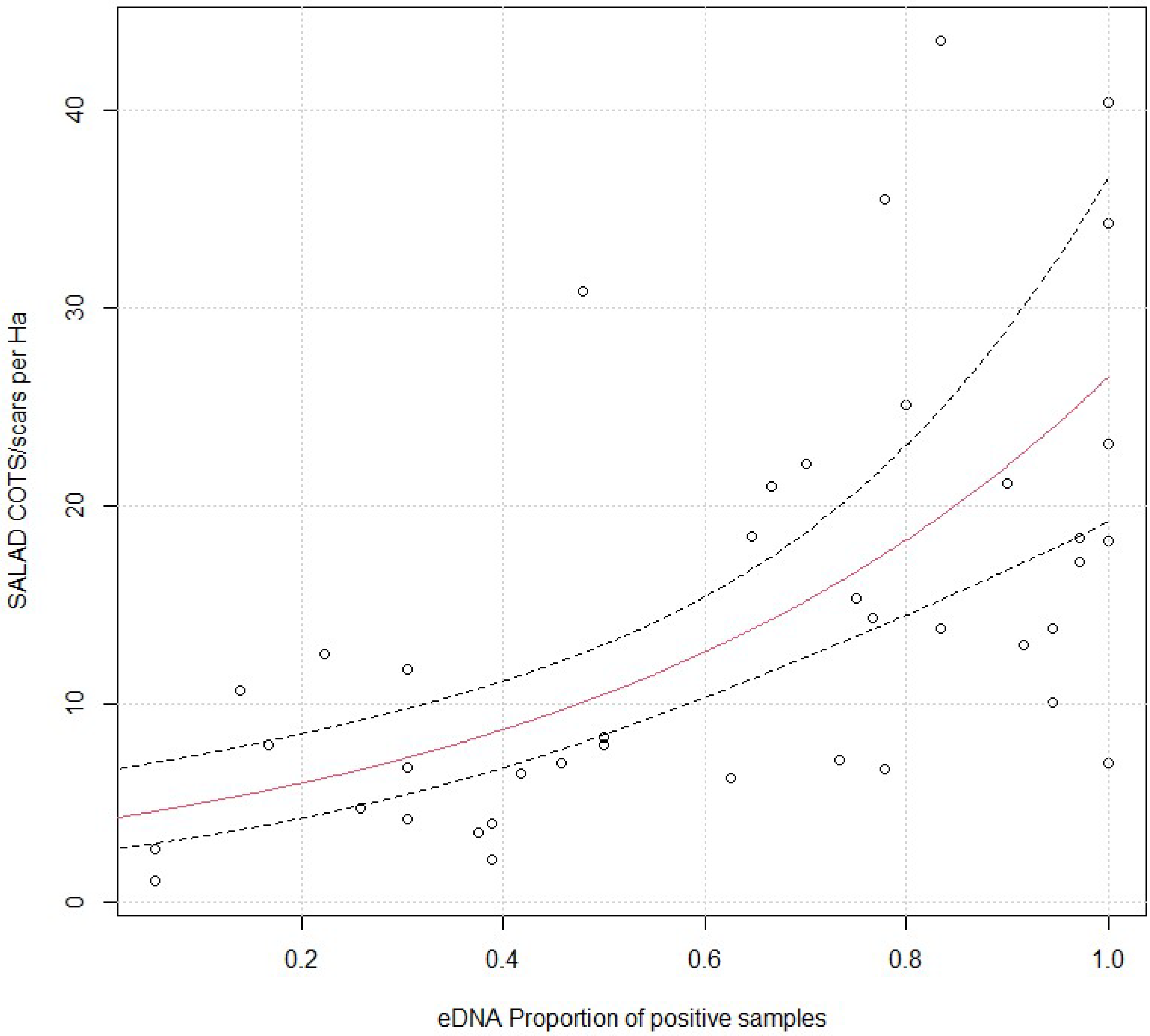

Figure 8. Estimated mean density of SALAD COTS/Scars per hectare as the eDNA proportion of positive samples varies. The dotted line represents the 95% confidence limits.

3.5 Results of manta tow vs cull dive modelling

A companion project, *CCIP-R-02 Empirical Decision Support* (Fletcher et al. 2026), examined the relationship between cull CPUE and manta tow COTS and scar metrics using operational monitoring data collected across the broader GBR. The results of *CCIP-R-02* are consistent with the findings from our calibration experiment, both analyses show a positive but noisy relationship between cull-derived estimates and manta tow measures. The greater noise/scatter in operational data is expected as unlike our controlled side-by-side experiment, the *CCIP-R-02* data were collected with less precise spatial and temporal matching between cull and manta tow records. The *CCIP-R-02* analysis suggests that manta tow COTS counts are a stronger predictor of cull CPUE than manta scar density. This is consistent with the operational data containing a wider range of COTS densities than our experiment, where counts were near-zero and proportion of tows with scars was the only usable manta tow-based signal. The scar-only analysis from *CCIP-R-02* is particularly informative, indicating scar density on manta tow is effectively zero across the vast majority of observations, confirming that scars function as a presence/absence indicator rather than a continuous measure of density. Together, the experimental and operational analyses support the conclusion that manta tow is better suited to detecting whether COTS are present at a site than to estimating their abundance, and that high variability in cull-derived densities limits the precision of any manta tow-based calibration regardless of the dataset used.

3.6 Results of qualitative tool comparison

The considerations around which monitoring tools are most appropriate to meet different monitoring objectives are largely based on the scale at which they collect data, the metrics collected, their primary utility e.g., the ability to measure low/high COTS densities, ease of implementation and relative costs. The data required to answer different monitoring objectives require measurements to be taken at different spatial scales (**Table 6**). Four scales are relevant to the COTS Control Program: sub-site (<10 hectares – the scale of individual observations within a cull site); cull-site (~10 hectares – the operational unit for culling and CPUE assessment); sub-reef (multiple adjacent cull sites along a reef section, relevant to strategic vessel deployment decisions); and reef (whole reef perimeter – used for outbreak detection and reef-level prioritisation). For example, the priority status of a reef for COTS control may depend on the coral cover at a whole of reef scale, but choosing which sites to cull depends on measurements taken at a cull site scale. As such, selecting a monitoring tool requires matching its operational scale to that of the decision it is intended to inform. A tool suited to only reef-scale assessment cannot directly support cull site threshold decisions and vice versa.

At sub-site scale, the SALAD tool collects metrics best designed to record the finer scale information that may be required to answer some monitoring objectives such as the size of COTS encountered and coral type found in the vicinity of COTS. However, the SALAD method is routinely deployed at larger scales (1 km transects) and so its ability to inform decisions at the cull site-level or smaller is limited. Manta tow and ReefScan provide some information at the sub-site scale, but their strengths are in collecting data quickly rather than detailed fine-scale information. All methods are informative at the cull site scale (and were deployed at that scale during the field work for this project) but cull, SALAD and ReefScan are more suited to the cull site scale. Manta tow and eDNA monitoring tools are ideally suited to the coarser reef scale but do provide some useful information at the finer scales like sub-reef. In addition, as stated above, eDNA may be able to be adapted to cull site scale measurements if required by changing the sampling regime.

Australian Government Reef Trust Great Barrier Reef Foundation Australian Government Australian Institute of Marine Science CSIRO James Cook University Australia The University of Queensland Australia

Table 6. Summary of the scale that each monitoring tool is capable of collecting data. Dark green indicates the method is suited to collecting data at that scale, light green indicates it is possible to collect data at that scale but the method may not be best suited to this, and white indicates the method is not suited to the scale.

SCALE	Cull	Manta tow	SALAD	eDNA	ReefScan
Sub-site					
Cull site					
Sub-reef					
Reef					

Each monitoring method has the potential to collect a unique set of parameters. These are summarised in **Table 7**. While all the methods are capable of measuring the presence/absence and number of COTS (or in the case of eDNA a comparable metric), some of the metrics are only recorded by a single or small number of the methods. For example, the GPS location of COTS is directly recorded by ReefScan and indirectly by SALAD (where the time of sighting can be linked to the GPS track of the diver). The number of scars is only recorded by SALAD (manta tow provides a coarse none/some/many attribution), although the ReefScan methods are currently working on being able to measure number of scars in the near future (Project *CCIP-D-04,* Bainbridge et al. 2025). The coral cover measurements are only collected by manta tow, SALAD and ReefScan and only SALAD records any coral genera information.

Table 7. COTS and coral monitoring metrics collected by each of the monitoring methods. Y= Yes, No = No, P/A = Presence/Absence, NA = Not applicable. * Samples collected could be analysed for coral eDNA and information obtained on genera. Note that COTS per hectare is a desirable metric but is derived from the raw data so is not included here.

Method	P/A COTS	COTS count	Scars count	Dive duration	Search area	COTS location	COTS size	Depth	Proportion visible	Coral cover	Genera of coral
Cull	Y	Y	N	Y	Y	N	Y	Y	N	N	N
Manta tow	Y	Y	P/A	Y	Y	N	N	N	N	Y	N
SALAD	Y	Y	Y	Y	Y	Time of sighting	Y	Y	Y	Y	Y
eDNA	Y	eDNA Concentration	NA	NA	NA	NA	NA	NA	NA	NA	NA*
ReefScan	Y	Y	Potentially	Y	Y	GPS	Potentially	Y	NA	Y	N

One of the key differences between the COTS monitoring tools is that some are best suited to measuring high COTS densities (manta tow and cull (only because it is expensive to deploy divers to measure low COTS densities)) and others have been recently developed to measure low COTS densities due to a gap in the tools able to measure pre-outbreak densities (**Table 8**). ReefScan (still under development) is showing signs of being able to measure high COTS densities, although there are difficulties accurately counting when several COTS are overlapping. Given the accuracy of counting COTS via manta tow is low, even in this situation, the relative accuracy of ReefScan is likely to represent an improvement. ReefScan is still being tested for its ability to measure COTS at very low densities. The eDNA and SALAD techniques are most suited to measuring lower COTS densities and detecting any increases that may suggest an outbreak.

A further consideration surrounding the suitability of each of the methods is the ease of use in the field and the ability to make immediate on-water decisions. Cull diving and manta tow are easily deployed in the field and are routinely used by the COTS Control operators. Standard operating procedures and training have been implemented to limit inconsistencies between operations (although observer bias can be difficult to control when there are many divers involved). While culling is a result of on-water decisions, manta tow is routinely used to decide where to cull during on-water operations and ReefScan could be used as a manta tow replacement for making immediate decisions around where culling should take place. While SALAD surveys could be used for immediate decision making (if the Control Program divers were trained to undertake them), the intensity, and dive and ecological training required to conduct this method mean that it would be unlikely to be deployed across vast areas of the GBR on a routine basis. On the other hand, eDNA has the potential to be incorporated into a routine monitoring program with some training required on the appropriate collection of water samples. The eDNA technique is not currently able to be used for immediate on water decisions but there is potential for this feature to be developed in the future if the need was there.

Table 8. Summary of the utility of each of the methods for use in meeting some key monitoring objectives.

Method	Ability to measure low COTS densities	Ability to measure high COTS densities	Ease of in-field use	Use for on-water decisions (immediate)
Cull	Yes, but not cost-effective to do so. A smaller dive team may be a cost-effective alternative.	Yes	Easy, following training.	Yes
Manta tow	No	Yes, in a relative sense.	Easy, following training.	Yes, for decision whether to cull.
SALAD	Yes, pre-outbreak densities.	Reduced due to dive time.	Medium, but need to have dive training + ecological expertise.	High (for numbers of COTS) but only if deployed by Control Program divers.
eDNA	Yes, pre-outbreak densities.	Yes	Easy, low to medium level of field skill requirements but can be addressed by training.	No (not currently but can be developed if required).

Method	Ability to measure low COTS densities	Ability to measure high COTS densities	Ease of in-field use	Use for on-water decisions (immediate)
ReefScan	Low (still under development)	Potentially good.	Moderate. Non-biological skill set.	Yes

Table 9 provides a comparative overview of the monitoring methods, considering factors such as relative cost, personnel requirements, number of cull sites that can be visited per day, additional processing time, and measurements per reef according to standard protocols. Despite being relatively high in cost, cull surveys are often considered cost-effective as they are a byproduct of culling activities and not the primary monitoring method. Manta tow surveys are characterised by their moderate cost and efficiency, with teams comprising a diver, observer, and driver. They cover a reef perimeter of around 200 meters per transect and can cover 40–55 cull sites per day (100–140 manta tows), with extra processing time of approximately 2 hours per night. ReefScan surveys are characterised by their low daily run cost (excluding cost of unit). Similar to manta tow, each team comprises a tender operator and a video operator and can cover 40–50 cull sites per day, but ReefScan requires very little processing time overnight. Continuous measurement is also a key feature of this method. SALAD surveys are time-intensive but provide detailed information. Each team, consisting of two divers and a tender operator, can cover 4–6 cull sites per day, with moderate extra processing time. eDNA monitoring is relatively low-cost in the field, with lab costs varying depending on objectives. Each team can cover approximately nine cull sites per day, with significant additional processing required. The number of sites per day is largely dependent on the speed of the boat and the distance between reefs. eDNA results are unavailable until several weeks after the field samples have been received in the lab.

Table 9. Summary of the relative costs of each of the COTS monitoring methods.

Method	Relative cost	People per site	Cull sites per day	Extra processing time	Measurements per reef (standard protocol)
Cull	Cull surveys are high cost because they are relatively slow and resource intensive.	6–8	4–8	Low. Tablet apps help this.	Reef perimeter/~500 m (cull sites are approx. 500 m x 200 m)
Manta tow	Tow speed is 2 knots nominally so time to do reef is the length of the perimeter in nautical miles divided by 2. Team consists of diver, observer and driver.	3	40–55 (100–140 manta tow 200 m transects)	Moderate. 2 hours at night.	Reef perimeter/~200 m although not always completed for very large reefs
SALAD	Surveys have a high time cost. 2–3 parallel (2 divers) transects performed a day. Team consists of two divers and a tender operator. Additional SCUBA purchase and maintenance costs (but	3	4–6 (2–3 SALAD 1 km transects)	Moderate. Manual data entry.	6 (2 per site)

Method	Relative cost	People per site	Cull sites per day	Extra processing time	Measurements per reef (standard protocol)
	no more than cull surveys). Scooters cost ~AUD$2,000 each and last 2–3 years.				
eDNA	Low cost in the field (if vessel already in place). Approx. 2 hours per reef for 3 sites x 12 samples. Maximum of AUD$4,000 lab costs per reef, less depending on objectives. Number of sites per day largely limited by speed of boat and distance between reefs.	2 (minimum)	9 sites (assuming on 3 reefs) largely dependent on distance between sites)	High. Lab processing time required.	Depends on monitoring objective. See *CCIP-D-03 eDNA monitoring* (Uthicke et al. 2025).
ReefScan	Low cost in the field assuming a towed unit is available. Requires a tender operator and a video operator. ReefScan-Deep is likely to cost AUD$20–25K per unit. Additional data storage costs (if storing) and maintenance costs. Software is open source.	2	40–50 (100–125 manta tow 200 m transect equivalent	Currently moderate. Goal to be low to very low.	Continuous measurement

4. DISCUSSION AND OUTPUTS

4.1 Advantages and limitations of traditional monitoring methods

Traditional monitoring methods, manta tow surveys and cull diver surveys, have been integral to the success of the COTS Control Program Integrated Pest Management (IPM) framework (Rogers et al. 2023). Manta tow surveys afford rapid coverage of extensive reef areas, enabling broad-scale surveillance. However, their efficacy is hampered by low detectability, stemming from the cryptic and patchy nature of COTS, as evidenced by Fernandes et al. (1990). Our findings corroborate these observations, revealing a consistent tendency for manta tow surveys to substantially underestimate COTS abundance relative to estimates derived from cull diver surveys. In addition, the relationship between manta tow and all other monitoring methods was highly uncertain across the range of COTS densities encountered in this study.

Furthermore, variability in coral cover and the difficulty in accurately estimating coral cover via manta tow (without regular ongoing training and calibration between observers) introduces potential biases and uncertainty, challenging the accuracy and reliability of data obtained through this method for estimating coral cover trends. While the AIMS Long-Term Monitoring Program (LTMP) collect long-term data on the condition and trends of coral reefs in the GBR using manta tow, they use a small set of highly trained divers to do so (Emslie et al. 2020). Conversely, the COTS Control Program has a large and often transient team of divers and so ensuring the same level of standardisation between companies, vessels and observers, as per AIMS LTMP, would be difficult and unlikely to be cost-effective. However, as a method to determine whether there is enough coral at a site to justify culling, the manta tow method offers a practical solution. Cull diver surveys, while labour-intensive, offer relatively precise assessments of COTS abundance (MacNeil et al. 2016), benefitting from the concerted effort of multiple divers scouring defined areas for COTS. These established methods, despite their limitations, have provided valuable insights into COTS populations and coral cover over the years and continue to do so.

In the past it has been difficult to match up the manta tow and cull data at the site level, although this has recently been automated (see *CCIP-R-02 Empirical Decision Support,* Fletcher et al. 2026). We carefully designed the fieldwork to minimise any measurement error, however this project highlights some of the challenges and time needed to do this accurately and the importance of the monitoring design for data collection.

4.2 Potential of novel monitoring technologies

The emergence of novel monitoring technologies, namely eDNA sampling, SALAD and ReefScan technology, provide promising alternative and complementary methods to traditional methods. These innovations hold the potential to enhance detection sensitivity, improve spatial coverage and data robustness while potentially reducing costs and decision-making uncertainty. However, their efficacy and suitability for specific applications must be rigorously evaluated and compared against established methodologies before they can be integrated into a comprehensive monitoring program.

At the time of conducting these experiments, the ReefScan-Transom and ReefScan-Deep were acknowledged for their potential in accurately estimating coral cover through the utilisation of machine learning algorithms. However, despite ongoing efforts to enhance the technology's algorithms for automatic detection of COTS, it was not yet deemed sufficiently dependable for accurate measurements during the project's fieldwork phase. The ability to improve the detection models over time for relatively low costs means that the current limitations have a pathway where they can be improved upon so while the models currently are limited, this may not be an on-going issue once the models are fully trained. Once the technology is developed it will be important to evaluate the impact of different tow paths on estimates of coral and COTS. To a certain extent this is an issue also faced by manta tow, however the observer on manta tow has more control over the survey path than the tender driver does for ReefScan. Repeating tows around several (or preferably many) reefs will be an important future exercise to get a handle on the measurement error.

The imminent availability of this advanced technology holds the promise of improving the volume of monitoring data attainable under the COTS Control Program (at this early stage though, the data volumes will be similar to manta tow). This is attributable to the efficiencies derived from continuous towing, automated data recording, and stepping away from in-water activities (e.g., diving) that are restrictive due to safety regulations. Moreover, the integration of this technology offers additional benefits, including the provision of precise GPS coordinates for COTS. Such data not only facilitates efficiencies in locating and culling of COTS but also holds potential for future research endeavours exploring the mechanisms driving COTS aggregations within reef ecosystems.

The SALAD measurement technique brings the benefit of being able to monitor lower COTS densities while also allowing additional information, such as the size of COTS and habitat information. COTS reproduction potential is heavily influenced by their size, with larger individuals, especially females, having a much greater capacity to produce offspring (Pratchett et al. 2021). The information about size distribution and reproductive capacity is valuable for deciding where to focus culling efforts and how to allocate resources for controlling COTS populations. Prioritising efforts to control populations dominated by larger individuals might be more efficient in slowing down population growth compared to targeting areas with higher population density but smaller individuals (Chandler et al. 2023).

While the comprehensive SALAD surveys provide valuable data on COTS populations and their habitat, the resource-intensive nature (need for scooters and two divers can only complete 2–3 transects a day covering ~4–6 cull sites) of these surveys may not always be feasible. In situations where funding for full SALAD surveys is limited, it might be worth considering adapting cull dive surveys to serve a more comprehensive monitoring purpose, capturing essential data on COTS size distribution, density, and habitat characteristics. To minimise the overall effort required, cull dive teams could be reduced to a smaller number and the survey area could also be reduced.

eDNA monitoring brings the potential to detect the presence of COTS eDNA in water samples, even at low concentrations (Uthicke et al. 2022), providing early detection of COTS in an area before they become visible during traditional surveys. COTS eDNA also correlates well with high densities (Uthicke et al. 2018) and thus at reef scale, provides a wide detectability range. eDNA monitoring can survey a wide range of habitats and depths, including areas that may be difficult to access using traditional survey methods which is becoming increasingly important with increasing densities in the Northern and Far Northern GBR where there are increased Occupational Health and Safety (OH&S) risks associated with diving (Chandler et al. 2023).

These novel tools open new opportunities for targeting field sampling to better focus the resources for culling activities. For example, eDNA could allow rapid synoptic surveying of reefs adjacent to reefs that are being culled to give a regional perspective. In the same way, tools such as ReefScan could be used to do rapid pre-surveys of non-surveyed reefs to again focus the work of the cull teams. Of course, each of these novel measurement tools also has limitations (summarised in the following section).

4.3 Importance of understanding comparative performance

There are advantages and disadvantages for each of the monitoring tools. In summary:

4.3.1 Manta tow

The primary utility of manta tow is rapid, broad-scale, relative estimates of COTS, scars and coral. The method has low COTS detectability but enough accuracy and precision to inform decision making around directing culling effort in the field and detecting COTS outbreaks.

Manta tow is the fastest method for covering large areas of the reef and is the only tool in this study that simultaneously records COTS, scars and coral cover in a single pass with minimal equipment. However, the calibration results in this study confirm its well-documented limitations as a quantitative COTS tool i.e., the COTS counts on manta tow were near-zero across all cull sites in the primary experiment and the relationship between the proportion of tows with scars and the cull diver CPUE was highly uncertain, with prediction intervals spanning the full range from 0 to 1 at all cull rates. This wide uncertainty reflects both the low and variable detectability of COTS from the surface and the coarseness of the scar presence/absence metric. Coral cover estimates from manta tow are similarly coarse, recorded in ordinal categories and subject to observer variability, though as a method for assessing whether sufficient coral exists at a site to warrant culling effort, the method provides a practical and rapid solution. Ensuring observer standardisation across the large and transient team of COTS Control Program divers remains a key challenge for using manta tow coral data reliably over time.

4.3.2 Cull dives

The primary utility of the cull dive is culling COTS in medium to high densities. Relatively accurate COTS density estimates are a byproduct of this process.

Cull diver surveys offer operationally grounded COTS density estimates, as the systematic effort of six to eight divers produces CPUE data that is relatively accurate at medium to high densities (MacNeil et al. 2016) and it is directly expressed in the units required for ecological threshold assessment (Fletcher et al. 2020). The large dataset accumulated through routine COTS Control Program operations also makes cull dive data a valuable source of historical information for calibration against other tools, as demonstrated by the CCIP-R-02 analysis (Fletcher et al. 2026). The primary constraint is that cull dive effort is deployed where and when COTS densities are already expected to be sufficient to justify culling which means the method does not provide independent unbiased surveillance and the resource requirements make it impractical to deploy cull teams solely for monitoring purposes at low densities. Cull dive data also provide no information on coral cover.

4.3.3 SALAD

The primary utility of the SALAD method is the detection and estimation of adult COTS and scars at low densities. Divers are able to stop and search for COTS and investigate scars that may not otherwise be apparent. This method is useful to document changes in abundance and size distribution of starfish, e.g., in the very early stages of outbreaks. It also offers fine-scale, site scale and detailed reconnaissance.

SALAD surveys demonstrated the strongest and most precise calibration relationship with cull diver CPUE of any method tested, with GPS-derived area estimates allowing density to be expressed in ecologically meaningful units (COTS and scars per hectare). The non-zero intercept of the SALAD to cull calibration reflects SALAD's higher sensitivity at low COTS densities, it detects both visible COTS and distinct sets of feeding scars, including animals that evaded cull diver detection. This sensitivity makes SALAD particularly valuable for early detection. Additional information on COTS size and coral composition, recorded as part of the standard SALAD protocol, provides data that no other method in this study collects at the cull site scale. The main operational constraint is resource intensity, two trained divers with scooters can complete only two to three surveys per day, limiting the spatial coverage achievable in a single deployment.

4.3.4 ReefScan

The primary utility of ReefScan is the automatic detection of adult COTS via high frequency high resolution images in real-time. The method can be used for either reconnaissance or surveys, but here we consider its use in a monitoring program. ReefScan can be used to conduct rapid, large-scale surveys of both COTS and coral. The future utility of the technology is expected to increase with the potential development of COTS scars models. It has a similar utility to a manta tow without the need for divers in the water, while also being able to provide the exact location of COTS detected.

ReefScan produced usable coral cover calibrations in this study, with ReefScan-Deep estimates broadly consistent with manta tow at low coral cover values and diverging upward at higher values, likely reflecting the greater spatial resolution of continuous imagery compared to coarse ordinal manta tow categories. Its key operational strengths, specifically continuous GPS-references imagery collected without divers in the water, rapid coverage of large areas, and a permanent image record that can be reprocessed as models improve, make it a promising complement to established methods, particularly for broad-scale reconnaissance in areas with OH&S constraints on the diving. The primary limitation demonstrated in this study is that COTS detection could not be calibrated: only a single COTS was recorded across all ReefScan deployments in the primary experiment, and the machine learning models for COTS and scar detection were still in development at the time of the fieldwork. This is a current rather than fundamental constraint, but it means that COTS-based decisions cannot yet be supported by ReefScan data alone.

4.3.5 eDNA

The primary utility of eDNA monitoring is the detection of COTS at low densities and/or over large areas, but it also has applicability in medium to high COTS density locations. The method could be used to detect the earliest stages of COTS outbreaks or follow-up surveillance post culling. The eDNA method can be used to sample a wide range of habitats and weather conditions and presents an ‘observation free’ alternative.

eDNA sampling showed a clear positive relationship with cull diver CPUE at the cull site scale, a promising finding given that the method was designed primarily for reef-scale surveillance. The proportion-positive metric increased strongly at low cull rates before beginning to flatten at approximately 0.10 COTS per minute, suggesting that eDNA approaches detection saturation at higher densities. Both proportion positive and copy number concentration were used in calibration models, with the former providing a more stable metric across varying field conditions (Uthicke et al. 2022). The key operational advantages are speed of sample collection, the ability to survey sites where diving is unsafe or impractical, and the capacity to store samples for later analysis. Limitations include the time lag between sampling and laboratory results, the risk of contamination, and the current ambiguity around which eDNA metric is most informative for different applications, an issue being addressed by the companion project CCIP-D-03 (Uthicke et al. 2025). eDNA does not provide any coral cover information.

4.4 Limitations of the project

In our project, we conducted two field trials to calibrate the COTS and coral monitoring tools but encountered several limitations during the process. The ReefScan technology was not fully developed for COTS detection, which prevented its calibration in our experiments (although we were able to calibrate the coral estimates). Additionally, although our field trips were carefully planned and produced the only side-by-side controlled calibration dataset currently available for these tools, the dataset remains small, limiting our ability to fit models and estimate the effects of other covariates such as habitat and depth. Furthermore, the recorded COTS densities were relatively low and attempts to address this by scheduling a second field trip were impacted by adverse weather conditions and equipment failure. It is also important to keep in mind that because we lack absolute estimates of COTS abundance, our comparisons among methods are relative. These limitations are discussed further below and should be considered when applying the calibration models to operational monitoring data.

The substantial difference between the two ReefScan-Transom calibration relationships (approximately double manta tow estimates in the primary experiment but markedly lower in the secondary) represents an important unresolved limitation for operational application of the ReefScan coral calibration (Section 4.4). Two aspects of the experimental design contribute to this. First, the two experiments encountered very different ranges of coral cover (0–25% in the primary, 0–80% in the secondary), meaning the calibration relationships were estimated under fundamentally different ecological conditions and cannot be directly compared or combined without additional data. Second, the primary experiment deployed manta tow and ReefScan sequentially from different vessels, while the secondary experiment co-deployed them simultaneously from the same tender, a protocol change that removed natural deployment variation and reduced spatial mismatch between the methods. Understanding which of these factors drives the discrepancy requires future deployments with a range of coral cover. Until a consistent calibration relationship can be established across a broader range of conditions, the ReefScan coral calibrations should be applied with caution and treated as preliminary estimates.

Each of the monitoring methods is best suited to measure COTS at different scales and densities. While ideally, we would have conducted the experiment by replicating the methods at many sites at many reefs, this was cost prohibitive. In particular, eDNA is currently designed for reef-scale application, and our analysis at the finer cull site scale, while showing a promising positive relationship with cull CPUE, was based on a relatively small number of sites. A complementary calibration of eDNA and SALAD at the reef scale, using data collected across multiple years and reefs is presented in a companion project *CCIP-D-03 eDNA monitoring* (Uthicke et al. 2025) which shows a stronger relationship between the two monitoring tools at the reef scale.

4.5 Conclusion

In conclusion, our project underscores the importance of understanding the comparative performance of monitoring tools for COTS populations and coral cover in coral reef ecosystems. While each method offers unique advantages, none are singularly ideal for all Program applications. Manta tow surveys, for instance, offer rapid, broad overviews but are not effective at measuring changes at low COTS densities and underestimate true COTS abundances due to low detectability. Conversely, diver culls are intensive but limited in spatial scale. Techniques like eDNA and SALAD bridge this gap by overcoming logistical challenges in surveying highly cryptic, low-density populations.

Integrating multiple monitoring tools that complement each other's strengths and weaknesses could significantly enhance the overall robustness of the COTS Control Program's monitoring and surveillance strategy. For example, coupling the rapid coverage of ReefScan surveys with the precision of diver culls could provide a more comprehensive understanding of COTS distribution and abundance dynamics. Introducing monitoring technologies such as eDNA and SALAD could vastly improve the detection of COTS outbreaks through the capability of measuring change in lower COTS densities.

Our calibration models play a crucial role in translating between the measurement units of different tools, enabling observations from any one tool to be expressed in the units of another, including the cull diver CPUE units required for threshold-based management decisions. This means managers can assess whether COTS densities observed by SALAD or eDNA exceed ecological thresholds, regardless of whether cull dive data are available for a given site. The models carry inherent uncertainty given the small dataset and the predominantly low COTS densities encountered and should be applied with appropriate caution. Continued side-by-side deployment of new and traditional methods is pivotal for refining calibration models and reducing uncertainty as novel techniques become integrated into routine monitoring practices.

Looking ahead, adopting an integrated multi-tool monitoring strategy holds the potential to enhance the operational efficiency and decision-making processes underlying the COTS Control Program. However, it's imperative to consider additional factors such as logistical requirements, costs, and scalability when deploying each method across the expansive GBR. By carefully weighing these considerations and leveraging the strengths of diverse monitoring tools, we can bolster the resilience of reef ecosystems against the threats posed by COTS outbreaks.

4.6 Project outputs

The outputs of this project are:

- New knowledge comparing observations from existing and emerging COTS monitoring tools (estimate error/uncertainty).
- Rosetta_COTS: An R package calibration estimation tool to facilitate conversion of COTS and coral estimates from one tool to another (and estimate the associated uncertainty). https://github.com/Scott-Foster/Rosetta_COTS
- A dataset with co-located surveys from multiple tools from two field trips.
- Comparison of the COTS monitoring tools including primary utility for monitoring and advantages and disadvantages of each method.

5. RESEARCH SYNERGIES AND NEXT STEPS

The outputs of this project provide the COTS Control Program with a calibration of the sampling tools and associated estimates of uncertainty. These outputs were directly incorporated into the *CCIP-D-01 COTS monitoring design* (Lawrence et al. 2025) project that aimed to develop a comprehensive multi-tool monitoring plan. Having a thorough understanding of both the qualitative and quantitative differences between the sampling tools is imperative to the success of the monitoring plan.

The R-scripts that were used to estimate the calibration between each sampling tool and every other tool have been incorporated into an R-package (Rosetta_COTS). This tool will allow the translation of the estimates from one sampling method to those of another. This will improve the data available for decision making, particularly for the COTS Control Program, who are often trying to make use of all available monitoring data when deciding which reefs are the highest priority for monitoring and control. We envisage that future modelling projects will also be able to make use of the tool to enable maximum use of the different COTS monitoring data sources.

Although the fieldwork was originally designed to include a near-finished ReefScan platform (*Project CCIP-D-04,* Bainbridge et al. 2025), the project provided valuable field time to test the development and collect data on which to train the COTS and scars machine learning models. The eDNA monitoring team (*CCIP-D-03,* Uthicke et al. 2025) and scooter-assisted large area diver-based survey team (*CCIP-P-04,* Pratchett et al. 2025) collaborated with us on this project and the key members contributed to the design of the field trip and participated in the trip itself, leading to a collective understanding around the comparison of the different sampling technologies.

We collaborated with *CCIP-R-02 Empirical Decision Support* (Fletcher et al. 2026) to undertake the calibration of manta tow and cull data collected as part of the routine operations of the COTS Control Program. We refer to and discuss those results in this report and compare them to those from the field trials. The data collected throughout the fieldwork has been uploaded to the COTS Information System developed under *CCIP-R-01 Information Infrastructure* (Fletcher and Rezvani 2026).

Through undertaking this project, several priority areas for future research and development were identified:

1. **Updating the calibration models**

   The uncertainty around the calibration models is large. As some of the new monitoring tools are incorporated into the COTS Control Program, it is likely that much more data will become available to allow more accurate calibration and hopefully reduce uncertainty. To facilitate this, it will be important to incorporate the more novel monitoring tools alongside the traditional methods for some time before completely replacing one with the other. This will also ensure that long-term monitoring time-series remain relevant for future use.

   Throughout CCIP, significant improvements have been made in how data are recorded and linked. For example, the accuracy with which the manta tow and the cull dives are linked at the site level has been greatly improved through *CCIP-R-02* (Fletcher et al.

2026). With data being collected and linked using these more accurate algorithms, it will also be pertinent to update the historical manta tow vs cull diver calibration model in time as it has direct use in the IPM Framework.

To maximise the utility of the eDNA monitoring technique in detecting COTS outbreaks, it will be important to improve our understanding of how the eDNA measurements translate to COTS densities. The most accurate way to undertake this would be to cull reefs shortly after taking eDNA samples. Even with this extra data, refinements to the eDNA measurement process should be considered. Project *CCIP-D-03 eDNA monitoring* (Uthicke et al. 2025) has investigated the field requirements for sampling (how many sites, samples and so on).

2. Small cull dive team surveys

One priority for further consideration is adapting the labour-intensive cull dive surveys into a more streamlined protocol akin to the SALAD methodology. Instead of deploying teams of six to eight divers to exhaustively search a full cull site (~10 hectares), a scaled-down team could survey a reduced area, enabling collection of key COTS metrics e.g., size distribution, density estimates and habitat information, in a less resource-intensive manner. Such a protocol would be particularly suited to low-density COTS environments where comprehensive site culling is not warranted and could help address monitoring objectives currently unmet by existing methods (see *CCIP-D-01 COTS Monitoring Design*, Lawrence et al. 2025). Before such an approach could be integrated with existing data streams, it would be critical to develop an appropriate Standard Operating Procedure, train divers in the protocol, and conduct calibration trials against established methods to enable meaningful comparison with historical data.

3. Monitoring for Sea Country

Traditional Owner / Traditional Custodian (TO) rangers (and more generally TO groups) want to be able to monitor their own Sea Country. There is an increasing need to work collaboratively with TO groups to develop tools and methods suited to small-scale monitoring of Sea Country, with a view to incorporating this monitoring into longer-term surveillance programs. Enabling this type of monitoring could increase the geographic coverage of COTS surveillance, particularly across remote areas of the GBR not currently reached by COTS Control Program vessels, whilst simultaneously supporting TO groups to better understand changes in their own Sea Country. Appropriate resourcing and co-design of such monitoring programs, in partnership with TO groups and relevant agencies, would be essential to ensure activities are meaningful, sustainable and culturally appropriate. Standardising methods for systematic long-term monitoring is a potential longer-term goal that applies beyond TO ranger programs i.e., community groups, citizen science organisations and other non-government partners could similarly contribute to expanding COTS surveillance coverage.

6. MANAGEMENT IMPLICATIONS AND IMPACT

The findings of our study have direct implications for management strategies aimed at mitigating the impacts of COTS outbreaks on reef ecosystems. By comprehensively understanding the strengths and limitations of various monitoring methodologies, managers can tailor monitoring programs to specific environmental contexts, optimise resource allocation, and enhance the effectiveness of management interventions.

Our study highlights the importance of both traditional and novel monitoring methods for managing COTS populations. Traditional methods like manta tow surveys and cull diver surveys have been pivotal but are hindered by limitations such as low detectability and labour intensity. However, they have provided valuable insights into COTS populations and coral cover over the years. Novel monitoring technologies such as eDNA sampling, SALAD, and ReefScan offer promising alternatives with improved detection sensitivity, spatial coverage, and data robustness. Despite their potential benefits, their efficacy and suitability need rigorous evaluation before integration into monitoring programs.

There are several management entry points where the results from this study can have clear impact. They are:

1. ***Annual reef prioritisation process:*** The annual reef prioritisation process is based on all available COTS and coral monitoring data. While it is robust to compare the relative estimates across the reef from a single method e.g., manta tow, having measurements from multiple sampling tools adds complexity to the decision making. As new monitoring technologies are introduced to the Program it is important that the data can be translated between the methods. Calibration models estimated throughout this project will help to facilitate this process. We calibrated the SALAD data using both COTS/minute and COTS/hectare to facilitate the translation of the traditional catch-per-unit-effort (measured in time) for the cull data to densities. It will be important for the COTS Control Program to later consider how this calibration compares to their current methodology of estimating the search area of the cull divers to estimate densities.
2. ***Integrated Pest Management (IPM) Framework:*** Integration of diverse monitoring tools can improve the effectiveness of the IPM Framework by enhancing detection and monitoring capabilities. Effective integration requires having a good understanding of the capabilities of the tools and how the estimates from the tools compare in a relative sense. For example, the inclusion of ReefScan in the COTS Control Program will likely require ongoing calibration between manta tow and ReefScan so that the ecological thresholds on which to base culling can be adjusted.
3. ***On-water operations and data collection:*** Adoption of novel monitoring technologies like eDNA and ReefScan can streamline on-water operations and data collection processes, enabling improved decision-making (and in the case of ReefScan enabling real-time decision making) and enhancing operational efficiency.

This research contributes to achieving the overarching outcomes and impacts identified in the CCIP's Research Impact Plan by improving detection and monitoring capabilities, facilitating more efficient and effective operational responses, and enabling more accurate prediction of COTS outbreaks. By integrating traditional and novel monitoring methods into the COTS Control Program and addressing key entry points such as governance, strategic management, reef prioritisation, and operational procedures, this study helps suppress and prevent COTS outbreaks, protect coral cover across the Great Barrier Reef, and benefit stakeholders including Traditional Owners, the tourism industry, and the community.

7. ACKNOWLEDGEMENTS

We would like to extend our sincere gratitude to the Queensland Parks and Wildlife Service (QPWS) for generously providing the vessel for the first field trip, which was made possible through funding from the Reef Authority. We are especially thankful to Sascha Taylor (QPWS) for leading the team with invaluable expertise in COTS monitoring and reef ecology. The collaboration and support of Blue Planet Marine and Pacific Marine Group during the fieldwork were instrumental to the success of this project. Their teams' enthusiasm and dedication greatly contributed to the advancement of our research objectives.

8. DATA ACCESSIBILITY

The data collected during the primary and secondary experiments are on the CSIRO Data Access Portal:

- *Calibration trial of crown-of-thorns starfish and coral monitoring tools in the Great Barrier Reef (https://doi.org/10.25919/b5jn-vg48)*
- *Comparison of coral cover estimates collected via manta tow and ReefScan technology at three reefs in the Great Barrier Reef (https://doi.org/10.25919/3vxx-am37)*

The fieldwork data and R scripts are also available in the Rosetta_COTS R package (Scott-Foster/RosettaCOTS: R-package for quantitative translation between COTS measurement tools).

Australian Government | Reef Trust | Great Barrier Reef Foundation | Australian Government | Australian Institute of Marine Science | CSIRO | James Cook University Australia | The University of Queensland Australia

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APPENDIX A – COTS FACTSHEET

Crown-of-thorns starfish survey methods project

Information Sheet

What is this research project about?

Crown-of-Thorns Starfish (COTS) eat coral and are considered a pest on coral reefs (**Figure A1**). The starfish have outbreaks where their numbers can increase to very high levels and when that happens, they cause a lot of damage to the health of the Great Barrier Reef.

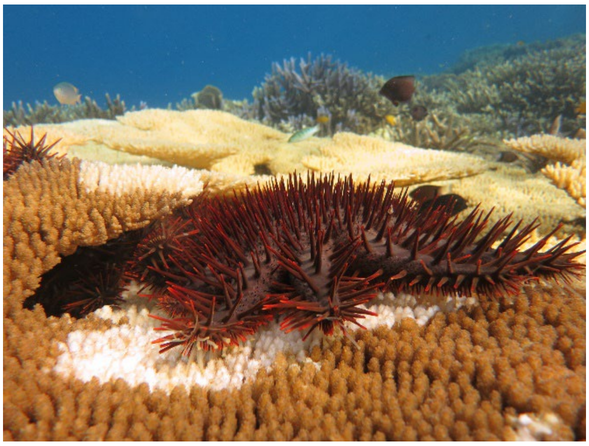

Figure A1. Crown-of-thorns starfish feeding on live coral.

Like many pests (e.g. cockroaches, rats), these starfish are good at hiding during the day which makes them challenging to find and control. Better methods are needed to monitor how many starfish there are on the reef and find the big groups of starfish to reduce their numbers through targeted culling.
Under this project, scientists from several organisations are working together to develop new methods to survey and detect coral-eating starfish. There are four methods the research team will be testing (**Figure A2**):

- Manta tow method – This is the current method that has been used for decades to survey starfish on the Great Barrier Reef. It involves a diver being pulled behind a small boat looking for the starfish. Every two minutes the boat stops and the diver writes down how many starfish they have seen.

- Scooter method – This new method is being developed to survey the starfish using small hand-held scooters to propel a diver along the reef while they look for starfish. The diver can stop and search in holes and crevices for starfish that are hiding and then write down how many they have seen.

- Environmental DNA method – This new method is being developed to detect starfish through the traces of DNA that they leave in the water. Researchers will collect water samples near reefs and then bring those samples back to the laboratory to test them for the presence of starfish DNA.

- Underwater camera and artificial intelligence method – This new method is being developed to survey the starfish using an underwater camera that is towed behind a small boat and takes photographs and video of the reef. These photographs and video will then be analysed using artificial intelligence software that is designed to find and count the starfish.

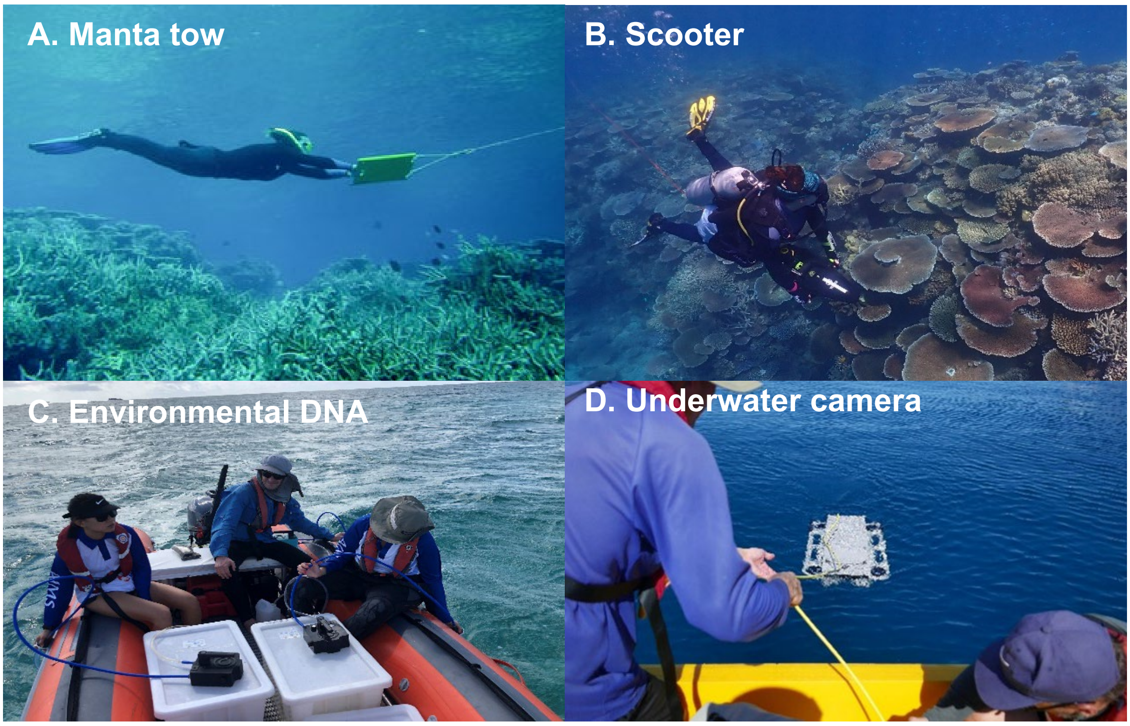

Figure A2. The four methods being tested in this project.

When and where will the research take place?

The research team will be testing these four methods side-by-side during a field trip from 24 March to 3 April 2023. The research team will depart and return from Townsville and spend 9 days at sea on a large vessel. The team plans to visit 6-8 reefs that are situated about 50-60 kilometers offshore from the Queensland coastline off shore from Townsville (**Figure A3**).

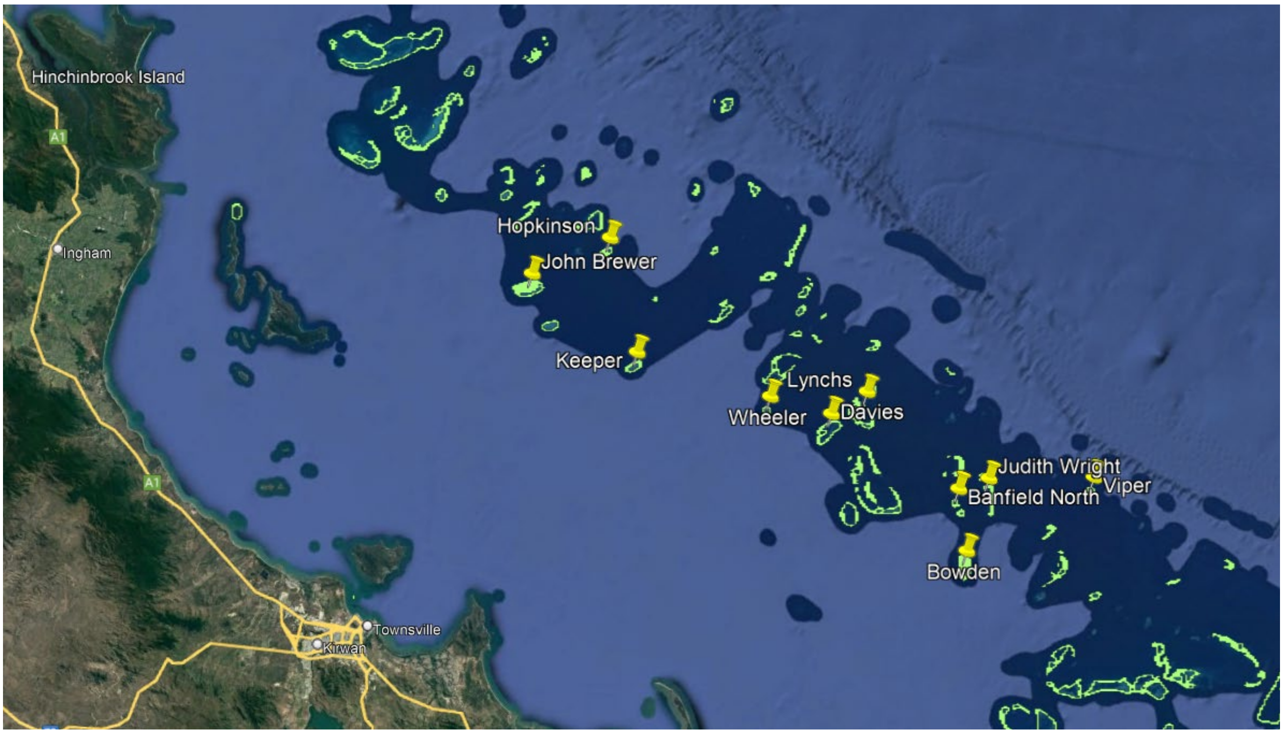

Figure A3. Map of the study area. Six to eight of the ten reefs will be visited.

Who is doing this research?

This project is being delivered by a team of researchers from the Australian Institute of Marine Science, CSIRO and James Cook University as part of the COTS Control Innovation Program. Logistical support, vessel resources and additional field personnel are being provided in-kind by the Great Barrier Reef Marine Park Authority via the Reef Joint Field Management Program and the COTS Control Program.

The research is funded by the Great Barrier Reef Foundation through its Reef Trust Partnership with the Australian Government.

For more information on this research please contact the Project Leader:

Emma Lawrence (CSIRO)
Email: Emma.Lawrence@data61.csiro.au

APPENDIX B – COTS CALIBRATION MODEL RESULTS

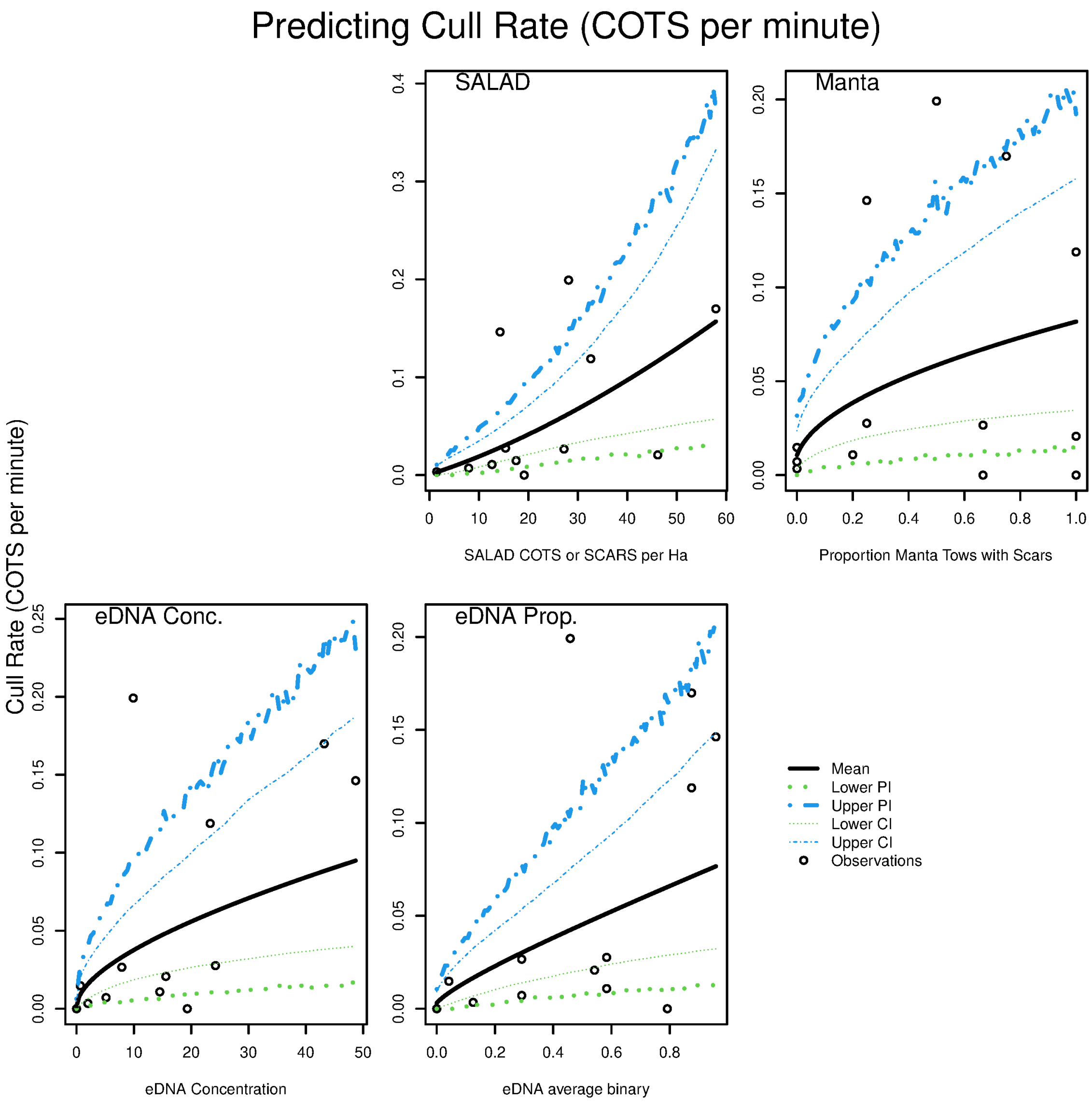

Figure B1. Predicting COTS cull rate per minute using SALAD, manta tow and eDNA (concentration and binary metric).

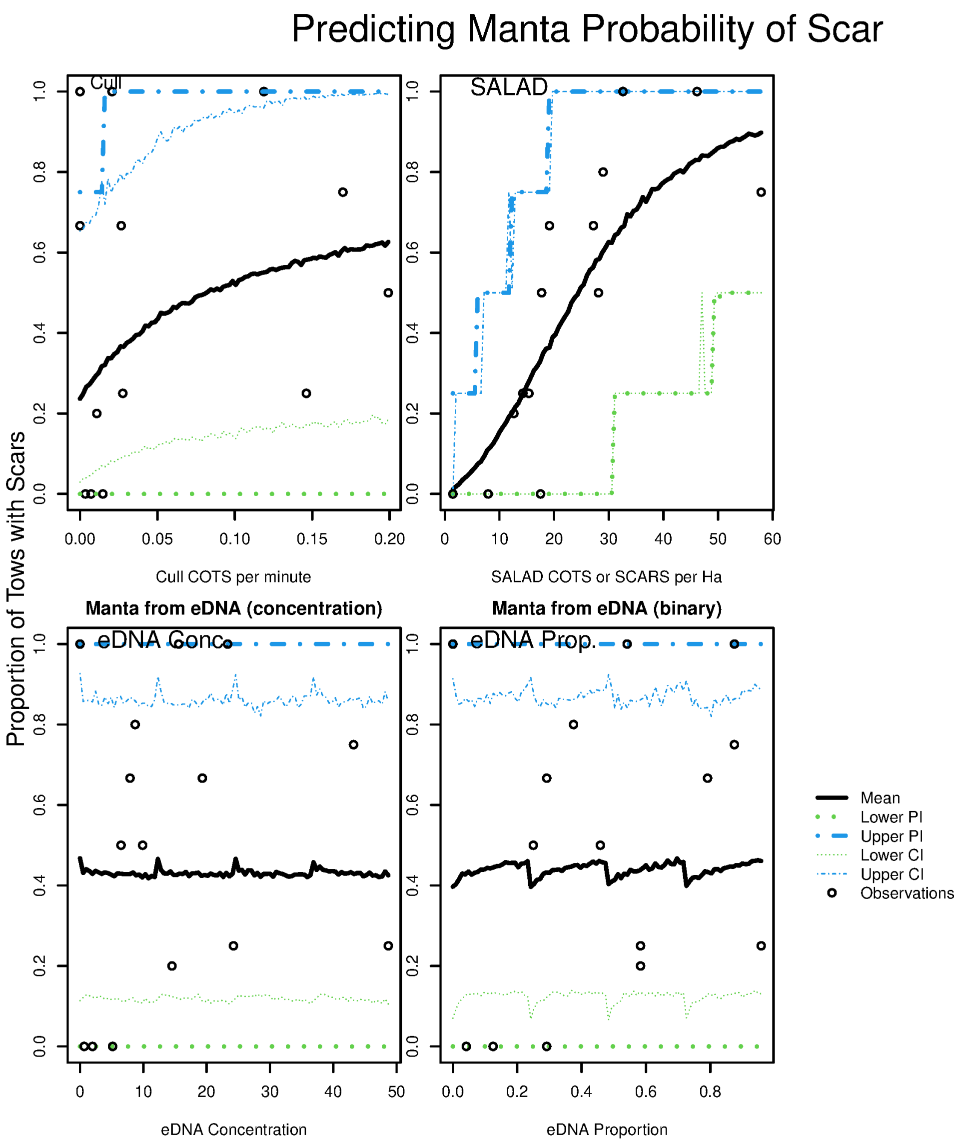

Figure B2. Predicting proportion of manta tows with scars using cull, SALAD and eDNA (concentration and binary metric).

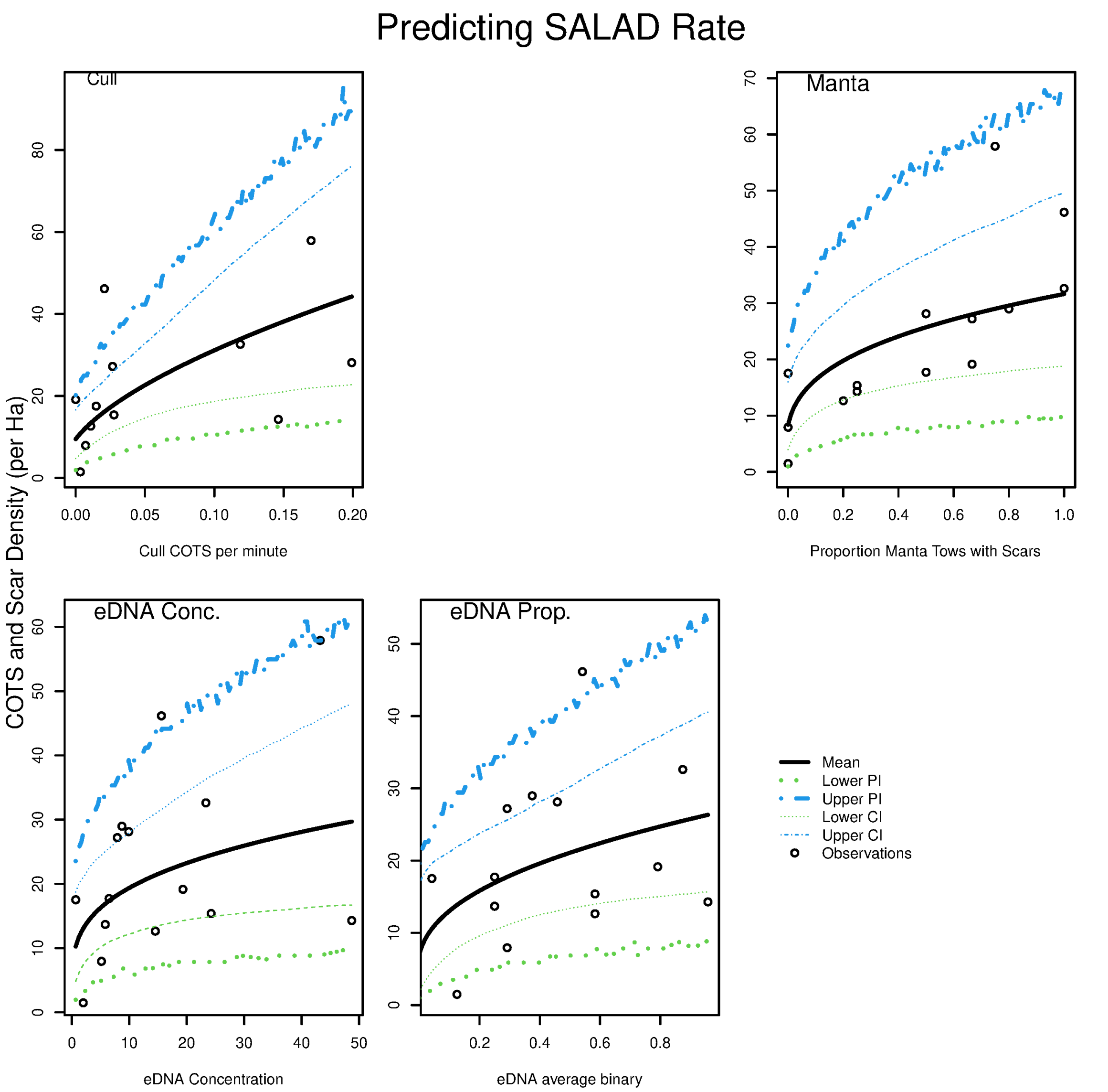

Figure B3. Predicting COTS and scar density on SALAD using cull, manta tow and eDNA (concentration and binary metric).

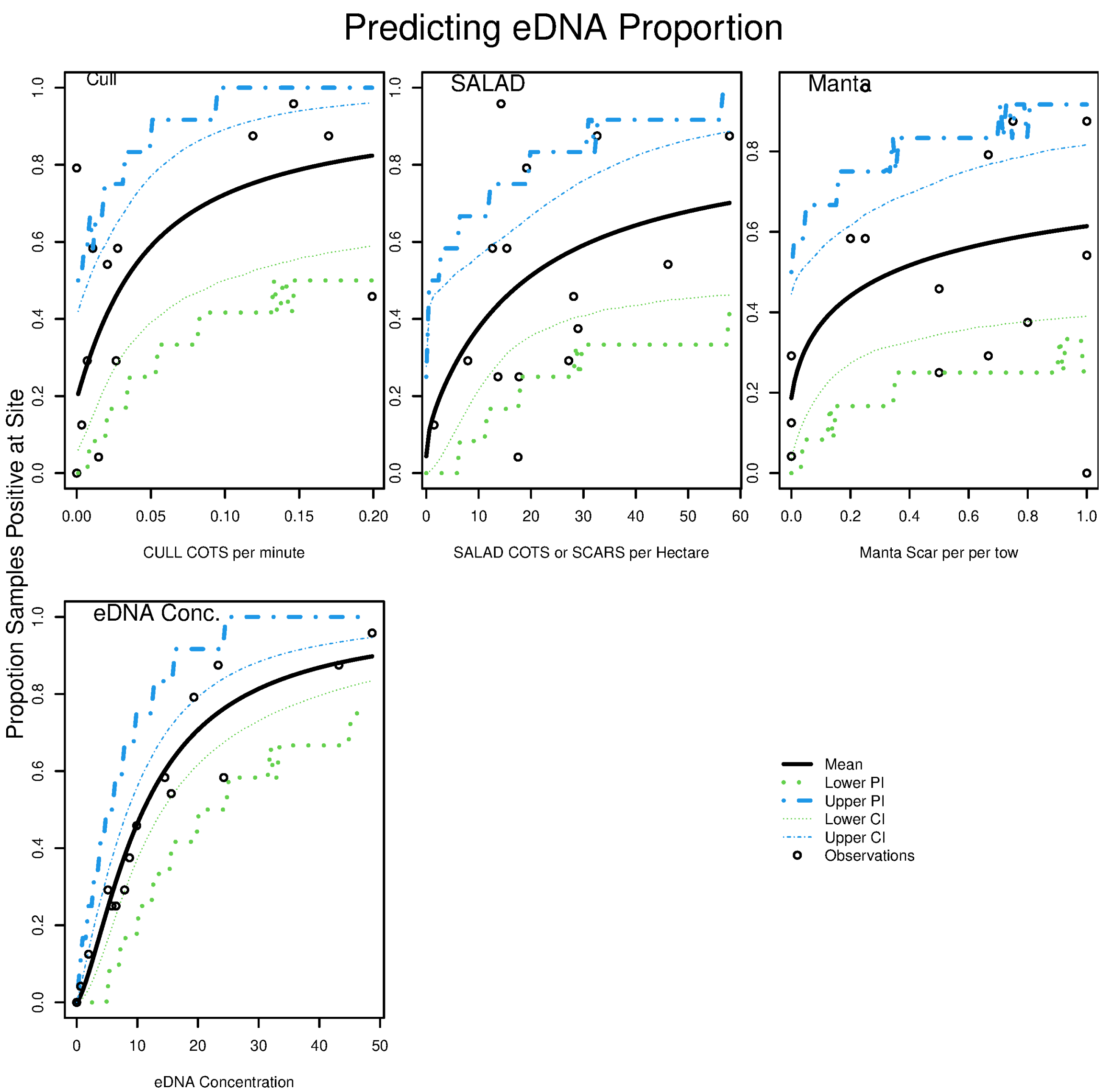

Figure B4. Predicting eDNA proportion of positive samples at a site using cull, SALAD, manta tow and eDNA concentration.

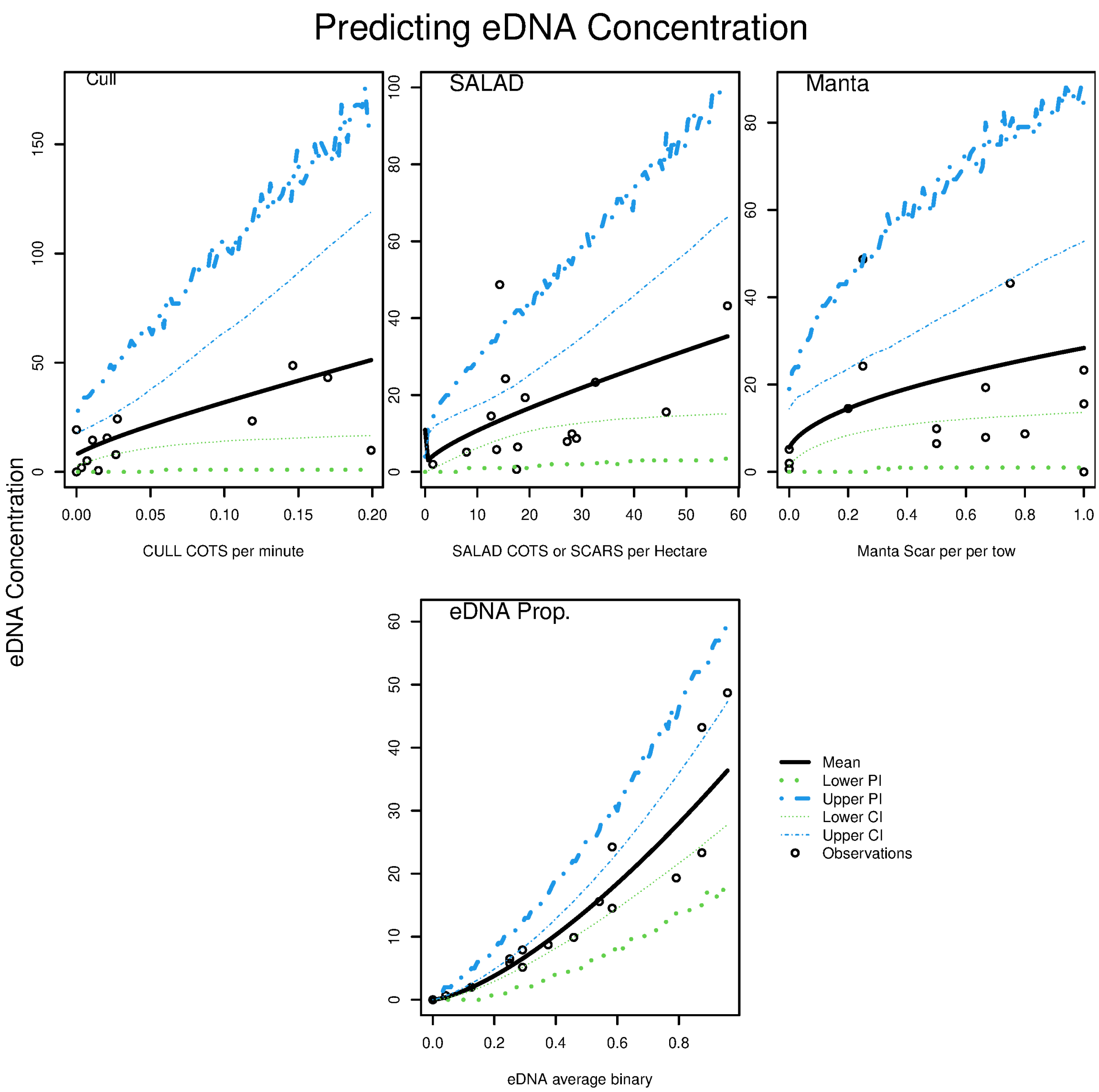

Figure B5. Predicting eDNA concentration at a site using cull, SALAD, manta tow and eDNA proportion of positive samples.

APPENDIX C – CORAL CALIBRATION MODEL RESULTS

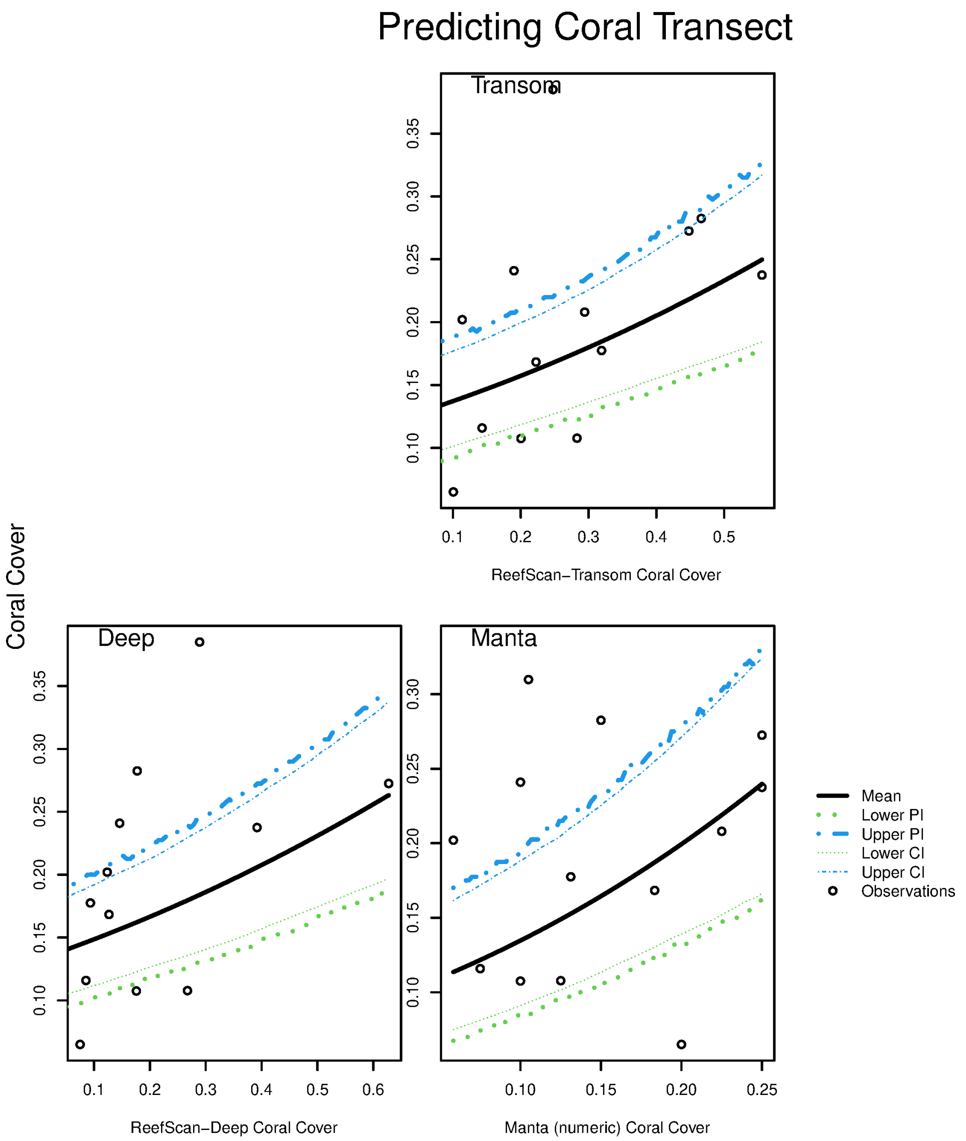

Figure C1. Predicting coral cover transect (collected at the start and end of SALAD surveys) using ReefScan-Transom, ReefScan-Deep and manta tow.

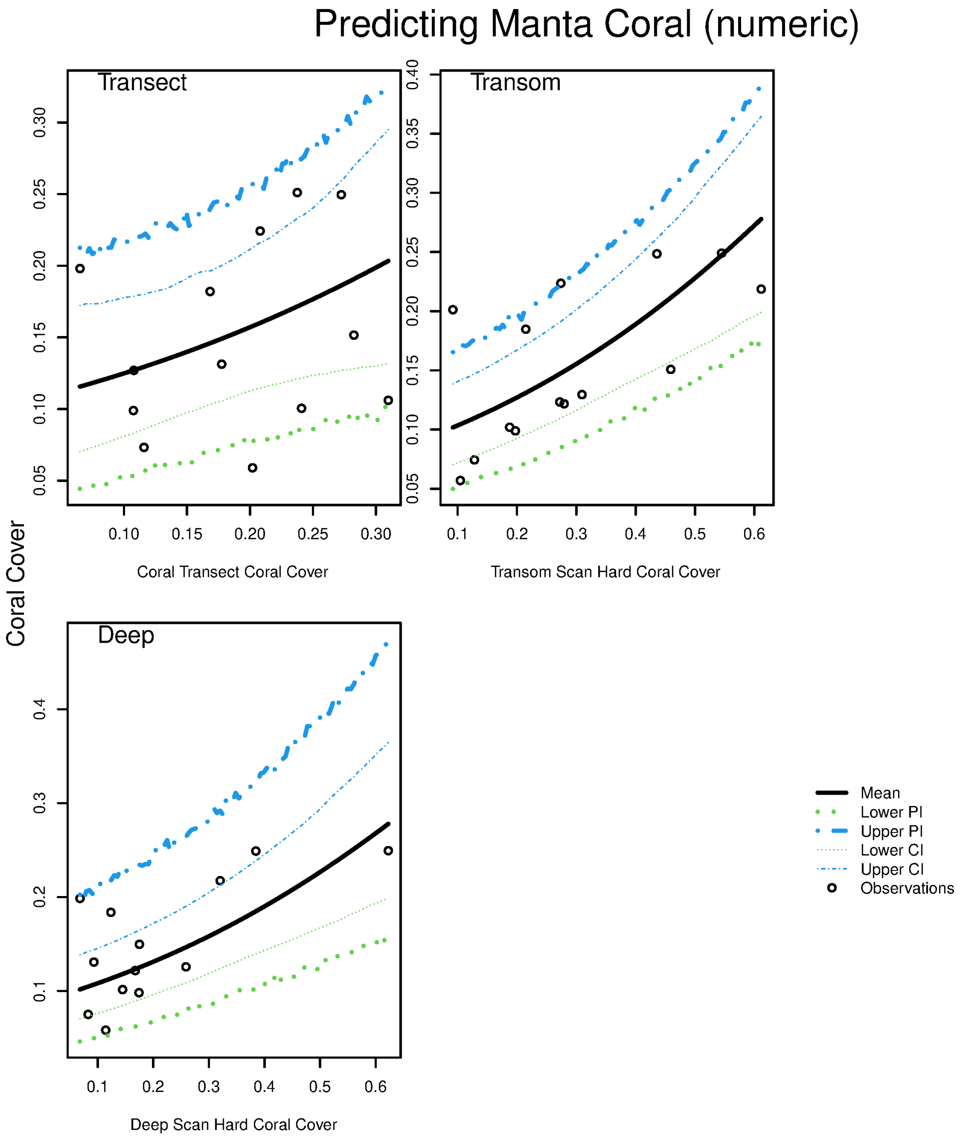

Figure C2. Predicting manta tow coral cover using coral transect (SALAD), ReefScan-Transom and ReefScan-Deep.

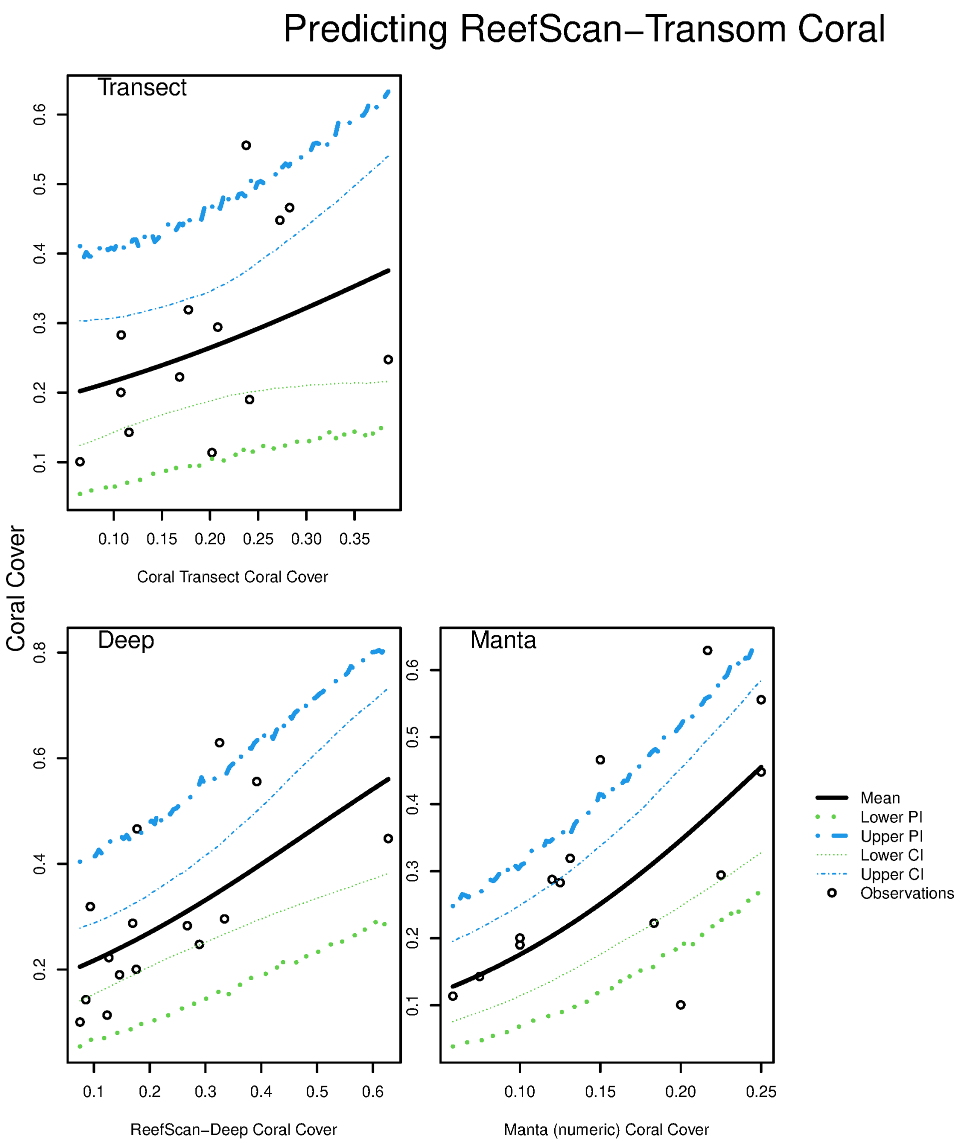

Figure C3. Predicting Reefscan-Transom coral cover using coral transect (SALAD), Reefscan-Deep and manta tow.

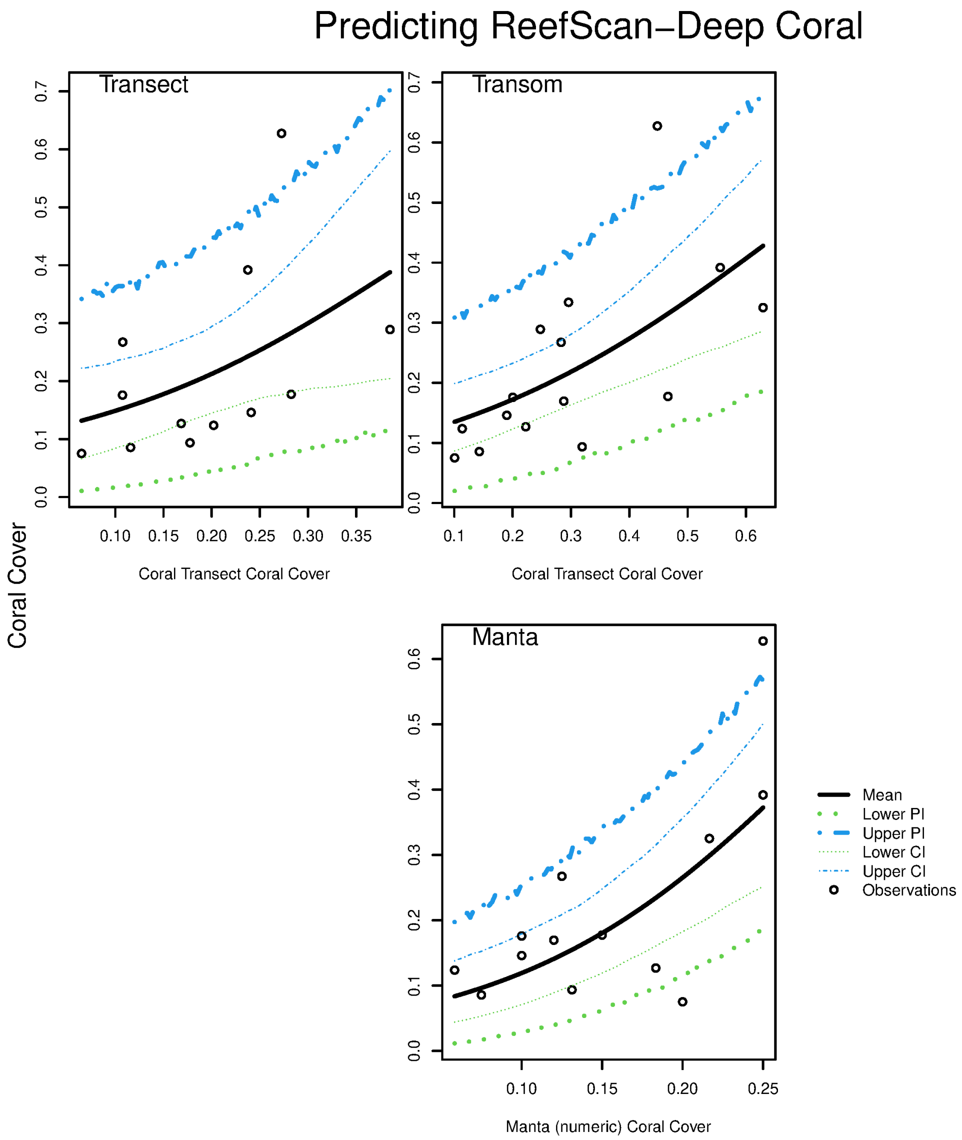

Figure C4. Predicting ReefScan-Deep coral cover using coral transect (SALAD), ReefScan-Transom and manta tow.

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

Australian Government | Reef Trust
Great Barrier Reef Foundation
Australian Institute of Marine Science
CSIRO
James Cook University Australia
The University of Queensland Australia