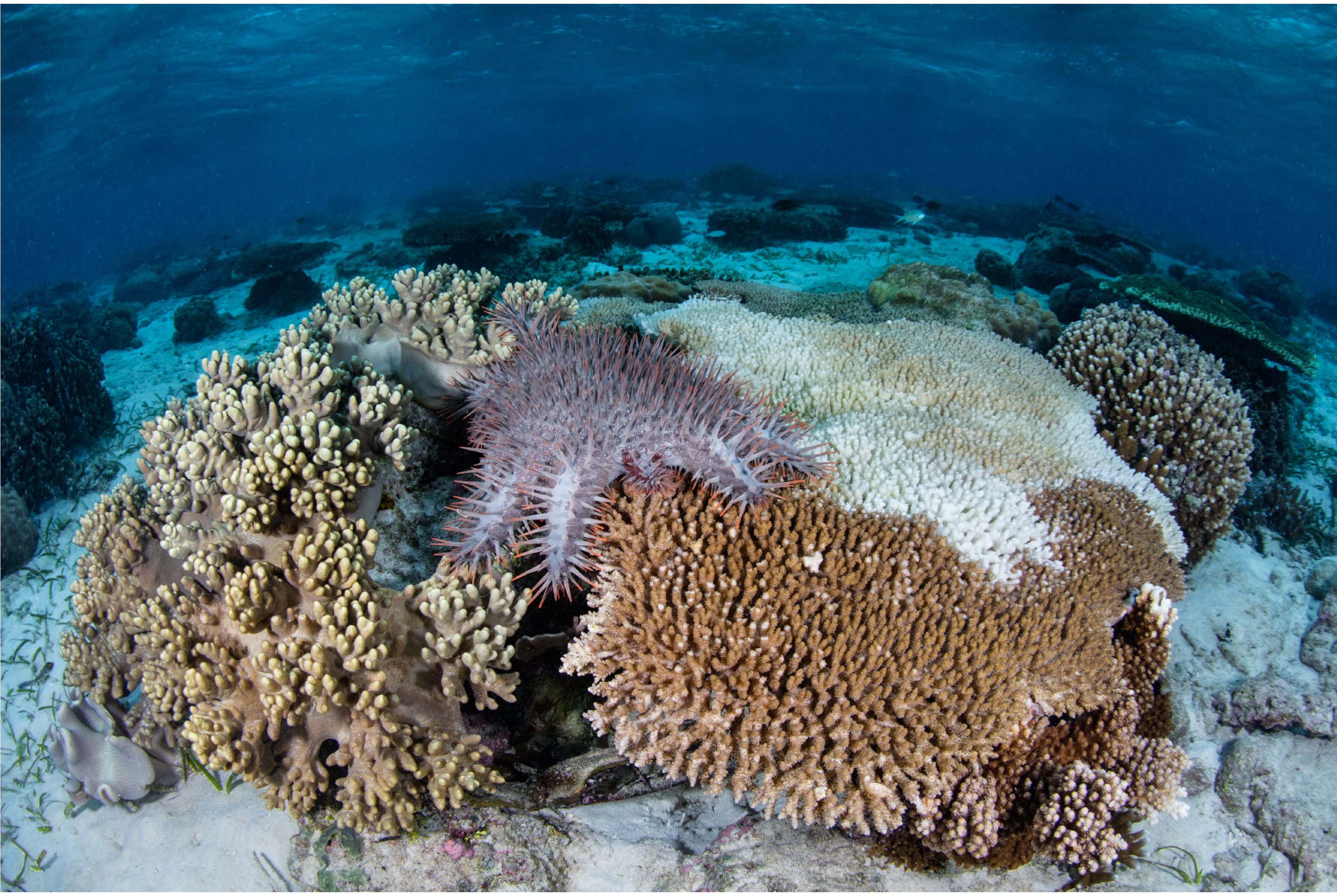
COTS Control Innovation Program

TECHNICAL REPORT

Crown-of-thorns starfish (COTS) monitoring and surveillance: sample designs for science and management decisions

Emma Lawrence, Scott Foster, Daniel Gladish, Sam Matthews, David Williamson, Sven Uthicke, Jason Doyle, Morgan Pratchett, Scott Bainbridge, Ali Armin, Joey Crosswell



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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

AI	Artificial Intelligence
AIMS	Australian Institute of Marine Science
BAS	Balanced Acceptance Sampling
BRUV	Baited Remote Underwater Video
CCIP	Crown-of-thorns starfish Control Innovation Program
CDOM	Coloured Dissolved Organic Matter
COTS	Crown-of-thorns starfish
CPUE	Catch-per-unit-effort
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CV	Coefficient of Variation
eDNA	Environmental DNA
ENSO	El-Niño Southern Oscillation
FNU	Formazin Nephelometric Units
GBR	Great Barrier Reef
GBRMP	Great Barrier Reef Marine Park
GBRMPA	Great Barrier Reef Marine Park Authority
GPS	Global Positioning System
HT	Horvitz-Thompson estimator
IMR	Integrated Monitoring and Reporting
IPM	Integrated Pest Management
JCU	James Cook University
LTMP	Long-term Monitoring Program
ML	Machine Learning
MMP	Marine Monitoring Program
NTU	Nephelometric Turbidity Units
PCR	Polymerase Chain Reaction
QDAF	Queensland Department of Agriculture and Fisheries
QPWS	Queensland Parks and Wildlife Service
Reef Authority	Great Barrier Reef Marine Park Authority
RHIS	Reef Health Information Survey
RIMReP	Reef 2050 Integrated Monitoring and Reporting Program
RJFMP	Reef Joint Field Management Program
RRAP	Reef Restoration and Adaption Program
RRRC	Reef and Rainforest Research Centre
SALAD	Scooter Assisted Large Area Diver survey
TO	Traditional Owner
TUMRA	Traditional Use of Marine Resources Agreements

UQ	University of Queensland
UVC	Underwater Video Camera
WQ	Water Quality

EXECUTIVE SUMMARY

Crown-of-thorns starfish (COTS) outbreaks are recognised as a leading cause of coral decline in the Great Barrier Reef Marine Park (GBRMP), with impacts that can act cumulatively with other stressors such as tropical cyclones, coral bleaching, and flooding events. Unlike other major causes of coral mortality, COTS outbreaks are amenable to direct management intervention. The COTS Control Program, established by the Great Barrier Reef Marine Park Authority in 2012, has demonstrated that systematic surveillance and well targeted manual culling can effectively suppress COTS outbreaks and protect coral from starfish predation across entire reefs and regions.

However, one of the greatest challenges facing COTS management is the vast scale and complexity of the Great Barrier Reef (GBR). With over 3,000 reefs spread across 344,440 km², baseline monitoring across the entire GBR is not feasible with current resources. To date, much of the data collected has been tactical in nature, focusing on surveillance at Target Reefs selected as high-priority for management intervention. While this approach has been pragmatic and effective for tactical decision-making, it risks biasing our understanding of COTS outbreak dynamics and limits the Program's capacity for strategic planning and comprehensive assessment of management effectiveness and outcomes.

Adaptive resilience-based ecosystem management requires both monitoring (systematic, long-term observation to track ecosystem health) and surveillance (active detection of specific threats requiring immediate intervention). The current COTS Control Program approach includes extensive surveillance but lacks the broad-scale, unbiased sampling design needed for comprehensive long-term monitoring. This limitation becomes critical when considering that COTS outbreaks have occurred across distinct waves spanning 15 to 20-year intervals since the 1960's, with recent research suggesting primary outbreaks may originate further North in the GBRMP than the previously postulated "initiation box" between Lizard Island and Cairns. Without systematic monitoring across the entire GBR, our understanding remains incomplete, potentially reducing the efficiency of resource allocation.

This report evaluates current monitoring and surveillance practices through analysis of the different monitoring purposes, simulation studies of sampling design options, assessment of existing tool performance and evaluation of emerging technologies.

The key findings are:

Current monitoring and surveillance approaches have significant limitations beyond day-to-day management. While current approaches effectively support tactical decision making on where to deploy culling effort, they do not provide adequate data to address strategic planning and assessment of management outcomes. Manta tow surveys are the primary surveillance method deployed in the COTS Control Program, yet they are well known to produce substantial underestimates of COTS numbers, and generate variable, and categorical, estimates of coral cover. Reef Health Impact Survey (RHIS) are used to augment the information on coral generated from manta tow surveys, however RHIS data typically show coefficients of variation exceeding 30% at most reefs, making the method unsuitable for reliable trend detection or strategic decision-making. Although significant resources are allocated to training and quality assurance within the COTS Control Program, manta tow and RHIS remain highly susceptible to observer biases and error in both COTS density and coral cover estimation.

Existing data collection focuses on Priority and Target Reefs, creating systematic bias. Priority reefs (approximately 500 reefs prioritised annually for potential management) and

Target reefs (200–250 highest priority reefs for active management) are selected based on outbreak risk, amongst other factors. Our simulation studies demonstrated that sampling only these management-selected reefs produce biased estimates of COTS densities and coral cover compared to true GBR-wide averages, limiting the Program's ability to assess its broader ecosystem impact.

Emerging monitoring technologies offer substantial improvements over current methods. Environmental DNA (eDNA) sampling can detect and quantify COTS presence at concentrations below visual survey detection limits, while emerging image-based data collection platforms and machine learning analytics technologies, such as ReefScan, promise semi-automated robust estimation of reef benthic cover, coral community composition and COTS detection. Scooter-assisted large area diver-based (SALAD) surveys provide detailed COTS size structure and can effectively estimate COTS at lower densities than manta tow. These emerging technologies address key limitations in current monitoring approaches.

Existing monitoring programs provide valuable but insufficient data for comprehensive COTS management assessment. Collectively, other existing GBR monitoring programs do not satisfy the full range of monitoring objectives required for comprehensive COTS management, necessitating a dedicated monitoring program specifically targeted to COTS Control Program objectives, operational needs and reporting requirements.

Environmental covariate collection could provide crucial insights into outbreak drivers. Systematic collection of water quality parameters such as temperature, salinity, chlorophyll-a, and nutrients at monitoring sites could advance understanding of COTS outbreak initiation and progression at relatively low additional cost, addressing critical knowledge gaps about outbreak causation and adding value to other water quality assessment programs.

We make the following recommendations:

Implement three distinct but complementary monitoring approaches: (1) continue routine surveillance at Priority/Target Reefs for tactical decisions, (2) introduce baseline monitoring for strategic planning and effectiveness assessment, and (3) introduce early warning monitoring at high-value reefs that are at high-risk of COTS outbreak.

Establish baseline monitoring using a spatially balanced cluster design to obtain unbiased estimates of COTS densities and coral status across the GBR. Contrary to initial expectations that monitoring the vast GBR would require enormous resources, our simulation studies demonstrate that 16–20 clusters of 3–4 reefs (60–80 reefs total) monitored annually can provide statistically robust trend data at the GBR level. The clustered approach minimises vessel travel costs and operational complexity while maintaining statistical rigour.

Integrate emerging technologies to enhance detection and assessment capabilities. Deploy eDNA sampling to detect low-density COTS populations that visual surveys miss, implement ReefScan technology for semi-automated coral cover assessment with concurrent COTS detection, and utilise SALAD surveys to provide detailed COTS size structure and coral-COTS relationship data not captured by current methods.

Discontinue RHIS surveys due to excessive variability in coral cover estimates and redirect this effort toward baseline monitoring and early warning activities. RHIS data variability makes it unsuitable for the strategic and tactical decisions it was intended to support.

Implement early warning monitoring at strategically selected high-value and high-risk reefs using eDNA and SALAD surveys to detect emerging outbreaks before they reach damaging densities. Data from early warning monitoring should be analysed separately from baseline monitoring due to inherent spatial bias in site selection.

Collect environmental covariates at baseline monitoring sites focusing on low-cost, high-value parameters to support research into outbreak drivers, improve predictive modelling of outbreak risk and value-add to other water quality monitoring programs.

Adopt adaptive management for resource allocation between monitoring and culling while maintaining the minimum baseline monitoring program. During periods of lower regional outbreak activity, monitoring emphasis can be increased, with rapid resource shifts toward culling when early warning signs are detected.

Implementation of these recommendations will significantly improve the COTS Control Program's ability to effectively detect, monitor, and respond to outbreaks across the entire GBR. The proposed integrated approach will enhance early detection capabilities, provide comprehensive data for strategic decision-making, enable robust assessment of management effectiveness, and advance scientific understanding of outbreak dynamics. This improved monitoring framework will support more effective protection of coral across the GBR, benefiting Traditional Owners, the tourism industry, and the broader community through enhanced reef resilience and ecosystem health.

1. INTRODUCTION

1.1. Background and context

Crown-of-thorns starfish (COTS) outbreaks are recognised as a leading cause of coral decline in the Great Barrier Reef Marine Park (GBRMP) over the past 40 years, as noted in the Great Barrier Reef Outlook Report 2024 (Great Barrier Reef Marine Park Authority 2024b). The impacts of these outbreaks compound with other stressors such as tropical cyclones, coral bleaching, disease outbreaks, and flooding events. COTS may also kill corals that survive bleaching, potentially removing these resilient genetic variants from the reef ecosystem. Unlike other major causes of coral mortality, COTS outbreaks are amenable to direct management intervention.

Strategic manual culling of COTS has proven to be an effective management action for protecting high-value reefs in the short to medium term (Fletcher et al. 2021; Matthews et al. 2024). The COTS Control Program was established in 2012 and delivers the tactical response to outbreaks as part of the Reef Authority's COTS Strategic Management Framework. Since November 2018, the Reef Authority has implemented an Integrated Pest Management (IPM) decision support framework to guide the COTS Control Program across the GBR. This scientific approach has revolutionised pest management strategies, delivering a more strategic and effective Control Program that surpasses previous efforts both on the Great Barrier Reef (GBR) and internationally. Both the Reef 2050 Long-Term Sustainability Plan (Great Barrier Reef Marine Park Authority 2015) and the Reef Authority's Blueprint for Resilience (Great Barrier Reef Marine Park Authority 2024a) identify COTS control as a key long-term investment priority.

Effective ecosystem management, such as COTS control, relies on two complementary processes: monitoring and surveillance. Monitoring involves systematic, long-term observation and data collection to track changes in ecosystem health over time. Surveillance, on the other hand, focuses on the active detection of specific threats or changes that require immediate attention or intervention. In the context of the GBRMP, both monitoring and surveillance of COTS densities and coral cover are fundamental to understanding the health and function of the GBR providing the foundation for management decisions, guiding management actions, and assessing the efficacy of those actions. Long-term monitoring is critical for tracking coral cover trajectories, understanding ecosystem resilience patterns, assessing the effectiveness of management interventions over time, and providing baseline data for predictive modelling of future outbreak cycles. Surveillance activities are essential for early detection of emerging COTS outbreaks before they reach damaging threshold levels, enabling rapid response deployment to priority reefs, and providing real-time information to guide immediate tactical control operations.

1.2. Current approaches and limitations

One of the greatest challenges of a COTS monitoring program is the vast scale and complexity of the GBR. With over 3,000 reefs spread across 344,440 km², it is not feasible to monitor all reefs over the short time periods necessary to predict, detect, and suppress COTS outbreaks at the individual reef scale, given current resources.

To date, much of the data collected by the COTS Control Program has been tactical in nature, primarily being for surveillance rather than long-term monitoring. This surveillance-focused approach has been essential for guiding immediate control efforts and making real-time decisions about where to deploy resources. The program routinely returns to specific reefs to assess changes in COTS populations and coral cover, using this information to determine whether to initiate, continue, or cease control efforts (Fletcher et al. 2020). However, these reefs are selected based on their immediate relevance to control operations, such as high COTS outbreak risk or economic importance, rather than their suitability as representative baseline monitoring sites.

While prioritising reefs for COTS control based primarily on surveillance data has been a pragmatic approach given limited resources, it risks biasing our understanding of where and why COTS outbreaks initiate and spread (Boyd et al. 2023), if complementary monitoring data is not also collected at a wider sample of reefs. This limitation becomes apparent when we consider the historical patterns of COTS outbreaks. Since the 1960s, there have been four distinct episodes (or waves) of COTS outbreaks on the GBR, occurring at 15 to 20 year intervals (e.g. Pratchett et al. 2014). Traditionally, these outbreaks were thought to originate in what was termed the "initiation box" - an area of the Northern mid-shelf reefs between Lizard Island (14.6°S) and Cairns (17°S) (e.g. Fabricius et al. 2010). However, more recent research challenges this assumption. Vanhatalo et al. (2016) demonstrated that during population irruptions in the early 1990s, elevated densities of adult COTS were apparent in the far northern GBR (around 12°S latitude) up to two years before population irruptions were detected near Lizard Island. This finding suggests that outbreaks may originate further north than previously believed, with the "initiation box" potentially representing a secondary accumulation point for COTS larvae (see also Pratchett et al. 2014; Pratchett et al. 2025). Recent monitoring in the Far North provides further support for this hypothesis (Chandler et al. 2023; Emslie et al. 2024).These findings underscore the need for comprehensive COTS monitoring throughout the entire GBR, not just on reefs directly under surveillance by the COTS Control Program. Without such broad-scale monitoring data, our understanding of COTS populations and outbreak dynamics will continue to be a major gap and perpetuate a cycle of reactive rather than proactive outbreak management.

While the COTS Control Program also makes use of data collected by other monitoring and surveillance programs in the GBRMP (e.g. Australian Institute of Marine Science (AIMS) Long-Term Monitoring Program (LTMP), the Reef Joint Field Management Program's (RJFMP) COTS Response project, the Eye on the Reef Program), these data do not currently provide the required resolution of COTS and coral measurements, nor do they provide the spatial extent that is needed for COTS monitoring. Without systematic, ongoing monitoring data, managers cannot effectively measure the extent to which control interventions are working, efficiently identify emerging outbreak patterns before they become severe, or adapt strategies in response to changing environmental conditions across the reef. While the current COTS Control Program approach (using data from a combination of monitoring and surveillance programs) has been effective for tactical decision-making, it lacks the systematic, unbiased sampling design ideal for a comprehensive, long-term monitoring program. Moreover, current survey methods have limited utility for measuring COTS at low densities and smaller size classes (MacNeil et al. 2016). The absence of dedicated monitoring limits our ability to become more targeted and adaptive in management responses, a critical capability as environmental change and cumulative impacts across the reef become more prevalent. A dedicated monitoring program would enable evidence-based evaluation of intervention effectiveness, early detection of outbreak precursors, and strategic allocation of limited management resources to maximise conservation outcomes. Westcott et al. (2021) provide further evidence of the need for a dedicated monitoring program and recommendations on its essential characteristics.

1.3. Designing a comprehensive monitoring program

This report focuses on the design of a comprehensive monitoring program, which could be integrated with current surveillance and monitoring activities to enhance the COTS Control Program's capacity for both tactical and strategic decision-making, ensuring the effective and efficient protection of coral throughout the GBRMP. Designing an effective ecological monitoring program requires addressing three key components: setting clear objectives, selecting appropriate locations for monitoring, and choosing the right tools and methods to measure relevant ecological variables.

Establishing clear objectives will be the foundation for any successful monitoring program. These objectives, as outlined by Gitzen and Millspaugh (2012), should be specific, practical, and aligned with real-life decisions about managing resources and policies (Lindenmayer & Likens 2010). In the context of COTS management, seeking input from diverse stakeholders - including those from management, scientific, and societal spheres - will ensure that the monitoring data collected can effectively answer important questions (Lindenmayer 2018). For the COTS Control Program, the primary interest lies in understanding spatio-temporal variation in COTS population density and coral cover to inform both strategic and tactical decision-making.

Location selection will play a critical role in shaping the monitoring program's scientific quality, cost-efficiency, and logistical feasibility. Ideally, locations should be chosen to provide unbiased estimates of coral cover and COTS densities, while maximising the information obtained from each survey with minimal effort. However, the remoteness of some locations can significantly affect both the cost and practicality of monitoring, limiting the ability to replicate data or cover a wide spatial footprint. Balancing these logistical challenges with the scientific need for comprehensive data is essential to ensure the program's effectiveness and efficiency.

The success of the monitoring program will be closely tied to the tools and techniques available for data collection. While the current COTS Control Program relies on established methods such as manta tows and catch-per-unit-effort (CPUE) from cull divers, more modern and potentially more accurate techniques are emerging. These include environmental DNA (eDNA) (Uthicke et al. 2018; Uthicke et al. 2022; Uthicke et al. 2024), Scooter-Assisted Large Area Diver-based (SALAD) surveys (Chandler et al. 2023), and ReefScan technology with machine learning (ML) algorithms (Bainbridge and Coleman 2024; Bainbridge et al. 2025). The choice of tools will depend largely on the spatial scale and objectives of the monitoring program, as different tools may be better suited for monitoring individual sites versus large reef areas. The trade-offs in accuracy and precision must also be carefully considered when selecting methods, particularly as the scale of the program increases (Westcott et al. 2021). In addition to monitoring COTS, assessing coral cover at multiple spatial scales remains critical for informed decision-making and outcome evaluation in the COTS Control Program.

1.4. Project aims and objectives

It is important that monitoring programs are designed and implemented in such a way that the resulting data are:

- appropriate for the research question under consideration;
- representative of the population under investigation;

- information rich so that uncertainty around inferences is reduced as much as survey budgets will allow (Foster et al. 2020);
- reusable for new and emerging research questions and management needs; and
- comparable with existing legacy data.

The focus for this COTS Control Innovation Program (CCIP) project (*D-01 COTS monitoring design)* was to develop a comprehensive monitoring design strategy that will help ensure the COTS monitoring program delivers data with these characteristics. The *D-01 COTS monitoring design* project forms an integral part of the CCIP Detection Subprogram and has worked closely with *D-02 Tool comparis*on (Lawrence et al. 2025), *D-03 Operationalising eDNA monitoring* (Uthicke et al. 2025), *D-04 The COTS surveillance system* (Bainbridge et al. 2025) and *P-04 Pre-outbreak monitoring* (Pratchett et al. 2025) to ensure the monitoring design is based on the most recent research in COTS and coral monitoring (**Figure 1**). Part of the project was a simulation exercise that was heavily reliant on model outputs generated from *R-04 Regional Modelling* (Skinner et al. 2025). The project aims to identify gaps in the available data to address the information and data needs of the COTS Control Program and the best mechanisms to collect the information in the future (both sample design and monitoring tool/s), improving the data available for decision making and innovation in COTS detection and monitoring. These innovations will lead to improved detection and monitoring of COTS and coral across the GBR.

Specifically, the project's aims were to:

- Clearly articulate the objectives of the COTS monitoring and surveillance to be conducted through the COTS Control Program.
- Evaluate the effectiveness of different monitoring designs using simulations.
- Assess the ability of the available monitoring tools to collect data to answer the stated objectives.
- Synthesise the relative costs and benefits of undertaking monitoring of parameters that fill gaps in knowledge of COTS, coral and COTS outbreak drivers.
- Provide recommendations on monitoring designs for future implementation.

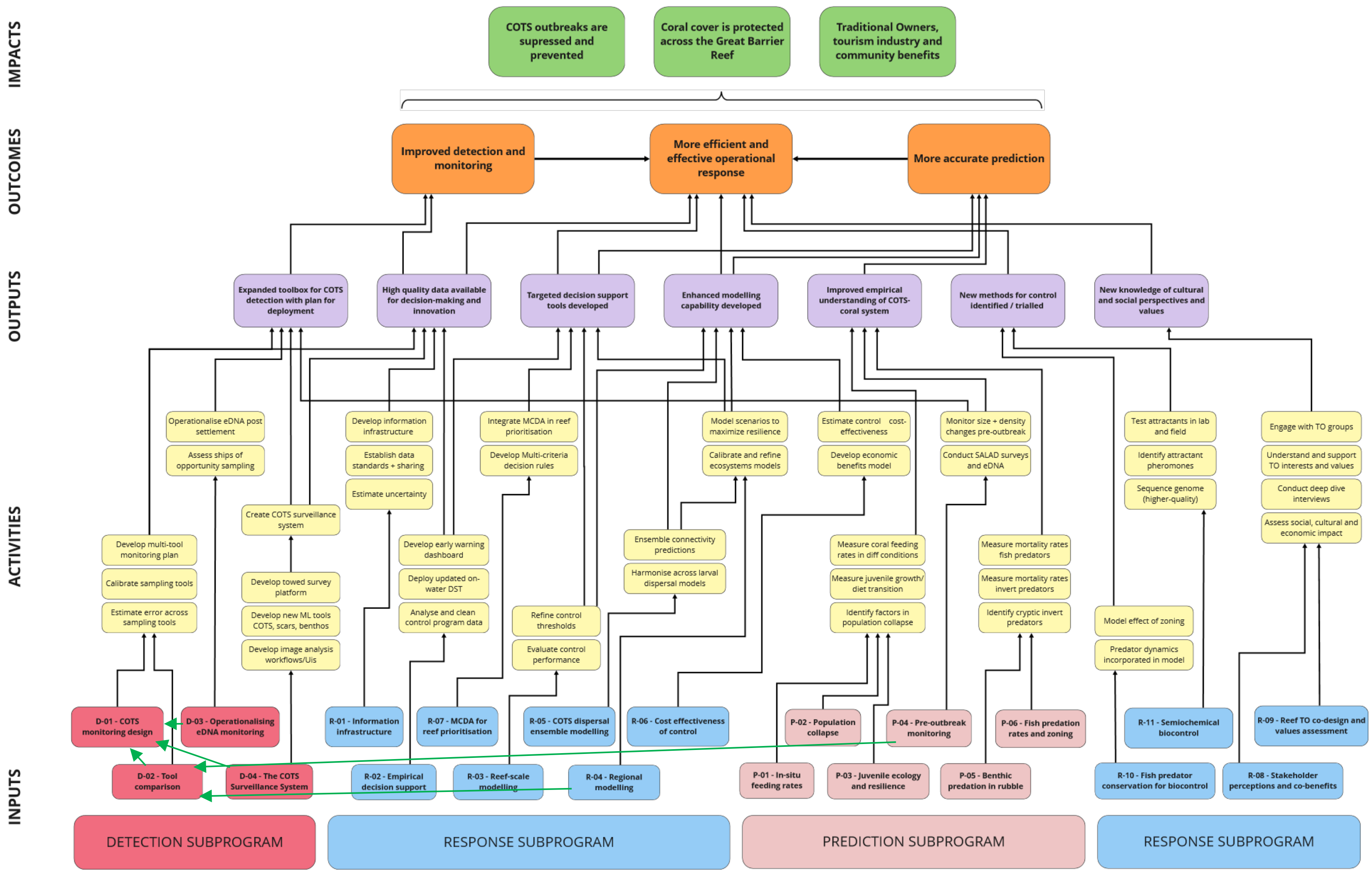

Figure 1. CCIP Program Logic. The linkages with other CCIP projects are shown using green arrows.

2. METHODS

2.1. Monitoring and surveillance information and data needs

Being clear about the monitoring purposes and information needs is the foundational step in designing an effective monitoring program. This process requires consideration of the data needs of a diverse range of stakeholders, including those from management, scientific, and cultural sectors, who rely on monitoring and surveillance data to address critical questions.

To begin the process of setting the monitoring purposes, we held a one-day workshop attended in person by 24 participants and five attended remotely. There were representatives from the Great Barrier Reef Marine Park Authority (Reef Authority), Great Barrier Reef Foundation (GBRF), Commonwealth Scientific Industrial Research Organisation (CSIRO), Australian Institute of Marine Science (AIMS), James Cook University (JCU), Reef and Rainforest Research Centre (RRRC), Queensland Parks and Wildlife Service (QPWS), University of Queensland (UQ) and members from three Traditional Use of Marine Resources Agreements (TUMRA) Committees (**Figure 2**).

Figure 2. Group photo of workshop participants.

The workshop participants were asked to come up with a list of priority management and science questions that rely on monitoring and surveillance data to answer. To inform the monitoring program design, the group engaged in a structured discussion process, grouping the questions into overarching purposes to meet the data collection needs of Day-to-day management, Strategic planning, Outcomes of management and Science and Knowledge gaps (defined in **Appendix A**). In addition, we reviewed the Integrated Pest Management (IPM) decision framework (Fletcher et al. 2020) and the COTS Strategic Management Framework (Great Barrier Reef Marine Park Authority 2020) to identify any additional formal requirements for monitoring data that might not have been captured by the project team or the workshop participants.

A monitoring program that incorporates numerous competing objectives is unlikely to succeed (Lindenmayer 2018). However, in the case of the COTS Control Program, it is impossible to reach a single objective for the monitoring program. While this might seem like the COTS monitoring program is therefore unlikely to be successful, when we identified the specific variables needed to address each monitoring purpose, there was a large degree of overlap in the measurement variables. We collaborated with COTS Control Program managers to prioritise the long list of questions, assigning each a ranking from 1 (high priority) to 4 (low priority). This systematic approach ensures that the most critical objectives guide the monitoring program effectively.

2.2. Existing monitoring and surveillance programs

The COTS Control Program primarily collects tactical surveillance data to guide immediate control efforts. While the program regularly revisits reefs to assess COTS populations and coral cover for operational decisions, these reefs are chosen for their control relevance (e.g. risk of COTS outbreak, ecological significance) rather than as representative monitoring locations (Fletcher et al. 2020). The Program currently relies on data collected by manta tow for broad scale COTS surveillance and coral cover estimates (Miller et al. 2009), and COTS Control Program divers for finer scale measurement of COTS densities that are estimated during cull dives (Fletcher and Westcott 2016).

There are several other established monitoring and surveillance programs in the GBR that also collect COTS and/or coral data, each with different objectives and often different monitoring tools and/or methods or deployment. We reviewed the main relevant programs to gain an understanding of the purpose, methods, and spatial and temporal scales across which they collect data, to make use of any relevant data in the design of the future COTS monitoring program and avoid creating a further standalone monitoring program with no complementarity to existing programs. These programs are summarised in **Appendix B**.

The most directly applicable monitoring and surveillance programs (where the data is directly used in the existing COTS Control Program) are the AIMS LTMP and the Reef Joint Field Management Program (RJFMP) COTS Response.

The AIMS LTMP is an established long-term monitoring program dating back to the mid-1980s. It provides data both at reef and within reef scale on COTS, coral and fish. It is designed to detect changes in reef communities at a subregional scale, including inshore, mid-shelf and outer shelf reefs (Australian Institute of Marine Science 2022). Between 80 and 130 reefs are monitored using manta tow and diver surveys annually as part of the program. Among other purposes, these data are used to inform reef prioritisation in the COTS Control Program.

The RJFMP spend approximately 60 field days each year undertaking both Reef Health Information Survey (RHIS) (Beeden et al. 2014) and manta tow surveys that provide valuable surveillance data to the COTS Control Program. The RHIS measurement protocol records quantitative and qualitative information about the reef at a site within a circular area of 5 m radius (78.5m^2), with each site taking approximately 20 minutes to survey. These surveys provide good spatial coverage, building our knowledge of COTS and their impact on the Reef, but do not include long-term fixed site monitoring.

Many of the monitoring questions that were identified in the early stages of the project require coral measurements at reefs being managed by the COTS Control Program. Many of these questions fall under a group we could summarise as “Measuring the outcomes of COTS management” e.g. what is the trend in coral cover at COTS management sites and what is the coral loss due to COTS? Matthews et al. (2024) recently demonstrated how the AIMS LTMP data can contribute to answering such questions in their analysis, where the data was used to show that targeted and sustained COTS management can effectively suppress outbreaks and promote coral growth at both reef and sector-wide scales. No such (published) analysis has been conducted with the RHIS data in the context of the COTS Control Program using the survey technique as it is currently deployed, although Westcott et al. (2020) conducted a site scale analysis using RHIS fixed site data. Mellin et al. (2020) assessed how RHIS data can complement data from long-term monitoring programs such as LTMP and reported the high-level of observer variance as a concern.

In recent years the RHIS have been deployed in a more formal manner in the COTS Control Program and so we conducted an analysis based on the most recent data available (i.e. data collected after the Mellin et al. (2020) publication), to determine the utility of the RHIS data in answering some of the COTS Control Program primary monitoring objectives. RHIS data are collected through several programs across the GBR, including through the RJFMP COTS Response Project, the Eye on the Reef program and the COTS Control Program itself, although the survey method is deployed in different ways depending on the program.

The two ways that RHIS are deployed in the context of the Control Program are the ‘Surveillance RHIS’ (repeated surveys at permanent GPS marked sites around the perimeter of a reef, conducted roughly twice a year) which was initiated in October 2021 and the ‘Cull Site RHIS’ (repeated surveys at permanent GPS sites within cull sites intended to monitor the decline/recovery of coral during and after culling visits). We examined these two datasets separately with a view to better understand how these surveys perform in terms of estimating coral cover and their statistical power to detect change. At the time of analysis, the available data spanned approximately 2 years starting October 2021. Linear trends were fitted to coral cover data for each reef to assess variability and temporal changes. The main analysis was restricted to reefs with sufficient data coverage (minimum 25 records for surveillance sites, 20 records for cull sites). Coefficients of variation (CV) were calculated as the ratio of standard deviation to mean coral cover, with values above 30% considered indicative of high variability. Statistical power analysis was conducted using square-root transformed coral cover data with a two-sample, two-sided t-test (power = 0.8, significance level = 0.05). Sample size requirements were calculated for detecting relative changes of 20% and 50% in mean coral cover, as well as absolute changes of 5%. For reefs with repeated surveys, the median standard deviation was used as the pooled standard deviation estimate (**Appendix C**).

2.3. Monitoring tools

The tools considered for monitoring COTS and coral in this project are described briefly below. We provide a more comprehensive description and review in *CCIP-D-02 Tool Comparison* (Lawrence et al. 2025). The first three are tools that are currently used operationally in the COTS Control Program, whereas the second three are tools that are being developed as part of CCIP:

- Manta tow: Manta tow is the standard surveillance technique used in the COTS Control Program (Miller et al. 2018). It involves towing a snorkel diver behind a tender at a constant speed. The diver, holding onto a 'manta board' attached by a rope, makes visual assessments during two-minute tows, each covering a transect length of about 200 m. The method assumes a transect width of 10 m, and the actual transect length is tracked using GPS, enabling accurate calculation of the surveyed area (approximately 0.2 ha per transect) and estimation of COTS density. This standardised methodology provides the COTS Control Program with rapid, broad-scale data on COTS abundance (counts and scar categories (used as a proxy for COTS presence)), coral cover categories, and enables efficient identification of outbreak locations requiring intervention. Multiple transects are typically conducted per cull site (following the reef perimeter) to ensure comprehensive coverage, making manta tow an essential tool for both initial surveillance and monitoring the effectiveness of control efforts across large reef areas.

- Cull dives: Culling surveys are a byproduct of COTS Control dives and are used to estimate COTS density and size distributions (Fletcher et al. 2020). This method involves 6–8 trained divers systematically searching defined cull sites of approximately 10 hectares (typically 200 x 500 m areas), lethally injecting sighted COTS while recording detailed data on the number and size of COTS culled and time spent searching. The data collected enables calculation of CPUE (COTS per minute bottom dive time), which serves as a standardised metric for estimating COTS density across different sites and time periods. This labour and resource-intensive method provides the COTS Control Program with dual benefits: actively removing COTS populations while simultaneously generating high-quality COTS CPUE estimates and size distribution data that inform population dynamics and control effectiveness. The method offers relatively high detection accuracy compared to visual surveys alone, though it is constrained by limited dive hours, requires specialised training for safe and effective COTS injection, and does not collect coral cover data. The CPUE data from cull dives is particularly valuable for assessing the success of control interventions and guiding adaptive management strategies within the program.

- RHIS: RHIS is a standardised underwater visual survey method that has been formally integrated into the COTS Control Program since October 2021. This method involves trained divers conducting detailed assessments within circular survey areas (5 m radius, approximately 78.5 m²) to record coral cover, COTS abundance, and reef health indicators including bleaching, disease, predation and physical damage. Within the Control Program, RHIS is deployed in two ways: 'Surveillance RHIS' conducted around reef perimeters at GPS-marked sites approximately twice per year to monitor broad-scale reef health, and 'Cull Site RHIS' involving repeated surveys at permanent sites within cull areas to track coral recovery following COTS removal operations.

- Scooter-Assisted Large Area Diver-based (SALAD) Surveys: SALAD surveys use Yamaha® Sea scooters (Chandler et al. 2023). Divers work in pairs, each covering approximately 1 km transects within a 5 m wide belt (totalling ~1 hectare per survey) to systematically search for and record COTS, feeding scars, and GPS locations. SALAD surveys also incorporate coral transects conducted at the start and end of each dive using 50 m tape measures to record coral genera and benthic composition every 50 cm, providing habitat context for COTS observations. This method provides the COTS Control Program with comprehensive data on COTS abundance, size distribution, feeding impact, and precise GPS locations across large reef areas, enabling detection of emerging outbreaks and assessment of habitat suitability for COTS populations.

- COTS Surveillance System Monitoring (ReefScan): ReefScan represents a modernisation of COTS surveying using remotely operated underwater camera systems analysed with machine learning (ML) models to identify COTS and assess coral cover. The system operates using two platform types: ReefScan-Transom, a camera system mounted on the transom of a tender vessel that scans shallow reef areas, and ReefScan-Deep, which is towed at controlled depths for stable imaging with continuous coverage along transects approximately 8 m wide. Both platforms incorporate GPS tracking to measure transect length, enabling calculation of COTS density estimates and coral cover assessment across surveyed areas. Image data is processed using ML models that can determine coral cover, with the goal of eventually replacing manta tow surveys for broad-scale reef monitoring. This method provides the COTS Control Program with automated, consistent analysis that reduces human bias, creates a permanent visual record, and enables either continuous monitoring or targeted transect surveys. The technology offers significant advantages in reducing observer fatigue and standardising data collection, though it remains limited to visible surface features and its accuracy depends on ML model training. While ML models for COTS and COTS scar detection are under development, they were not yet deemed reliable for operational use at the time of recent trials (Lawrence et al. 2025), indicating the technology is still in the development phase for full COTS surveillance implementation.

- Environmental DNA (eDNA): eDNA surveillance involves analysing water samples for COTS genetic material via digital droplet PCR (Uthicke et al. 2018; Uthicke et al. 2022). Multiple samples are taken at each site, with samples measured for copy numbers of mitochondrial COTS eDNA. The method provides metrics including the proportion of samples containing detectable levels of COTS eDNA and the concentration of COTS eDNA copy numbers, which can indicate relative COTS abundance in the surveyed area. This approach offers significant advantages for the COTS Control Program by enabling detection of low COTS densities, including cryptic and juvenile individuals that may be missed by visual survey methods, while being completely non-invasive and suitable for deployment in areas with poor visibility or high dive risk. This method is described in detail in project *CCIP-D-03 Operationalising eDNA monitoring* (Uthicke et al. 2025).

2.3.1. Monitoring tool comparison

Selecting the appropriate monitoring tools for collecting data that aligns best with the objectives of the COTS Control Program requires a comprehensive comparison of the attributes of each tool and assessment of their relative errors. *CCIP-D-02 Tool Comparison* (Lawrence et al. 2025) provides both a qualitative and quantitative comparison of the tools described above. We defer the reader to that companion report for the methods used.

In addition to the tools compared in CCIP-D-02 (Lawrence et al. 2025), throughout this report we also consider the utility of RHIS (described earlier) as a method in the COTS monitoring program.

2.4. Monitoring potential environmental outbreak drivers

In addition to core monitoring of COTS and coral populations, monitoring other environmental factors has potential to shed light on what causes COTS outbreaks. Despite research on potential environmental factors that initiate or exacerbate outbreaks (e.g. Fabricius et al. 2010; Wooldridge & Brodie 2015), there is currently a lack of clear evidence or consensus among experts about which factors are likely to be most important in driving outbreaks (Caballes et al. 2024) and this is unlikely to be resolved without the collection of monitoring data that is fit for purpose. In the absence of clear evidence or consensus regarding the key environmental drivers, ideally, we would monitor as many of the candidate drivers as possible while simultaneously monitoring COTS and coral demography.

Existing environmental datasets often lack the spatial resolution, temporal frequency, or duration needed to detect relationships with COTS population dynamics, particularly given the multi-year lag times between environmental conditions and observable outbreaks. Many available datasets are collected at broad regional scales rather than at the reef-specific level where COTS populations are monitored, creating spatial mismatches that limit analytical power. Furthermore, most environmental monitoring programs were not designed with COTS research objectives in mind, resulting in parameters that may not capture the specific environmental conditions most relevant to larval survival, settlement, and juvenile recruitment processes that drive outbreak dynamics. We consulted various experts in the field of COTS outbreaks to assess the data that would be needed to answer such questions and the feasibility of collecting such data.

2.5. Collecting data to meet monitoring objectives

Monitoring design refers to the strategic decisions about which reefs to monitor, how often to monitor them, and using which monitoring tools. This involves balancing statistical rigour (to ensure data is representative and unbiased) with practical constraints like cost, logistics, and available resources. The effectiveness of any monitoring program depends on both the tools used to collect data and the design strategy that determines where and when those tools are deployed. Different combinations of tools and sampling strategies will have different strengths for answering specific management questions. To evaluate how different approaches might enhance the COTS Control Program's ability to meet its monitoring objectives, we considered various scenarios that represent incremental changes to current practices. These scenarios range from minimal changes to current operations through to more comprehensive monitoring approaches that incorporate new technologies, expanded spatial coverage and formal statistical design. By systematically analysing these variations, we aimed to refine the monitoring strategy to ensure it is both efficient and effective in achieving its goals.

The scenarios rely on a key distinction between 'surveillance' (conducted at reefs selected for immediate management intervention) and 'baseline' monitoring (statistically designed monitoring across representative reefs to provide unbiased GBR-wide estimates). While surveillance supports tactical decisions, baseline monitoring is essential for strategic planning, measuring management outcomes, and answering scientific questions that require generalisable results.

Specifically, we considered the following scenarios:

1. *Routine (cull dives and manta tow)*: This is the bare minimum for the Control Program and is less than what is currently delivered through program operations. It involves manta tows around the entire perimeter of a reef before and at regular intervals during culling, as well as six months post-culling. Cull dives are undertaken at 10-hectare sites when manta tows have detected a COTS or a COTS feeding scar. Cull dives continue until an ecological threshold is reached, focusing on cull sites within reefs that have higher COTS numbers and coral cover as first priority.

2. *Control Program (cull dives, manta tow and some RHIS)*: This is the current standard approach and includes manta tows before culling, at regular intervals during culling, and six months post-culling. Cull dives are undertaken at any sites where manta tow detects a COTS or a COTS scar. RHIS surveys are conducted at the start of culling on sites within target reefs that have a high initial COTS CPUE (>0.08), repeated approximately every three months until culling is complete. A final RHIS survey is conducted once a cull site is "closed”.

3. *Control Program + LTMP*: Building on the Control Program data, this adds the benefits of the LTMP – both the reef wide manta tow and the fixed transects - to the current COTS Control Program. The data collected through LTMP complements the routine data gathered by the COTS Control Program, enhancing the overall monitoring efforts.

4. *Control Program + LTMP + RJFMP*: Building on the previous strategy, this approach incorporates additional manta tow surveillance from the RJFMP. This added surveillance runs alongside the current COTS Control Program data, extending and enhancing the data available for monitoring and decision-making. **This is the extent of the data currently available to the COTS Control Program.**

5. *Routine + LTMP + extra baseline manta tow*: This approach continues routine reef and cull site monitoring and surveillance via manta tow and cull dives, and collects extra COTS and coral data by deploying manta tow at extra baseline reefs using a spatially balanced sample design. It could also reallocate some RJFMP effort to cover these extra baseline sites.

6. *Routine + eDNA surveillance*: This monitoring approach integrates eDNA surveillance at specific sites. For some objectives this may be at COTS Control Program Target reefs and for others it may be at proposed baseline monitoring reefs using a statistical design. While we would presume LTMP would continue, it has not been included in this scenario to demonstrate differentiation of adding eDNA to Routine monitoring alone.

7. *Routine + SALAD surveys*: Incorporate SALAD survey monitoring at some reefs. For some objectives this may be at COTS Control Program Target reefs and for others it may be at proposed baseline monitoring reefs using a statistical design. While we would presume LTMP would continue, it has not been included in this scenario to demonstrate differentiation of adding SALAD surveys to Routine monitoring alone.

8. *Routine + ReefScan + extra baseline ReefScan*: Replace routine reef and cull site monitoring via manta tow with towed underwater video (following adequate or continued side by side calibration period). Collect COTS and coral data at extra baseline reefs selected using a spatially balanced sample design (method/s). While we would presume

LTMP would continue, it has not been included in this scenario to demonstrate differentiation to Routine monitoring alone.

9. *Routine + baseline + environmental covariates*: Continue to use the routine reef and cull site monitoring via manta tow and cull dive surveys. Collect COTS and coral data at extra baseline reefs selected using a spatially balanced sample design (manta tow + ReefScan). Collect environmental covariate data at least at baseline reefs (particularly water quality (WQ) parameters).

We considered the ability of each monitoring scenario to collect the data to answer each monitoring objective. We also scored the ability of each scenario to meet each objective (fully meets = 1, almost meets = 0.7, partially meets = 0.4 and doesn't meet = 0). We then sum the scores for each monitoring scenario to determine their overall ability to meet the COTS and coral monitoring objectives.

2.6. Monitoring design evaluation for baseline monitoring

One of the most challenging aspects of designing the monitoring and surveillance program is arriving at a design that will continue to meet the tactical day-to-day operational surveillance needs of the COTS Control Program, while also increasing the monitoring data on COTS and coral at a broader scale to inform strategic decision making. Prioritising information collected at fine spatial and temporal scales, which is useful for tactical management decisions, will come at the expense of collecting data to assess trends at broader spatial and temporal scales, which is useful for strategic decisions.

The 'routine' COTS Control Program surveillance operations are conducted at reefs selected as a priority for management intervention. The surveillance includes manta tows before, during, and after culling operations, plus cull dive data collection as a byproduct of control activities. This surveillance is primarily designed to support tactical day-to-day management decisions about where to deploy effort, when to stop culling, and how operations are progressing at managed sites.

Here we introduce the idea of 'Baseline' monitoring, statistically designed monitoring to sample reefs across the entire GBR to provide representative data on COTS densities and coral cover. This monitoring would provide the foundational dataset for strategic planning, measuring management outcomes, and answering scientific questions that require generalisable results. To demonstrate the different choices in developing a baseline monitoring program we tested a set of monitoring designs using a simulation study (**Appendix D**).

Comparing different statistical monitoring designs requires a representation of the dynamics of coral and COTS over all reefs that are under consideration for monitoring. Unfortunately, as is common with ecological and environmental problems, observed data is not available at a sufficient number of reefs and times across the vast scale of the GBR to form a comprehensive representation and simulated data is needed. While it is important that the simulated COTS and coral dynamics capture key patterns such as growth rates, coral loss, and COTS outbreak cycles, the monitoring design evaluation does not depend on the models perfectly reflecting reality—rather, we are testing whether our proposed designs can effectively estimate the patterns within the assumed reality of each model. Fortunately, two simulation models focusing on coral-COTS reef community dynamics have been developed and applied successfully on the GBR: (i) CoCoNet (Condie et al. 2021) and (ii) ReefMod-GBR (Mumby et al. 2007; Bozec and Mumby 2020). Given their success in underpinning GBR research and support in COTS control

(Westcott et al. 2021), and given that both are calibrated using observational data from the AIMS LTMP, we generate simulations from both CoCoNet and ReefMod-GBR as substitutes for observational data of coral cover and COTS densities at the reef scale on the GBR over time. Specifically, we generate 500 simulations from both CoCoNet and ReefMod-GBR. Both CoCoNet and ReefMod-GBR have options that implement COTS control using a specified number of vessels. In our implementation, we specify no COTS control as we did not want assumptions about the level of COTS control and which reefs were assumed culled, to affect the monitoring design outcomes.

2.6.1. CoCoNet

CoCoNet is a spatially explicit agent-based model modelling the changes in coral cover and COTS density at the reef level across the GBR (Condie et al. 2021; Fletcher et al. 2021), while accounting for disturbances such as heatwaves and cyclones. The estimates of each reef are an average of the reef-associated (non-spatially explicit) sites, where each site corresponds to approximately 14 ha of a reef (Westcott et al. 2021), or about ~8 ha of coral habitat. COTS are reported on a per hectare basis and are classified into age groups, aged 1 year through 6+ years. Active (severe) COTS outbreaks are defined as 68 COTS/ha, which is equivalent to approximately 1 COTS/manta tow. Coral dynamics are grouped into six coral groups, which are then aggregated into coral cover. CoCoNet is calibrated at the regional scale to the AIMS LTMP data. Simulations were run starting from 1901 but recorded from 2000 through 2020. Adult COTS densities and coral cover were estimated for 3,806 reefs on an annual basis.

The version of CoCoNet we used (version 3) was under development throughout CCIP. Previously version 1 was developed for a generic reef network (Condie et al. 2018), and version 2 framed to the GBR (Condie et al. 2021). Our simulations are based on the version of CoCoNet v3 available in March 2024. While newer versions are now available, the specific model version is not critical to this exercise since our objective is to evaluate monitoring design performance rather than to precisely reconstruct historical reef conditions—as long as the model generates realistic variability in coral and COTS dynamics, it serves our purpose of testing whether proposed monitoring designs can effectively detect and quantify ecological patterns.

2.6.2. ReefMod-GBR

ReefMod-GBR (Mumby et al. 2007) is an agent based model that simulates coral growth, mortality, settlement, bleaching, larval dispersal, and cyclonic disruption typical of mid-depth (~5-10 m) on the reef (Bozec and Mumby 2019; Bozec and Mumby 2020; Fletcher et al. 2021). The model itself is spatially explicit via a horizontal grid lattice, tracking individual coral colonies which can be combined to generate estimates of coral cover on an individual reef as well as COTS densities (Bozec et al. 2022), reflective of COTS per manta tow. Output is generated at 3,806 reefs on a 6-month time step, with hindcast results from winter 2007 through summer 2022. Coral and COTS trajectory dynamics may be forecast up to 2100.

For our purposes, we implemented ReefMod-GBR using only the hindcast, averaged to the annual level (e.g. 2008–2022) to provide the best comparison to the CoCoNet results. Simulations of ReefMod-GBR were generated using v6.8, available from https://github.com/ymbozec/REEFMOD.6.8_GBR.

2.6.3. Simulating the monitoring designs

While the CoCoNet and ReefMod simulations provide a range of COTS and coral distributions across the GBR, we then needed to test how choices in the baseline monitoring design affect the precision and accuracy of different ecological metrics (primarily mean COTS density and coral cover) based on the simulated 'populations'. Our method for selecting reefs in each design scenario follows the methods of (Foster et al. 2017) and Foster et al. (2024), implementing the balanced adaptive sampling (BAS) design of (Robertson et al. 2013) and (Robertson et al. 2017). Fundamental to creating a monitoring design of GBR reefs is specifying inclusion probabilities, that is, the probability that a reef will be chosen for monitoring. These inclusion probabilities reflect the goals of the overall design and are the key control device for producing a statistical survey design. A reef with an inclusion probability of zero will not be selected for monitoring in a given design, while higher probabilities increase the chance of inclusion. Fundamentally, setting up a monitoring design is a function of altering the inclusion probabilities and selecting the specified number of reefs for monitoring based on that inclusion probability. As a result, the basic process of each monitoring design is the same – but with the key difference that the method for defining the inclusion probabilities changes. See **Appendix D** or more information on how the inclusion probabilities are created and projected on the GBR.

After inclusion probabilities have been specified, reefs are sampled using the 'MBHdesign' package (Foster 2021) using R v4.2.1 (R Core Team 2024). For each monitoring design, we estimated average coral cover and COTS densities at each reef over the entire GBR. Given our method for altering inclusion probabilities will result in some reefs being sampled with higher probability than others, resulting in a biased sampling process, our estimator needs to account for the associated probability of inclusion. This is done via the Horvitz-Thompson (HT) estimator (Horvitz and Thompson 1952). That is, for observation y_i (representing either coral cover or COTS density) from reef i in a monitoring design with given set of reefs S, where the size of S is n, then the mean estimated (coral cover or COTS density) value is

$$\hat{\mu} = \frac{1}{|S|} \sum_{i \in S} \frac{y_i}{\pi_i^{(o)}}. (1)$$

where $\pi_i^{(o)}$ is the *observed* inclusion probability – equal to $\pi_i^{(s)}$ for non-clustered designs and approximating $\pi_i^{(s)}$ for clustered designs. **Table 1** shows a summary of the monitoring scenarios we considered, with more detailed descriptions below.

The number of sites specified here are the number of sites as defined by CoCoNet and is a function of the size of the reef. The number of sites may differ from the number of cull sites defined by the COTS Control Program, which consider both the size and logistics of culling a site as a single unit. Note that four sites was chosen as the lower cutoff for many monitoring designs as 95% of the Priority reefs had at least four sites but there are a greater percentage of small reefs across the entire GBR. Our initial modelling results showed that our results were being highly influenced by smaller reefs and so we chose to limit the occurrence of these in most of the scenarios to ensure valid comparisons between the different scenarios.

Table 1 Summary of monitoring design scenarios that were explored. Descriptions of each possible design are provided in Section 2.3.4.

Monitoring Design	Number of Reefs Monitored	Minimum Number of Sites per Reef
Random Reefs	30, 50, 70, and 100	4
Clustered Random Reefs	~50 reefs (5, 10, 16, and 25 clusters)	4
Fishing Intensity	50 reefs, 25 in each zone	4
Region based	50 reefs, ~25% in each control Region	4
Priority Reef Based	50 reefs	4
Target Reef Based	50 reefs	4
COTS Risk Layer Based	50 reefs	4
Size Distribution Based	50 reefs	1
LTMP Based	50 reefs	1

Lastly, each monitoring design was repeated 1,000 times to obtain a distribution of possible estimates of average coral cover and COTS density. We first calculated reef-level values by averaging coral cover and COTS density across the 500 CoCoNet and ReefMod-GBR simulations for each reef. These reef-level averages then served as our 'population' values. For each of the 1,000 repetitions of a monitoring design, we sampled reefs from this population according to the specified sampling design and calculated the mean of the sample. We then compared how closely each sample mean matched the true population mean of the associated sampling frame (i.e. if the monitoring design only included reefs with at least four sites as specified by CoCoNet, then the sample means were compared to the population mean calculated over only those reefs meeting this criterion).

2.6.4. Monitoring Design Scenarios

A large number of monitoring design scenarios were considered. We chose to run and present the results for nine scenarios that provide the best contrast in how decisions might affect the ability of the monitoring data to answer the COTS science and management objectives. Below we provide a brief outline of each selected scenario and the rationale for inclusion. In each scenario, the reefs are selected in the first year and the same reefs are assumed monitored throughout the period of study.

Random Sampling

Random sampling serves as the fundamental baseline for comparison with all other monitoring designs, as it provides statistically unbiased estimates and represents the gold standard against which other approaches can be evaluated. The random sampling scenario is the base case as it is a simple survey design and automatically provides unbiased estimates for any metric. Reefs with at least four sites were selected with equal probability. We considered scenarios where 30, 50, 70, and 100 reefs were included for monitoring. This is to provide an understanding of how variability in estimated average coral cover and COTS density decreases with increasing reefs monitored. Additionally, we are able to use this scenario to consider how the probability of detecting a COTS outbreak changes as a function of the number of reefs monitored (from 10 through 100). Understanding this relationship is crucial for determining minimum monitoring effort required to achieve acceptable precision and outbreak detection capability.

Clustered Random Sampling

Clustered sampling reflects the operational reality of reef monitoring, where logistical constraints and travel costs often require visiting multiple reefs within a limited geographic area during a single survey trip. This design tests how much such operational efficiencies come at the cost of statistical precision. The clustered random sampling scenario initially assigns equal probability to each reef with at least four sites. Clusters were set to have a radius of 25 km, reflective of the distance a vessel could cover within a day's voyage. In each case the number of reefs monitored is approximately 50, considered in 4 different cluster sizes:

1. 5 clusters of 10 reefs.
2. 10 clusters of 5 reefs.
3. 16 clusters of 3 reefs (noting this results in expected 48 reefs monitored).
4. 25 clusters of 2 reefs.

The number of reefs was set to be approximately equal to 50 in order to determine the effects of varying cluster sizes on uncertainty of the estimator rather than changing the amount of observations. This comparison is essential for optimising the trade-off between field logistics and statistical performance, helping to determine optimal cluster sizes for cost-effective monitoring.

Fishing Intensity Sampling

Marine protected areas (no-take green zones) and fished areas (of varying fishing intensity) may exhibit different coral community dynamics and COTS population patterns due to varying COTS predator abundances. Ensuring balanced representation across these management zones could be important if we wish to better understand the impact of marine park zoning on COTS abundance and coral cover. For the purposes of the simulation, reefs in the GBR Marine Park were classified into two zones regarding fishing: green (no-take) and blue zones (all other management areas). The blue/green zone sampling design adjusts inclusion probabilities so that amongst n monitored reefs, $n/2$ are expected to come from the green and blue zones each. This is done first by determining the number of reefs with at least four sites in the green zone, N_G, and blue zone, N_B. Each reef in the green zone is then assigned inclusion probability $n/(2N_G)$, and likewise $n/(2N_B)$ for blue zone reefs (noting inclusion probabilities should sum to n). For our purposes, we set $n = 50$ reefs monitored and employed random sampling using the specified inclusion probabilities.

Regionally Stratified Sampling

The GBR spans over 2,300 km and encompasses diverse environmental conditions, with different regions experiencing varying levels of COTS pressure, cyclone impacts, and bleaching events. Balanced regional representation ensures that monitoring captures this environmental heterogeneity and provides reliable estimates for management decisions that must account for the distinct challenges facing different regions of the reef system. Reefs are divided into four regions: Far North (FN), North (N), Central (C), and South (S), as classified by CoCoNet (Condie et al. 2021). Reefs with at least four sites are set to have equal inclusion probability in each region in a manner similar to that of Fishing Intensity zone sampling. That is, each reef with at least four sites in each region is set to have inclusion probability $n/(4N_r)$, where N_r is the number of reefs in region r with at least four sites. We again set $n = 50$ reefs monitored and chose the reefs using random sampling. This will result in an expected number of 12.5 reefs per region. Since 0.5 of a reef cannot be monitored, some regions will have 13 or more reefs selected for monitoring, some 12 or less over the 1,000 replications.

Priority Reef Sampling

Since COTS control efforts are necessarily focused on a prioritised subset of reefs due to resource constraints, it is essential to evaluate whether monitoring designed around these same priority reefs can provide adequate information for both local management decisions and GBR-wide assessments. This scenario tests the trade-offs between management relevance and statistical representation. The prioritisation process is outlined in the *CCIP-R-07 Multi-Criteria Decision Analysis (MCDA_* project report (Fletcher et al. 2025). In this scenario, only the 500 reefs on the COTS Control Program's 2023–2024 Annual Work Plan (Great Barrier Reef Marine Park Authority 2023) priority list were given a non-zero chance of selection. In 2023–2024, 500 reefs were designated as priority reefs in the GBR, 95% of which have at least 4 sites. Monitoring under the priority reef sampling scenario is limited only to those priority reefs with ≥ 4 sites, with each assigned equal inclusion probability.

Target Reef Sampling

Target reefs represent the highest-priority locations for immediate COTS management intervention. This scenario evaluates whether such highly focused monitoring can still provide meaningful insights for system-wide COTS dynamics and evaluate the effectiveness of the COTS Control Program on coral recovery. Amongst the 500 priority reefs identified by the COTS Control Program, 200–250 are assigned as target reefs. The 235 target reefs from the COTS Control Program's 2023–2024 Annual Work Plan were used for these simulations (Great Barrier Reef Marine Park Authority 2023). Similar to priority reefs, we assigned equal inclusion probability to target reefs with at least four sites.

COTS Risk Sampling

This approach tests whether incorporating prior ecological knowledge can enhance monitoring effectiveness compared to purely random or management-driven monitoring approaches. As COTS are neither evenly nor randomly distributed throughout the GBR it may be desirable to use prior information on COTS habitat preferences to formally bias the monitoring design. Matthews et al. (2020) used historical data from multiple monitoring programs on the GBR to identity the risk of a COTS presence as a function of multiple predictors including environmental, water quality, connectivity, and spatial location among others. For this monitoring design scenario, we use the ensemble output of Matthews et al. (2020) as a means of informing the inclusion probability for a given reef. That is, for reef i, output from Matthews et al. (2020) is defined as p_i, which is then rescaled to be π_i so that all the associated inclusion probabilities sum to $n = 50$, the number of reefs to be monitored. We set the minimum number of sites on a reef to be four.

Reef Size-Based Sampling

Reef size may influence both coral community structure and COTS population dynamics and time taken to monitor e.g. manta tow a reef. This scenario tests whether maintaining proportional representation across reef sizes improves precision and whether size-based sampling offers advantages for GBR-scale assessments. The 500 priority reefs vary in size, ranging from 1 site on the reef to 615 sites (using the 14 ha definition of a site applied in

CoCoNet). The reef size-based monitoring design scenario seeks to sample reefs so that the size distribution of the monitoring design resembles that of the size distribution of the priority reefs. We do this by first determining the 25th, 50th, and 75th percentiles of the number of sites for priority reefs, creating 4 separate bins (0–25th, 25th–50th, 50th–75th, and 75th–100th percentiles). Each reef on the GBR is then placed into one of these bins in accordance with their number of sites. The inclusion probability of each reef for a given bin is then determined in the same manner as the Fishing Intensity sampling and Region Sampling scenarios, described above.

LTMP Based Sampling

The LTMP is a long running monitoring program by AIMS, critical to understanding the overall status and general trend of reefs in the GBR. Surveying between 80 and 130 reefs each year for over 35 years (72 core reefs surveys every year), the program is vital to understanding the long-term status over the entire GBR. Evaluating this existing network for COTS monitoring purposes addresses whether this established network of reefs can serve dual purposes, potentially eliminating the need for additional baseline data to answer more specific COTS science and management objectives. In this scenario reefs surveyed by the LTMP program were assigned equal inclusion probability, and all other reefs set to zero inclusion probability. The minimum number of sites for a reef for this scenario is 1 so as not to exclude any of the AIMS LTMP reefs.

2.7. Stakeholder engagement

Stakeholder engagement was a critical component of our project, ensuring diverse perspectives were integrated into the monitoring program's development. We held an initial workshop with key organisations such as the Reef Authority, the Great Barrier Reef Foundation (GBRF), CSIRO, AIMS, James Cook University (JCU), Reef & Rainforest Research Centre (RRRC), Queensland Parks and Wildlife Service (QPWS), the University of Queensland (UQ), and several Traditional Owner (TO) groups were represented. This diverse participation facilitated rich discussions and insights into the objectives and challenges associated with monitoring in the GBR.

Additionally, through our companion project *CCIP-D-02 Tool Comparison* (Lawrence et al. 2025), we engaged in consultations and fieldwork with two vessel operators of the COTS Control Program, Pacific Marine Group and Blue Planet Marine. These discussions were instrumental in highlighting logistical constraints and practical considerations for effective monitoring.

We considered and, where relevant, included recommendations from stakeholders in our report, ensuring that their insights directly informed the methodology and objectives of the monitoring program. This inclusive approach is vital when implementing changes in monitoring practices, as it ensures that all critical aspects are addressed and that the program is both practical and relevant to stakeholders' needs. Getting it right in the early stages lays the foundation for successful outcomes in managing the GBR's health.

3. RESULTS

3.1. Monitoring purposes and data needs

The important tangible outcomes of the monitoring objective-setting activities are a priority set of management and science questions (**Appendix A**) that fall under the four categories of data needs. The four categories of monitoring purposes and information needs are:

1. *Tactical day to day management*: The data needed to ensure that cull operations are effective and efficient on a daily to weekly basis. These questions are largely related to tactical decisions. The day-to-day management questions rely on estimates of the status of both COTS (density, size) and coral (cover, type, condition) at a fine spatial and temporal scale (within strategically chosen reefs and within management action time frames). Both surveillance and monitoring data are appropriate to answer most of these questions.

2. *Strategic planning for future management*: The data needed to make effective management decisions about resources 6–12 months ahead. The strategic planning questions rely largely on estimates of the status and trend of both COTS (density, size) and coral (density, type, condition) at a broader spatial scale (reef/region) and at 6–12 monthly temporal scales (e.g. for voyage planning). Most of these questions require monitoring data (surveillance is not sufficient).

3. *Measuring outcomes of management*: The data needed to assess the effectiveness of COTS program management. The outcomes of management questions rely largely on estimates of the status and trend of both COTS (density, size) and coral (density, type, condition) at a range of spatial scales (within reef/reef/region) and at locations where any potential effect of management actions are likely to be seen (and reference sites too). Long term monitoring data is essential for answering these questions.

4. *Science and knowledge gaps*: The data needed to answer key science and knowledge gaps regarding COTS outbreaks. The science and knowledge gap questions are varied, each requiring very specific data to be adequately addressed. However, data pertaining to status and trend of COTS and coral at various spatial scales and temporal resolutions will be beneficial to allow potential environmental drivers to be analysed alongside COTS and coral data.

Despite the large number of questions identified across these four categories, there was substantial overlap in the measurement variables needed to address each monitoring purpose.

3.2. Existing monitoring and surveillance programs

Our review identified several established monitoring and surveillance programs in the GBR that collect COTS and/or coral data (summarised in **Appendix B**). The programs vary considerably in their spatial coverage, temporal frequency, and data collection methods, creating opportunities for complementary data use while highlighting gaps in current monitoring coverage.

The most directly applicable programs where data is currently used in the COTS Control Program are the AIMS LTMP and the RJFMP COTS Response. The AIMS LTMP monitors 80–

130 representative reefs annually using manta tow surveys, photographic transects, and visual counts, providing both reef-scale and fine-scale data on COTS density and size, coral cover and type, and coral condition. These data are used to inform reef prioritisation in the COTS Control Program, and Matthews et al. (2024) demonstrated how LTMP data can effectively assess COTS management outcomes at both reef and sector-wide scales.

The RJFMP conducts approximately 60 field days annually of RHIS and manta tow surveys across the GBR, collecting data on COTS density and size, coral cover, type and condition. These surveys provide valuable surveillance data with good spatial coverage but do not include long-term fixed site monitoring.

Other relevant programs include the Marine Monitoring Program (MMP) Inshore, which monitors 32 inshore reefs adjacent to major catchments and collects COTS and coral data alongside water quality measurements, and the Eye on the Reef RHIS program, which conducts site-scale surveys across the GBR. However, most of these programs focus on different objectives (water quality impacts, restoration planning, fish monitoring) and are located primarily in areas outside the main COTS management zones.

Since 2021, the COTS Control Program has begun deploying RHIS in two specific ways to address its monitoring needs: 'Surveillance RHIS' and 'Cull Site RHIS'. We analysed approximately two years of data from these deployments to assess their utility for addressing COTS monitoring purposes.

3.2.1. Surveillance RHIS

Given that Surveillance RHIS is intended to provide data to assess coral health across reefs managed by the Control Program, we initially examined how the mean hard coral cover can change through time at reefs that had undergone repeat RHIS surveillance visits (**Appendix C**). In general, the mean hard coral cover estimates fluctuate far more than one would realistically expect. One may expect a large negative drop with a cyclone or COTS outbreak but not a large positive change (hard coral cover increase) within a short time period. We also examined the coefficient of variations (CVs) for each reef at each point in time (CV = standard deviation of sample / mean of sample).

Figure 3 shows the results for all reefs and the results can be viewed by Management Region in **Appendix C**. The figure indicates a line at an arbitrary value of 30%; a CV of 30% is considered very high for useful information gathering, but unfortunately in ecology it would not be uncommon due to the natural variability. However, the great majority of the CVs are greater than 30% with many points far exceeding 30% (maximum of 97%). CVs that are very large like these suggest that the survey data is not adequate for estimating long term trends due to the very large amount of variability in the data. The variability is likely due to the patchiness of coral at the reef scale not being adequately captured by such small-scale measurements (of the order of 78.5 m^2), variance due to multiple observers collecting survey data within a single visit to a reef, and the imprecise return to site (GPS location not a fixed stake).

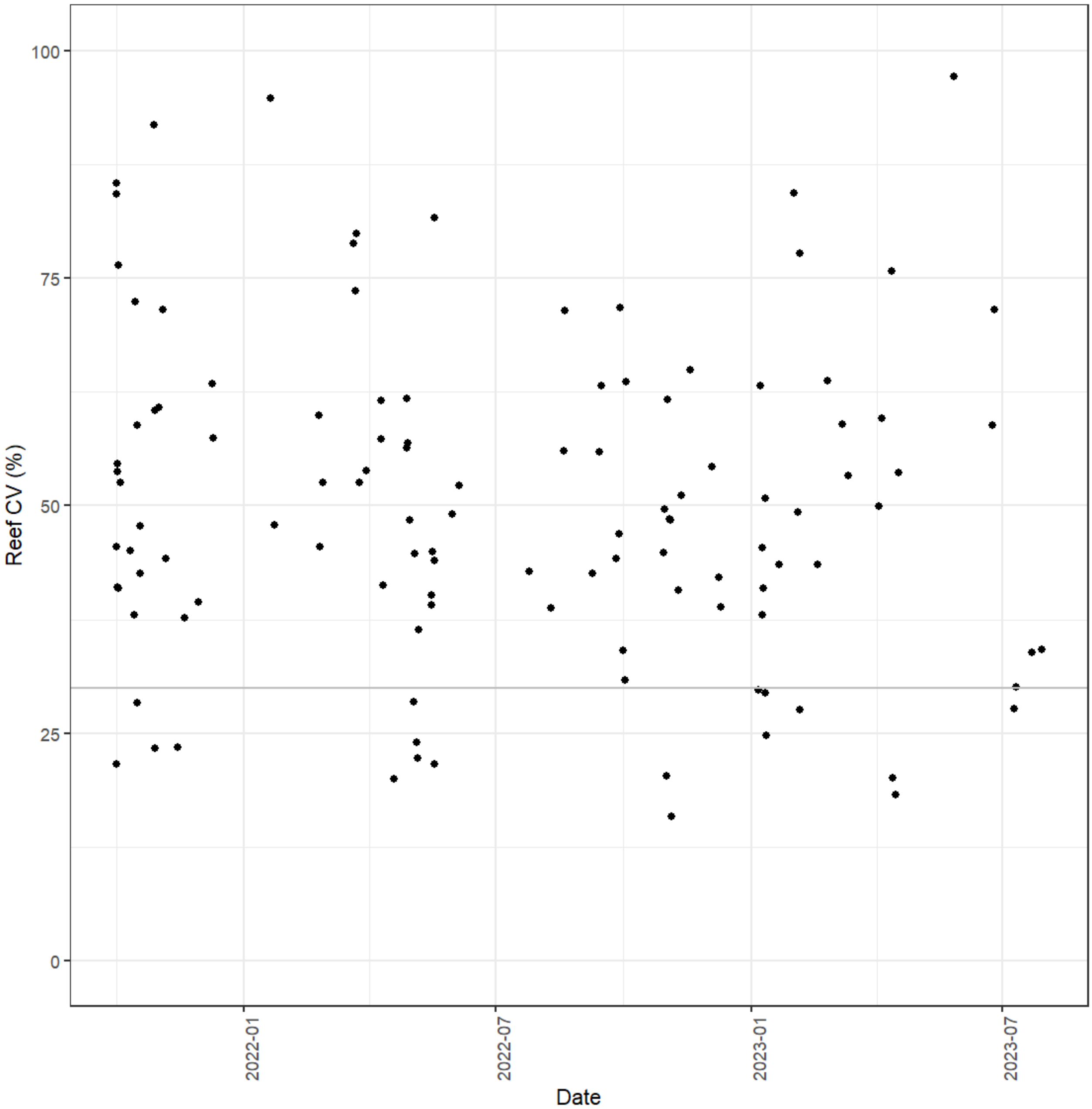

Figure 3. Coefficient of variation for Surveillance RHIS data combined to a reef level. Each data point is for a single visit to a single reef (multiple RHIS observations per visit). The grey horizontal line is for CV = 30%, which is an arbitrary indicator of a high CV.

3.2.2. Cull site revisit RHIS

We also analysed the RHIS data collected at cull sites before and after culling. Some cull sites have had more than twenty RHIS revisits (cull sites within two GBR management regions). We calculated the mean hard coral cover at each site for each RHIS visit for these sites that had been frequently visited. The results are in **Appendix C** and show a huge amount of variability. For example, consecutive visits to cull sites (within a couple of months) show mean hard coral cover estimates increasing by 40% (absolute coral cover).

Appendix C shows the results of the power analysis for detecting a relative change of both 20% and 50%. However, for reefs with low coral cover (e.g. <20%) this can mean trying to detect a very small absolute change in coral cover which would require 60–300 RHIS per reef, a sample size that is prohibitive resource wise. Instead, here we present the results for detecting an absolute change in coral cover of 5%. The results (**Figure 4**) show the number of replicate RHIS required per site per visit to detect an absolute change of coral cover of 5% ranges between 12 and almost 300, with the higher estimates being for reefs with the highest existing coral cover.

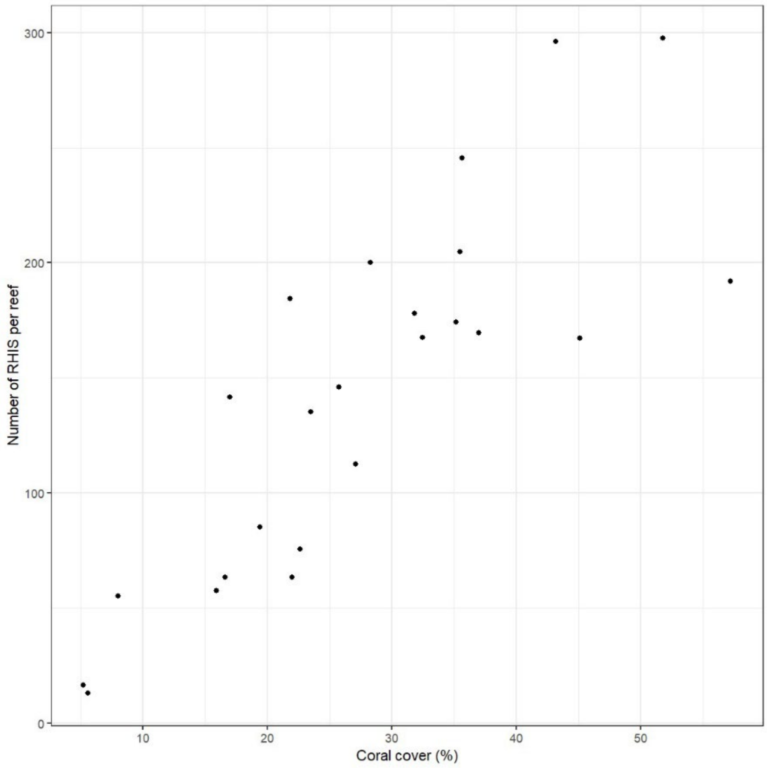

Figure 4. Power study results: Estimated number of RHIS required per reef per visit to be able to detect a 5% absolute change in coral cover vs coral cover (%). The average number of samples required, over all these reefs, is 143.

3.3. Monitoring tools

In making recommendations around monitoring design, it is important to understand how the COTS and coral monitoring tools compare both qualitatively and quantitatively. A comprehensive evaluation is provided in the *CCIP-D-02* report (Lawrence et al. 2025) which should be read in conjunction with this report.

3.4. Monitoring potential environmental outbreak drivers

Here we describe the basic premise for each potential COTS outbreak driver and the monitoring data that might contribute to answering monitoring questions related to them.

3.4.1. Links between coral cover (especially *Acropora*) and COTS reproductive potential

Cyclical or recurrent outbreaks of COTS on the GBR may be attributable to predator-prey oscillations (Babcock et al. 2016), and in particular, it is apparent that changes in the abundance of *Acropora* spp. can affect the reproductive capacity of COTS (Caballes et al. 2016). Fit-for-purpose data to investigate this hypothesis would require covariate data on coral cover (especially *Acropora* cover), COTS (juvenile and adult) abundance and distribution and adult fitness (e.g. condition, reproductive potential).

3.4.2. Water quality

COTS larvae are part of the zooplankton community in the GBR, which is influenced by complex biogeochemical cycles and environmental drivers. Water quality parameters include sediments (which can reduce light availability and cause smothering), nutrients (which can promote phytoplankton blooms that serve as food sources), and other pollutants. The parameters by which these cycles can be measured is denoted here by the general term "water quality". Terrestrial runoff can have a major impact on water quality from the coastline to midshelf reefs while marine forcing, such as upwelling, can be the dominant control on water quality of outer to midshelf reefs. Due to the lack of coordinated monitoring data, the link between water quality, related environmental drivers, and COTS larval survival remains equivocal (Caballes et al. 2024).

The enhancement of larval survivorship through nutrient-induced phytoplankton blooms is one mechanism that has been suggested to exacerbate COTS outbreaks. During high river discharge events, elevated nutrient levels can cause phytoplankton blooms that increase food availability for COTS larvae, potentially enhancing their survival, growth, and development rates. However, this hypothesis is not universally accepted and is unlikely to be fully supported or rejected without monitoring data that allows thorough analysis through time and resolution of variable nutrient sources such as terrestrial runoff and ocean upwelling (Babcock et al. 2016). An appropriate monitoring dataset would include (at a minimum) observations of COTS, larval abundance and environmental factors, including water quality parameters (e.g. *in situ* measurement of temperature, dissolved oxygen, pH, salinity, turbidity and chlorophyll-a, combined with discrete sample collection for total suspended solids, nutrients, and planktonic composition). There is existing COTS larval surveillance data conducted via DNA probing of plankton samples, both collected by AIMS and by COTS control vessels (Doyle et al. 2017; Uthicke et al. 2019) and parallel measurement of some water quality metrics has also been trialled by JCU that provide an existing contribution in this area (Kroon et al. 2021).

Thus, the list of water quality monitoring metrics that are likely to help research on potential outbreak drivers in the future is summarised in **Table 2**.

3.4.3. Predation

Previous studies on the effect of fish predation on COTS densities (e.g. Kroon et al. (2021)) have been based on adult COTS, coral and coral reef fish data obtained from the LTMP and fisheries catch and effort data supplied by the Queensland Department of Agriculture and Fisheries (QDAF). The LTMP has been surveying COTS and coral cover at reefs across the GBR since 1983 and benthic and reef fish assemblages since 1995. Research undertaken through CCIP indicates that certain species of predators may be particularly important, including a fish predator for adult COTS (spangled emperor, *Lethrinus nebulosus*; CCIP-P-06 Doll et al. 2025) and similarly for juvenile COTS (red decorator crab, *Schizophrys aspera*; Wolfe et al. 2025a). However, to resolve persistent controversies regarding predation and mortality rates of COTS at different life stages across the entire GBR, key fish predators would need to be measured in both protected and fished management zones and spatially distributed at latitudinal and cross-shelf scales. Similarly, CCIP research indicated that large differences in juvenile predator densities exist between reefs, and juvenile predators are likely to have a much larger effect on population dynamics. Hence, new monitoring methods (e.g. transects, eDNA) would need to be devised and systematically deployed to understand spatio-temporal variation in the presence and abundance of juvenile predators (Wolfe et al. 2025a; Wolfe et al. 2025b).

3.4.4. Water retention and self-recruitment

There is some evidence that hydrodynamic circulation patterns on the GBR may also influence the origination and establishment of primary outbreaks (Wooldridge and Brodie 2015). For example, long-term fluctuations in the strength and direction of currents driven by the El Niño-Southern Oscillation (ENSO) may allow for accumulation of larvae over successive years of recruitment (see Pratchett (2005)) in areas of high water retention and low flow conditions. The major focus of recent and previous hydrodynamic studies has been on dispersal of COTS larvae, to account for connectivity among reefs and the spread of established outbreaks. However, understanding when and where high levels of retention allow for high levels of self-recruitment and conditions promote “clustering” of nearby reefs that share larvae, may assist our understanding of the initiation drivers of primary outbreaks.

3.4.5. Summary of priority environmental covariate data needs

To establish a robust monitoring system for potential outbreak drivers, the minimum recommended water quality sampling would involve water column profiles obtained with an instrument cage, complemented by discrete water sampling. This approach is likely to require several years of consistent data collection to yield meaningful insights, e.g. statistically significant relationships. That said, observational data in key regions, such as the initiation zone can be readily used to validate existing modelling tools, such as eReefs (Steven et al. 2019), to test COTS ecological theories and water quality management actions. Such a foundational dataset is crucial for understanding long-term trends and patterns in the water column, and hence how these patterns are related to COTS population dynamics. For a more comprehensive sampling strategy, additional discrete samples could be included to track food sources and ecosystem dynamics more effectively, such as phytoplankton (e.g. through direct counts, metabarcoding or pigment analysis), organic matter, and Coloured Dissolved Organic Matter (CDOM). Furthermore, it is important to monitor water history and carbonate dynamics to better understand connectivity and coupled biogeochemical cycles. The feasibility and logistics of these data collection methods are summarised in **Table 2**.

Table 2. List of variables that could be collected as part of water quality monitoring that may help research on potential outbreak drivers in the future.

Method	Instrument	Parameter	Driver	Spatial scale	Need	Cost (time + money)
Water column profile	Multiparameters sensor on profiling cage	Temperature (°C)	Water quality	Site (depth stratified)	High	Low
Water column profile	Multiparameters sensor on profiling cage	Salinity	Water quality	Site (depth stratified)	High	Low
Water column profile	Multiparameters sensor on profiling cage	Chlorophyll-a (µg/L)	Water quality	Site (depth stratified)	High	Low
Water column profile	Multiparameters sensor on profiling cage	Turbidity (NTU/FNU)	Water quality	Site (depth stratified)	Medium	Low
Water column profile	Multiparameters sensor on profiling cage	Dissolved oxygen (µmol/kg)	Water quality	Site (depth stratified)	Medium	Low
Water column profile	Multiparameters sensor on profiling cage	pH	Water quality	Site (depth stratified)	Medium	Low

Method	Instrument	Parameter	Driver	Spatial scale	Need	Cost (time + money)
Discrete sample	Bulk water from surface and depth, depending on profile results	Total suspended sediments (mg/L)	Water quality		Medium	Low
Discrete sample	Bulk water from surface and depth, depending on profile results	Dissolved and total nutrients: e.g., organic & inorganic nitrogen (mg/L)	Water quality		Medium	Medium
Discrete sample	Bulk water from surface and depth, depending on profile results	Dissolved and total organic carbon (mg/L)	Water quality		Medium	Low if with Organic Nitrogen
Discrete sample	Bulk water from surface and depth, depending on profile results	Algal cell numbers	Water quality		High	Low
Discrete sample	Bulk water from surface and depth, depending on profile results	Phytoplankton composition (manual or photopigments)	Water quality		Low	High
Discrete sample	Bulk water from surface and depth, depending on profile results	Zooplankton Composition	Water quality/ COTS life cycle		Medium	High
Discrete sample	Bulk water from surface and depth, depending on profile results	CDOM: Chromomorphic dissolved organic material	Water quality/ remote sensing		Low	High
Discrete sample	Bulk water from surface and depth, depending on profile results	Dissolved Inorganic Carbon	Water Quality/Water source/history		Low	Medium
Discrete sample	Bulk water from surface and depth, depending on profile results	Total Alkalinity	Water Quality/Water source/history		Low	Medium
Continuous bioacoustics profiling	Echosounder	Zooplankton, phytoplankton	Water quality/ COTS life cycle		Medium	Medium

3.5. Collecting data to meet monitoring objectives

A simplistic evaluation of how well the current COTS monitoring program addresses the different monitoring questions and how incremental changes in tools and statistical design (and combinations of those) could enhance the program's ability to meet these needs is shown in **Table 3**. The priority given to each monitoring question, by the COTS Control management team, is also given. The questions are grouped by overarching monitoring purpose. The cells are colour coded and scored to indicate whether the scenario will fully meet the monitoring question (dark green = 1), comes close to meeting the monitoring question but improvement is possible (light green = 0.7), partially meets the monitoring question (amber = 0.4) or doesn't meet the monitoring question (red = 0).

A more comprehensive evaluation is presented in **Appendix E**, which contains a description of the ability of each scenario to meet each monitoring question. **Table 3**reveals a substantial variation in performance across the different monitoring scenarios, with total scores ranging from 10.1 to 21.3 out of a possible 28 points. The current monitoring approach (Control Program + LTMP + RJFMP) achieves a moderate score of 14.6, indicating room for improvement in meeting the program information needs.

The highest-performing scenario is ReefScan + Routine + extra baseline ReefScan (21.3 points), followed by SALAD + Routine (18.8 points) and Routine + baseline + environmental covariates (18.3 points). The basic Routine monitoring alone (10.1 points) addresses many day-to-day operational needs, though it falls short on answering the strategic planning and management effectiveness purposes.

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

Current monitoring adequately supports most tactical decision-making needs, with existing methods providing sufficient data to answer day-to-day management questions. All scenarios, including basic Routine monitoring, show strong performance (predominantly green and light green scores) for questions such as where to deploy cull effort and when to stop culling individual reefs. The addition of new monitoring tools primarily provides incremental improvements rather than addressing critical gaps in this category.

Strategic planning questions (6–12-month decision-making) show the largest potential for improvement, with substantial improvements possible across most scenarios. Key limitations include inadequate data for determining COTS densities and demographics across the GBR, understanding outbreak origins, and tracking how COTS persist outside outbreak periods. Enhanced scenarios, particularly those incorporating eDNA and ReefScan, show marked improvements in addressing these strategic questions.

The assessment of COTS program effectiveness represents the area of poorest current performance, with several high-priority questions (priority = 1) receiving red or amber scores under current monitoring. Critical gaps include the inability to determine whether the program is enhancing reef resilience, adequately track coral trends at management sites, or attribute coral loss specifically to COTS. The addition of SALAD monitoring shows the strongest improvement for these purposes, particularly for determining reef resilience enhancement.

Current monitoring provides limited data to address fundamental scientific questions about COTS outbreaks. Questions about outbreak drivers, initiation zones, and coastal progression patterns are poorly served by existing approaches. Environmental covariate collection and eDNA monitoring and surveillance show the greatest potential for advancing scientific understanding, though substantial resource investments would be required.

3.5.1. Specific high-impact improvements

eDNA monitoring and surveillance emerges as particularly valuable for tracking COTS larval densities during spawning seasons, delineating initiation zones, and monitoring outbreak progression along the coastline. This approach is specifically suited to detecting COTS at low densities, providing early warning capabilities not available through visual surveys alone. The method would support the specific early detection monitoring program outlined in Uthicke et al. (2025), and offers unique advantages when vessels are deployed across different GBR regions, providing contrast in COTS densities that cannot be achieved through traditional visual methods. However, a key limitation is that collecting eDNA data in the absence of additional visual surveys at baseline sites would compromise the program's ability to answer critical management questions regarding coral outcomes.

SALAD monitoring provides the most comprehensive improvement for coral-related monitoring questions, offering superior data on coral type, cover, and the relationship between COTS presence and coral outcomes. This method uniquely enables assessment of whether control activities enhance reef resilience and delivers the single best outcomes for determining dominant coral types and cover at COTS-affected reefs. SALAD monitoring also provides detailed information about COTS size structure and aggregation patterns that are not currently collected through routine monitoring and is effective for monitoring COTS at low to mid densities, contributing to early warning capabilities. The primary constraint is that the intensive monitoring effort required prevents deployment across large numbers of reefs within short timeframes.

ReefScan technology, when combined with expanded baseline monitoring, offers the highest overall performance (21.3 points) by enabling concurrent COTS and coral assessment across larger numbers of reefs. This approach shows particular strength in supporting both tactical decisions and strategic planning information needs through its ability to provide directly comparable data between reefs, offering the best indication of reefs with the greatest coral cover once the technology is fully developed. ReefScan is likely to increase the number of reefs that can be monitored in a given timeframe and may improve the speed and accuracy of decisions around ecological thresholds compared to manta tow methods. The technology provides sufficient resolution and data volume to track COTS densities outside outbreak periods, particularly when used in conjunction with eDNA for detecting lower COTS densities. The key assumption underlying this analysis is that ReefScan will successfully develop COTS detection capability, which is currently under development.

Environmental covariate collection at baseline monitoring sites represents a critical component for addressing fundamental scientific questions, particularly the key drivers of primary COTS outbreaks. While this data would not contribute to many operational information needs, it would provide a substantial step forward for understanding outbreak causation and may lead to improved modelling around which reefs respond best to culling efforts, helping identify "effort sinks" and improving models around ecological thresholds and sustainable densities. The data could also enhance predictive modelling of which reefs are more likely to have COTS populations. However, the temporal frequency of sampling required to contribute significantly could lead to substantial resource requirements, and this approach is unlikely to provide data at sufficient scale to answer within-reef questions about COTS habitat preferences.

Enhanced baseline monitoring using additional manta tow surveys represents the most cost-effective improvement option, achieving a meaningful performance increase using existing, proven monitoring tools. This approach ensures that all high-priority objectives from day-to-day and strategic planning categories are at least partially addressed, with no priority-1 objectives remaining completely unmet.

Table 3. Table of monitoring questions vs monitoring scenarios based on monitoring tools and programs that are currently used by the COTS Control Program for decision making. The scenarios are described in the methods section. In summary, Routine = cull + manta tow, Control Program = cull + manta tow + RHIS. The priority given to each objective by the COTS Control management team is also given. The questions are grouped by overarching objective group. The cells are colour coded to indicate whether the scenario will fully meet the objective (dark green), comes close to meeting the objective but improvement is possible (light green), partially meets the objective (amber) or doesn't meet the objective (red).

Overall objective	Questions	GBRMPA Ranking (1–4)	Routine	Control Program	Control Program + LTMP	Control Program + LTMP + extra manta	Routine + LTMP + extra baseline manta	eDNA + Routine	SALAD + Routine	Reefscan + Routine + extra baseline Reefscan	Routine + baseline + environmental covariates
What monitoring data do we need to collect to ensure that cull operations are effective and efficient on a daily to weekly basis?	Where should the cull effort be deployed to get maximum benefit?	1									
	Where are the highest densities of the largest COTS?	2									
	Where is the most coral to be 'saved' (individual reefs and/or regions)?	1									
	Where are we most likely to find COTS (which reefs, or which part of a given reef) and why (prediction)?	1 reef level, 2 site level									
	What is the dominant coral type and cover at reefs where COTS are present?	2									
	When should we stop culling individual reefs?	1									
What monitoring data do we need to make effective management decisions about resources 6–12 months ahead?	How much effort should be put towards monitoring vs suppression of known COTS outbreaks?	NA									
	Where are the highest priority areas for COTS management?	1									
	How do COTS persist outside of outbreaks?	3									

Overall objective	Questions	GBRMPA Ranking (1–4)	Routine	Control Program	Control Program + LTMP	Control Program + LTMP + extra manta	Routine + LTMP + extra baseline manta	eDNA + Routine	SALAD + Routine	Reefscan + Routine + extra baseline Reefscan	Routine + baseline + environmental covariates
	What is the status of coral cover and composition within regions and across the GBR?	2									
	What are the COTS densities and demographics across the GBR?	1									
	What is the area of reefs that have been culled for the first time/multiple times over the reporting period?	1									
	How do COTS densities change during spawning season?	2									
	Where do outbreaks originate in the northern or far northern GBR?	3									
	Do outbreaks in the southern GBR originate independently of outbreaks in the far north, north and central GBR?	3									
What monitoring data do we need to assess the effectiveness of COTS program management?	How does reef condition across the GBR change due to COTS management actions?	1									
	What is the trend in coral cover at reefs being managed for COTS?	1									
	What happens on reefs we aren't actioning?	2									
	Are we suppressing COTS numbers across the GBR through the COTS Control Program (trend through time)?	1									
	Is the COTS Control Program enhancing reef resilience?	1									

Overall objective	Questions	GBRMPA Ranking (1–4)	Routine	Control Program	Control Program + LTMP	Control Program + LTMP + extra manta	Routine + LTMP + extra baseline manta	eDNA + Routine	SALAD + Routine	Reefscan + Routine + extra baseline Reefscan	Routine + baseline + environmental covariates
	How much control effort is required to reduce COTS outbreaks to sustainable densities?	1									
	Do culling activities cause any negative impacts on coral (e.g. damage/disease)?	4									
	What is the coral loss due to COTS?	1									
What monitoring data do we need to answer key science and knowledge gaps regarding COTS outbreaks?	What are the key drivers of primary COTS outbreaks?	1									
	Where is the COTS initiation box?	4									
	What is the progression of COTS outbreaks along the coast?	2									
	When/where are COTS likely to be aggregated?	1									
	When and where are COTS outbreaks most likely to occur?	1									
Total score			**10.1**	**11.9**	**14.6**	**14.6**	**16.7**	**16.5**	**18.8**	**21.3**	**18.3**

3.6. Monitoring design evaluation for baseline monitoring

We present the results of the monitoring design evaluation described in the methods section here. The results of each monitoring design are presented via boxplots and time series plots for each monitoring design scenario in **Appendix D**. While we describe the results for all of the designs here, the reader should refer to the Appendix for the relevant figures. The results are presented as COTS per hectare (ha) and percent coral cover.

3.6.1. Random Sampling

The Random Sampling scenario was conducted based on 30, 50, 70 and 100 reefs. **Figure 5** shows the estimated coral cover and COTS densities through time (and associated uncertainty) based on random sampling of 50 reefs (see **Appendix D** for 30, 70 and 100 reefs). As expected, increasing the number of reefs monitored decreased the variation in the estimated average coral cover and COTS density in all models over the years. This decrease diminished with each increase in reefs monitored. That is, the decrease in variability from 50 reefs to 70 reefs was less than that from 30 to 50. Increased estimates of coral cover or COTS densities tended to increase variability as would be expected.

Special mention should be made of the estimated average COTS density predicted by ReefMod-GBR in 2018 for 50 randomly sampled reefs, which showed a larger variation than all other years. While zero is still within the bounds of the estimator, often the estimated average COTS density is projected lower than the true average. This was due to the heavily skewed distribution of COTS densities at different reefs over this year. Closer inspection showed that on average, in 2018 90% of the 50 randomly sampled reefs had estimated 0.3 COTS/manta tow, while the maximum ranged from 47 to 167 COTS/manta tow. The mean COTS density for 2018 (across all simulations) was near 0.4 COTS/manta tow. This amount of variation was not seen in any of the other years for ReefMod-GBR and likely due to the random sample including many reefs with severe outbreaks in the Southern Swains and potentially Townsville. The high skewness of 2018's COTS densities for ReefMod-GBR explains why the results were significantly wider, which became less pronounced with increasing number of reefs monitored. Lastly, while the estimator showed high variability in 2018, it was still unbiased, as evidenced by the time series plots in **Figure 5**.

The probability of detecting a COTS outbreak during a given year can also be calculated empirically from the simulations. **Figure 6** shows this probability as a function of both number of reefs monitored and proportion of reefs with a severe COTS outbreak, defined as 68 COTS per ha (equivalent to 1 COTS per manta tow). Both CoCoNet and ReefMod-GBR show similar results, noting that the predicted proportion of outbreaking reefs was smaller in ReefMod-GBR than in CoCoNet. Not surprisingly, lower proportions of outbreaking reefs will require a higher number of reefs that need to be monitored in order to detect a severe outbreak. For instance, there is a 50% probability of detecting a severe outbreak when monitoring 50 reefs if approximately 2% of the reefs on the GBR have severe outbreaks, while the probability of detecting a severe outbreak increases to approximately 75% if 100 reefs are monitored. If 5% of the reefs have a severe COTS outbreak, then monitoring 50 random reefs will detect an outbreak with probability approximately 75%, increasing significantly to above 90% for 100 reefs monitored.

Time series plots showing the estimated average coral cover and COTS densities over the GBR for 50 randomly sampled reefs is shown in **Figure 5**. The mean estimates from the random sampling designs line up directly with the true mean coral cover and COTS densities of reefs over the entire GBR with at least four sites for both CoCoNet and ReefMod-GBR, with the variability decreasing as the number of reefs monitored increases.

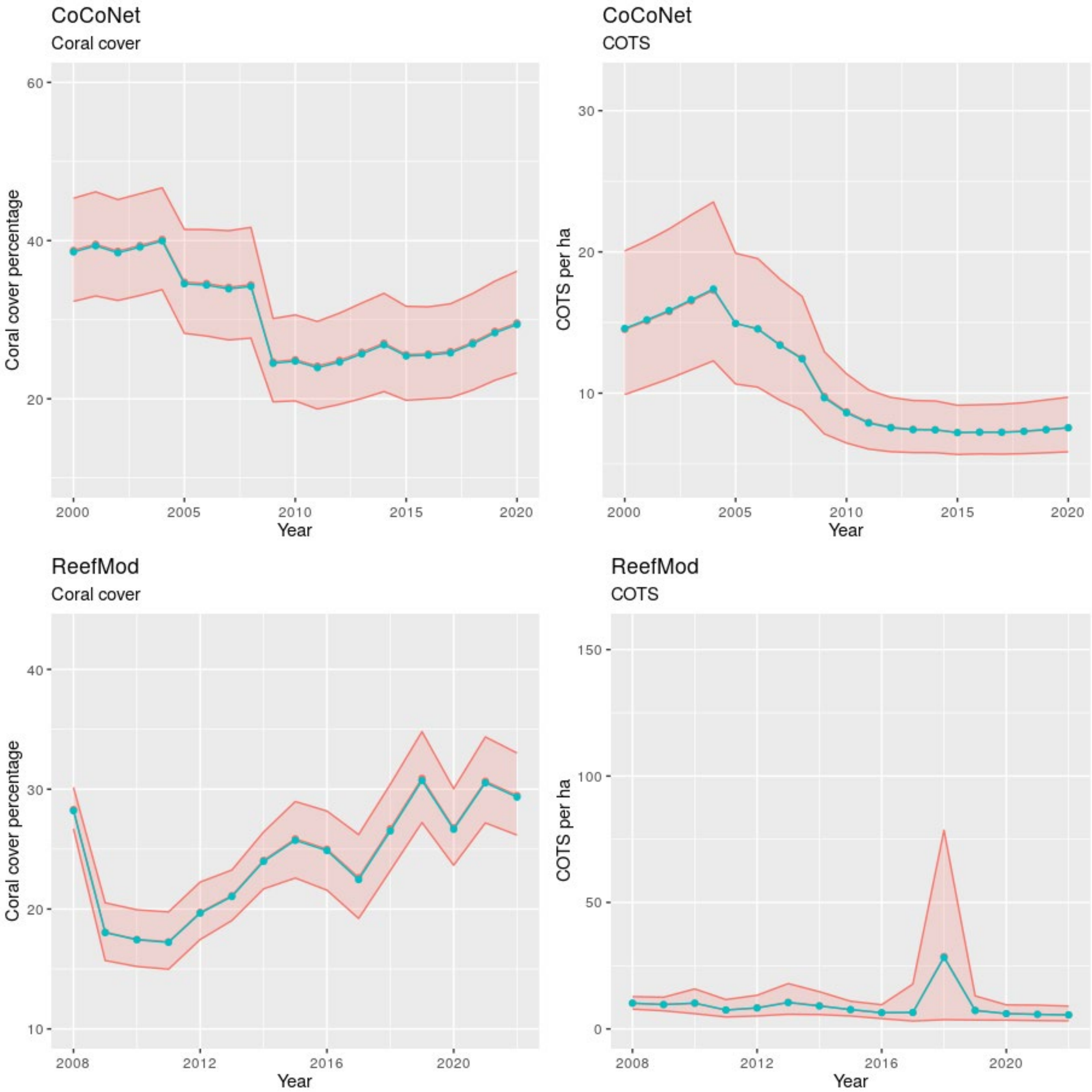

Figure 5. Time series plots showing sample estimates (red) and GBR-wide estimates (blue) from Random Reef Monitoring of 50 reefs over years with 95% intervals (shaded red). Plot shows total average coral cover percentage (left column) and average COTS densities per ha (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

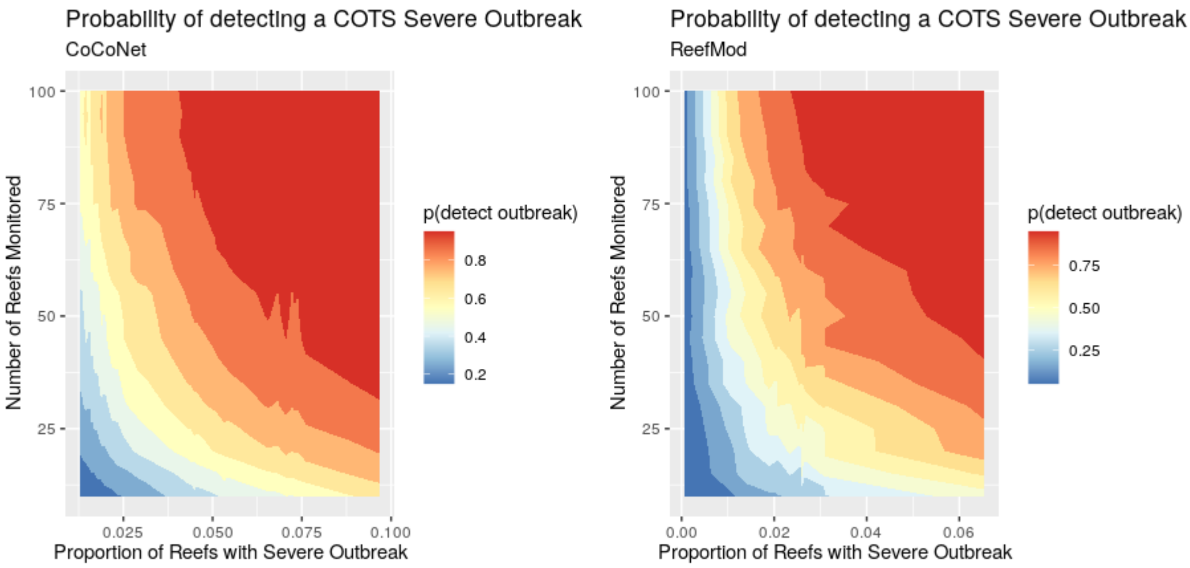

Figure 6. Probability of detecting a severe COTS outbreak (68 COTS per ha or 1 COTS per manta tow) given number of reefs monitored (y-axis) and proportion of outbreaking reefs on the GBR (x-axis). Left plot shows results based on CoCoNet. Right plot show results based on ReefMod.

3.6.2. Clustered Random Sampling

Figure 7 shows the time series results for the clustered design with 16 clusters of 3 reefs over the years. As with the random sampling case, the estimated average from the sample matched well with the true average coral cover and COTS density in both simulation models. Increasing the number of clusters decreased the variability despite the (approximately) same number of reefs being monitored. Further investigation found that increasing the number of reefs per cluster found negligible decrease in variability (not shown). As with the Random Sampling designs, the decrease in variability between 25 and 16 clusters was smaller than that from 16 to 10 and again from 10 to 5 clusters (**Appendix D**). In this sense, the number of clusters performed in a similar manner to that as the number of reefs in the Random Sampling design. Interestingly, the difference between 16 and 25 clusters appeared negligible, nor did the 16 cluster scenario significantly increase the uncertainty compared to the 50 random reefs (**Figure 5**) suggesting that clustering reefs would be a sampling strategy that is nearly as good from a statistical perspective as sampling 50 reefs randomly, but with significant logistical advantages.

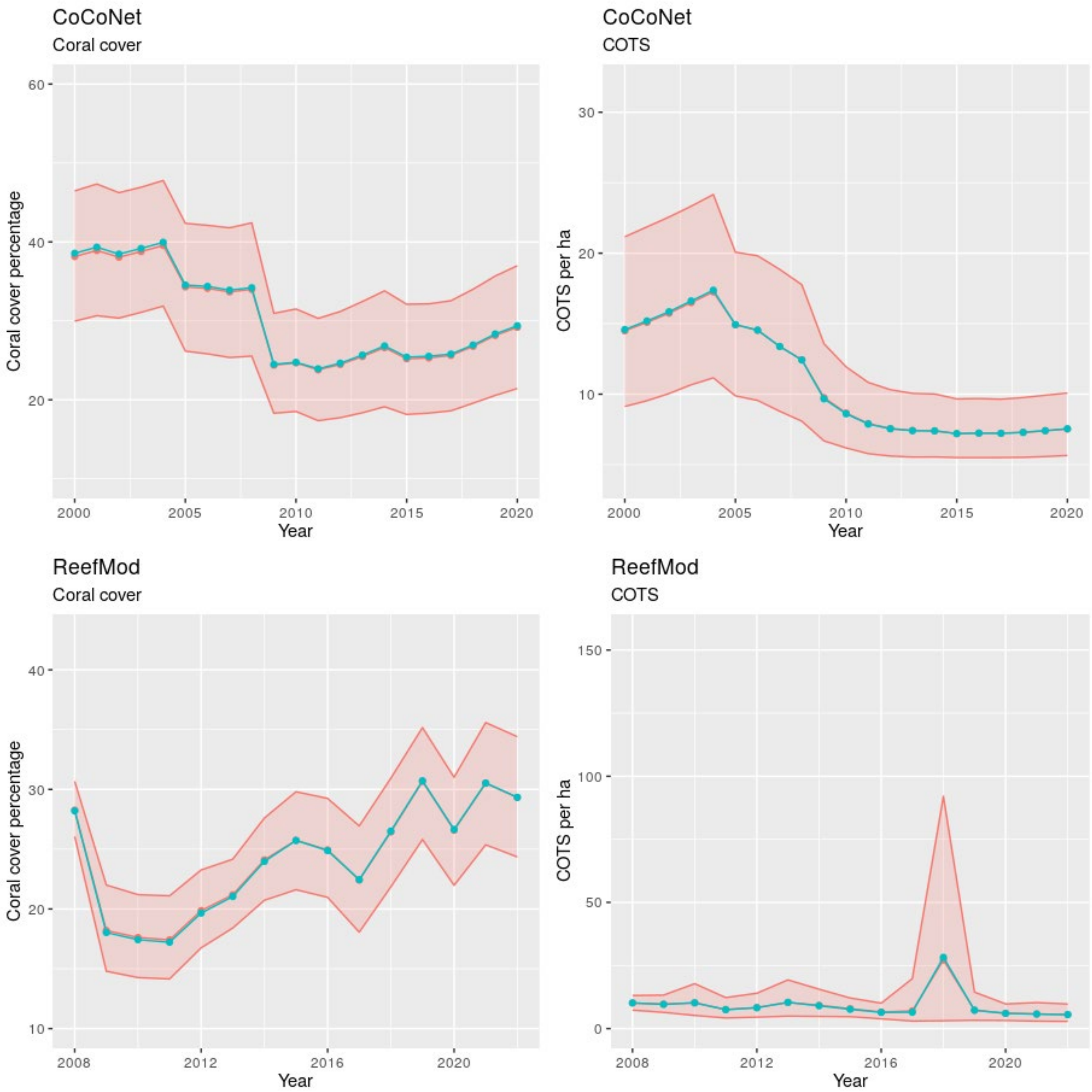

Figure 7. Time series plots showing estimates (red) and true value (blue) from Clustered design with 16 clusters of 3 reefs over years with 95% intervals. Plot shows total average coral cover percentage (left column) and average COTS densities per ha (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

3.6.3. Fishing Intensity Sampling

The estimators for the Fishing Intensity Sampling strategy were unbiased, with boxplots covering zero over all years and simulations, and the time series plot showed good agreement between the estimated values and true mean (**Appendix D**). However, there was a small increase in variation with wider boxplots and larger confidence regions in the time series plots when compared to the Random Sampling scenario with 50 reefs, although this increase was small. This may indicate that a design that differentially samples green vs other zones will give a good estimate at the cost of increased variability, though if comparing densities between green and other zones was a key objective of the monitoring program it could still be considered.

3.6.4. Region based Sampling

The Region based Sampling scenario was again unbiased, resulting in an unbiased measure for the average coral cover and COTS density over the entire GBR, but with a noticeable increase in variability when compared to random sampling (**Appendix D**). Stratifying by region means a lower proportion of reefs are sampled in the Far North and South regions than the North and Central regions. Considering only reefs with at least 4 sites, there are 649 in the Far North, 185 in the North, 107 in the Central, and 1,233 in the South. Under this sampling design, we would expect 6.8% of North region reefs and 11.7% of Central region reefs to be monitored while only 1.9% of Far North and 1.0% of South region reefs. However, if Region level estimates are more important than overall GBR estimates then this would be a good design to consider.

3.6.5. Priority Reef Sampling

Figure 8 shows the time series estimates for the Priority Reef Sampling scenario. There was a noticeable difference between the estimated average coral cover and COTS density from monitoring only priority reefs compared to the average over the entire GBR. Estimates based on CoCoNet consistently overestimated average coral cover while underestimating COTS density. This is because COTS have higher densities at non-priority reefs in CoCoNet simulations. The same estimates using ReefMod-GBR generally were within uncertainty bounds, though the estimated means did not match with the true means, indicating bias in the sample. There did appear to be a negligible increase in estimated variation compared to the 50 Random Sampling scenario.

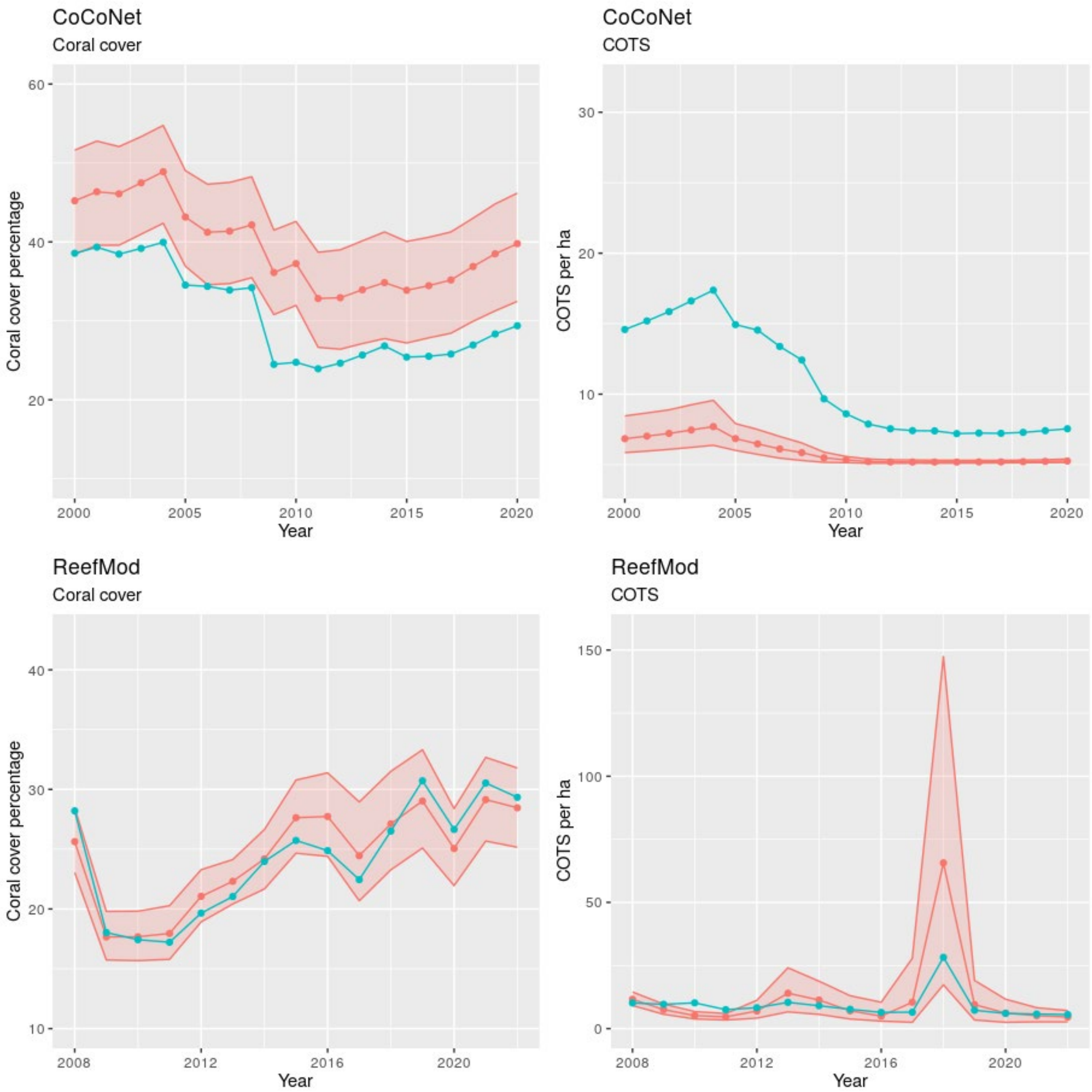

Figure 8. Time series plots showing estimates (red) and true value (blue) from priority reef based monitoring design over years with 95% intervals. Plot shows total average coral cover percentage (left column) and average COTS densities per ha (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

3.6.6. Target Reef Sampling

The estimated averages for monitoring only target reefs were closer to the estimated true average for CoCoNet for coral cover than the Priority Reef Sampling, however they still underestimated COTS densities for the entire GBR (**Appendix D**). Estimates based on ReefMod-GBR were similar to the true average. Compared to monitoring designs based only on priority reefs, the estimates did not appear to have a noticeable difference in variation, though coral cover estimates did appear to have less variability.

3.6.7. COTS Risk Sampling

The COTS Risk Sampling monitoring scenario showed good agreement in the estimates of coral cover and COTS density with the true averages over the entire GBR, see **Figure 9**. The exception to this was estimated COTS densities for CoCoNet which consistently underestimated the average. The reason for the underestimate was that there are 205 individual reefs that have been assigned zero COTS risk so they have no chance of selection in the sample, however they have a non-zero estimated COTS density in CoCoNet. The Far Northern area of the COTS risk layer has zero values due to the lack of current environmental information in that region (so they are really NAs but have had no chance of selection due to the lack of information). If we removed the zero COTS risk reefs from the sample frame, then we would also expect the CoCoNet COTS density estimates to be unbiased. The estimated variability is increased for coral compared to Random Sampling with 50 reefs but similar or slightly less for COTS.

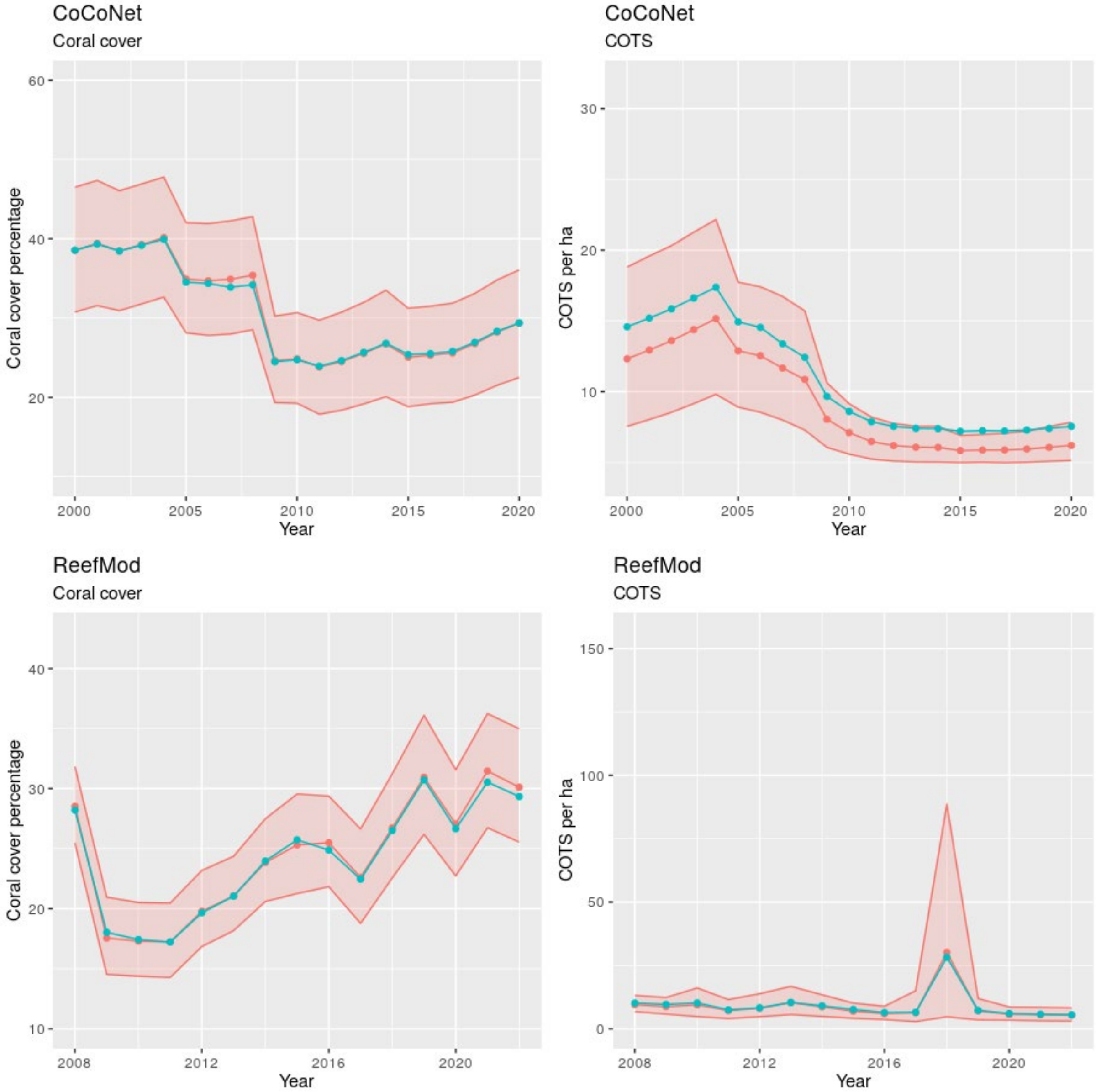

Figure 9. Time series plots showing estimates (red) and true value (blue) from COTS risk-based monitoring design over years with 95% intervals. Plot shows total average coral cover percentage (left column) and average COTS densities per ha (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

3.6.8. Reef Size-Based Sampling

The Reef Size-Based monitoring design, where reefs are sampled that have the same size distribution as those in the 500 priority reef list, is unbiased (**Appendix D**). However, the estimated variation did appear slightly more than the Random Sampling with 50 reefs scenario, particularly for coral cover based on ReefMod-GBR simulations and COTS density estimates based on CoCoNet. Importantly though, the sampling frame was different from that of Random Sampling, with the Reef Size Based design considering all possible reefs and not just reefs with at least four sites.

3.6.9. LTMP Based Sampling

The LTMP monitoring design that randomly sampled 50 reefs from the list of 130 reefs monitored by the LTMP, was somewhat biased when compared to GBR-wide estimates. CoCoNet consistently overestimated the average coral cover over the entire GBR while consistently underestimating COTS densities (**Figure 10**). Similar to that of the Priority Reefs sampling scenario, COTS densities were likely higher at reefs that were not classified as LTMP reefs in CoCoNet simulations. Some of the discrepancy was likely modelling related, LTMP reefs have more sites on average than the GBR average and reefs with lower numbers of sites tend to have higher average COTS densities in CoCoNet. For ReefMod-GBR, the estimator was considerably better, though not within the uncertainty bounds for many years prior to 2016 for coral cover (**Appendix D**). The variation was comparable to that of Random Sampling with 50 reefs. However, in both models, the trend over time had patterns that were not consistent with the GBR-wide pattern.

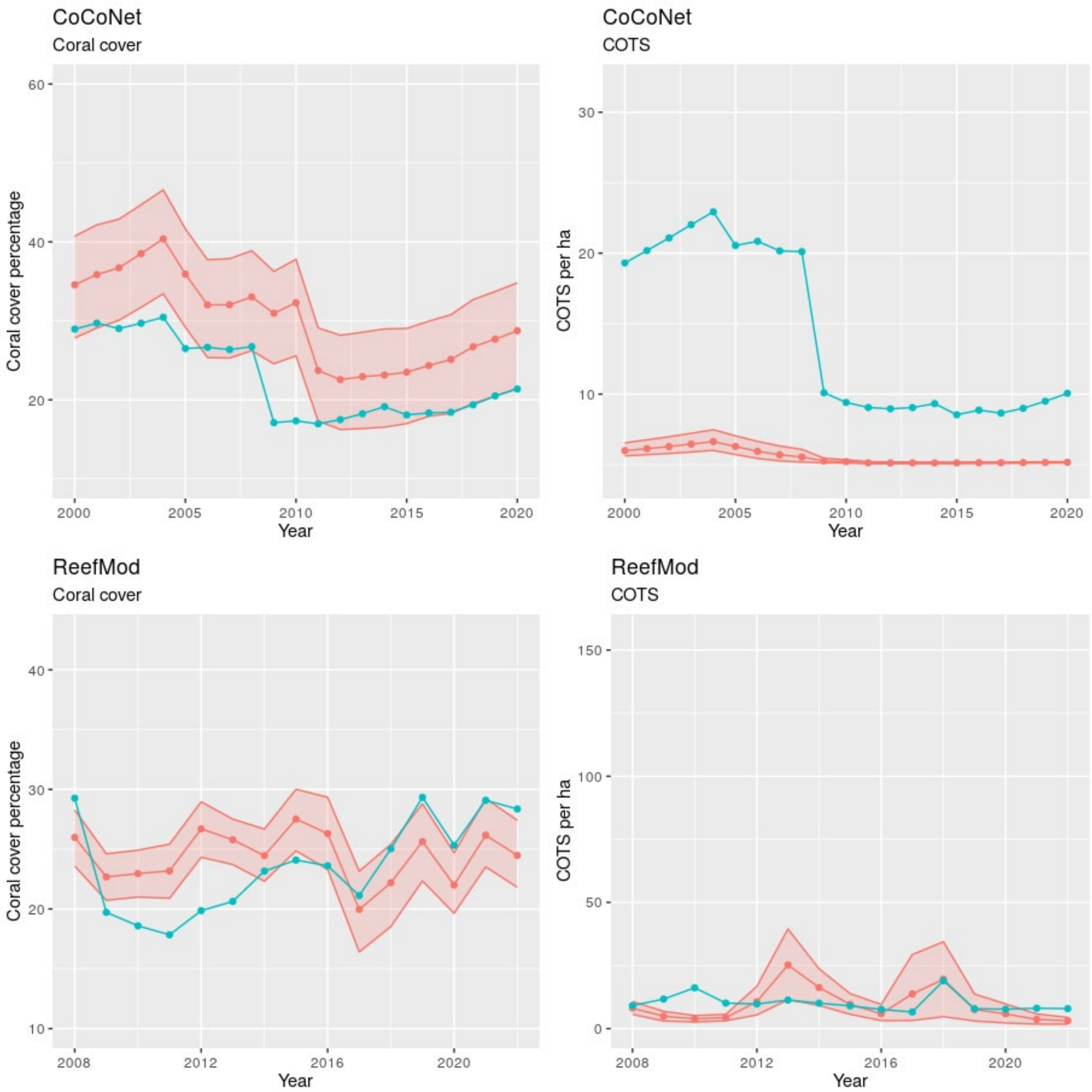

Figure 10. Time series plots showing estimates (red) and true value (blue) from LTMP reef-based monitoring design over years with 95% intervals. Plot shows total average coral cover percentage (left column) and average COTS densities per ha (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

Because CoCoNet is calibrated to LTMP data at the regional scale instead of the more coarse GBR wide or finer individual reef scale, we further investigated the estimates of coral cover and COTS densities at the Region scale (**Appendix D**, **Figures A71–74**). The estimated average coral cover compared to the true average coral cover (as indicated by the sample simulation), grouped by control region showed that while there was still disagreement between the estimated and true averages, with the estimates being higher, the uncertainty bounds contained the true estimate more often. **Figure A72** in **Appendix D** shows the estimated average COTS densities per region compared to the true averages. The discrepancy with the averages at the GBR scale are apparent here, with good agreement between the estimated and true average COTS density in the North and Central regions and strong disagreement in the Far North and South regions. This indicates that CoCoNet is indicating larger COTS densities in areas not typically surveyed by LTMP. The proportion of reefs that are surveyed by LTMP in the North and

Central are also higher than that in the Far North and South, indicating that LTMP based monitoring will be more accurate in the North and Central regions.

For comparison purposes we also investigated region-based results from ReefMod-GBR (**Figure 73–74**). The main region that is not well represented for coral cover is the South while the main region that is not well represented for COTS density is the Far North. Again, this shows the disproportionate representation of the LTMP in the different regions. In comparison the estimators for the Random sampling scenarios are unbiased at the region level in all cases, but there is noticeable similarity in uncertainty.

4. DISCUSSION AND OUTPUTS

4.1. Existing monitoring and surveillance

Monitoring and surveillance data currently collected directly by the COTS Control Program are primarily designed to inform most of the day-to-day management information needs (Westcott et al. 2021). The data collected effectively informs tactical responses to COTS outbreaks, offering valuable insights into localised starfish densities and the direct impacts of control efforts at sites and reefs under management. However, the data are less suited to strategic planning and evaluating long-term outcomes of management action as the data cannot be used to make inference beyond the reefs that are measured. These data also fall short in bridging some significant scientific knowledge gaps, including around the drivers of outbreaks, that ultimately need to be filled to prevent outbreaks in the future. Notably, there are exceptions where current data meets both strategic management and scientific objectives, such as estimating how much cull effort is required to reduce COTS densities to below ecological thresholds.

The current monitoring and surveillance approaches for COTS management face two primary limitations. The first concerns the limitations of current monitoring tools (i.e. manta tow, cull dives and RHIS). Cost-effective measurement of low COTS densities outside outbreak periods is challenging, especially across vast spatial and temporal scales. Manta tows are well known to have low detection rates especially when COTS densities are low (Fernandes 1990; Fernandes et al. 1990; MacNeil et al. 2016), while cull dives have higher detection but are prohibitively expensive to use as a primary monitoring tool (Lawrence et al. 2025). A potential solution might be modifying cull dive methods to cover smaller areas with fewer divers (two to three) for monitoring purposes. Moreover, our research across projects CCIP-D-01 (this project) and CCIP-D-02 (Lawerence et al. 2025) has shown that the coral cover data collected using manta tow and RHIS is significantly limited in accuracy and precision for coral monitoring objectives. Coral cover estimates are highly variable due to the patchiness of coral cover and the difficulty in calibrating estimates using these methods among divers (Mellin et al. 2020). This problem is exacerbated by the involvement of multiple companies and a large and transient workforce, which requires that the Control Program invest significant time and effort into ongoing training and calibration across observers. Furthermore, our analysis showed that RHIS data cannot detect informative changes in coral cover under current deployment approaches (i.e. Surveillance RHIS, Cull site RHIS). Producing reliable results would require a five-to-ten-fold increase in effort, which is cost-prohibitive.

Secondly, this study has shown that the design (locations monitored) of the data collection is a significant constraint. Currently, the data collected by the COTS Control Program is primarily from a set of several hundred Target reefs selected each year. From a statistical perspective, a major problem with this approach is that the list of Target reefs changes from year to year and a sample frame needs to be fixed through time to provide high quality data for assessing whether management interventions are working, tracking coral recovery, and understanding COTS population dynamics at regional and GBR-wide scales. In effect, changing the sampling frame (the list of reefs that could be sampled) provides a ‘break’ in the time series each time a change is made – it becomes difficult, very quickly, to understand how the data could be interpreted when making Region or GBR wide inferences. Another risk of only monitoring Target reefs is potentially missing detection of new outbreaks at reefs not identified in the current list, which could later impact the Target reefs.

Our study also assessed the data collected by other key monitoring and surveillance programs across the GBR to understand their contributions to addressing COTS management objectives. The RJFMP COTS Response predominately adds spatial surveillance to the data available for use by the COTS Control Program by conducting additional manta tow and RHIS at Target reefs. This information is largely used to help make the Control Program operations more efficient by covering some of the surveillance across the target reefs and as broadscale reconnaissance to search for new outbreaks or re-emergence of outbreaks in problem areas that are not Target reefs. The AIMS LTMP provides important long-term coral and COTS monitoring on the reef. LTMP observers, being a small group of highly trained scientists, provide reliable coral cover estimates, which is particularly important for trend analysis. While limited to a specific set of reefs that were not selected using a statistical design, LTMP offers valuable historical long-term data on COTS, contributing to temporal datasets that are crucial for predictive modelling. Annual sampling at consistent reefs, when combined with Control Program data, offers insights into COTS dynamics across various environmental conditions. However, LTMP's limitations from the perspective of COTS management, include restricted geographical coverage, particularly in the Far North where outbreaks are increasingly evident, and the need for careful comparison with Control Program data due to lack of calibration between the observers. The main limitation for use by the COTS Control Program, however, is that the LTMP was not designed to assess the effectiveness of the Control Program and is unable to be relied on for this purpose.

High-priority management and science questions that current monitoring and surveillance (across all current programs) cannot measure effectively include:

- Quantifying COTS densities and demographics across the GBR (beyond culled sites).
- Assessing how coral cover changes in response to COTS management actions.
- Evaluating whether COTS numbers are being suppressed across the GBR over time through the Control Program.
- Determining the key environmental drivers of COTS outbreaks.
- Establishing the locations and extent of the putative initiation area, where GBR-wide outbreaks start.

Addressing these gaps is crucial for enhancing the strategic planning, evaluating effectiveness and scientific foundation of COTS management efforts.

4.2. Emerging tools

Emerging monitoring technologies, such as eDNA sampling (Uthicke et al. 2018; Uthicke et al. 2022), ReefScan (Bainbridge and Coleman 2024), and SALAD surveys (Chandler et al. 2023), offer promising advancements for the COTS Control Program. For example, eDNA monitoring is capable of detecting the presence of COTS through water samples at minimal concentrations, thus providing early detection of lower COTS densities than is currently possible with traditional surveys (Uthicke et al. 2018; Uthicke et al. 2022; Uthicke et al. 2025). The eDNA monitoring method is particularly advantageous because samples can be collected in the field by non-scientists and because it enables assessment of COTS presence in habitats and at depths that aren't accessible to divers, thereby enhancing spatial coverage and early detection of outbreaks. Our analysis demonstrates that incorporating eDNA into routine monitoring would enable the Control Program to address specific questions that current methods cannot adequately answer. For example, depending on the timing of sampling it would be possible to elucidate changes in COTS densities during the spawning season and low density inter-annual changes (Uthicke et al. 2024), monitor the progression of COTS outbreaks along the coastline, and potentially delineate the COTS initiation box. With vessels operating in different regions simultaneously, eDNA can offer a comparative analysis of COTS densities along the GBR at specific points in time (see Uthicke et al. 2024 and Uthicke et al. 2025). However, collecting eDNA data without supplementary visual surveys that also collect coral data at baseline sites may limit the ability to answer management questions pertaining to coral outcomes.

Although ReefScan technology is still transitioning from development to operational testing, it has potential to significantly enhance the monitoring capacity of the Program, allowing for the concurrent estimation of COTS and coral on the same transects, a capability that represents a fundamental advancement for assessing management effectiveness (Bainbridge et al. 2025). Our research demonstrated that the Control Program struggles to directly link COTS removal efforts with coral outcomes because these metrics are collected using different monitoring tools at different spatial scales. ReefScan's ability to simultaneously quantify both COTS presence and coral cover on identical transects will enable direct assessment of whether culling activities are protecting coral and enhancing reef resilience, questions that our analysis identified as poorly addressed by current monitoring approaches. ReefScan utilises imagery collected via towed camera and machine learning algorithms to estimate coral cover and is advancing in its ability to precisely detect COTS and scars. Bainbridge et al. (2025) reported machine learning model validation demonstrated detection accuracies of 87% for COTS identification, 91% for COTS tracking across sequential images, 40% for feeding scar recognition, and 73% for hard coral habitat mapping. Importantly, this image-based approach addresses a critical limitation identified in our research: observer bias that currently undermines data quality in the Control Program. This method will facilitate direct comparisons between metrics, sites, and reefs; providing robust measures of coral cover once fully developed. Transitioning away from manta tow surveys to ReefScan may improve both the speed and accuracy of ecological threshold assessments. Its continuous towing and automated data recording is expected to increase both the volume and accuracy of data, while providing precise GPS coordinates for COTS, thereby aiding in efficient culling while also collecting data that can be used to assess the effectiveness of COTS management. The high resolution and extensive data volume that could be generated by ReefScan, especially when integrated with methods like eDNA for monitoring lower COTS densities, should also enable effective tracking of COTS densities outside of outbreak periods.

The SALAD survey technique provides estimates of adult COTS and associated scars at low densities, giving detailed monitoring and documentation of changes in COTS abundance and size distribution (Chandler et al. 2023, Pratchett et al. 2025). Integrating SALAD into routine monitoring at selected Control Program Target reefs and statistically selected baseline monitoring reefs would allow the identification of the dominant coral type and cover at reefs with COTS presence. SALAD monitoring data also supply information on COTS size and aggregation patterns, which are not currently captured through routine monitoring and surveillance. While SALAD is well-suited for monitoring COTS at low to mid densities and can provide early warnings of outbreaks, it suffers limitations: the intensive monitoring effort and specialist scientific expertise required is a limiting factor for its scalable deployment across a large number of reefs and the method requires scientific expertise.

The integration of these novel tools promises enhanced detection sensitivity, improved spatial coverage, and data robustness, potentially reducing costs and decision-making uncertainty (Lawrence et al. 2025). More specific details of each novel monitoring method can be found in other CCIP reports (Bainbridge et al. 2025; Pratchett et al. 2025; Uthicke et al. 2025). However, on-going and rigorous evaluation and comparison with established methodologies are necessary to ensure their efficacy and suitability for specific applications within the comprehensive COTS monitoring program. For this, co-deployment and calibration of the methods will be necessary, but not for every observation. See the CCIP-D-02 project report (Lawrence et al. 2025) for a more detailed discussion on this topic.

4.3. Monitoring potential environmental drivers

Our study also considered monitoring environmental covariates that are potential drivers of COTS outbreaks, as this is crucial for understanding the underlying mechanisms and developing effective management strategies. There are several reasons why collecting environmental covariates at the sites being monitored for COTS and coral cover would be valuable:

- Identify environmental drivers: Analysing relationships between environmental covariates and COTS/ coral data may finally shed light on key environmental drivers that trigger or exacerbate outbreaks or increase coral resilience/ recovery.
- Predict future changes: If we understand how COTS and corals correlate with different environmental conditions, we can potentially use environmental data to forecast or predict future changes based on projected environmental scenarios (e.g. warming temperatures, increased rain-drought event intensity (ENSO variability), southern migration of the South Equatorial Current).
- Improve model predictions: Environmental covariates can be incorporated into predictive models (e.g. CoCoNet and ReefMod) to improve their accuracy in estimating COTS densities and coral cover across broader scales.
- Disentangle multiple stressors and cumulative impacts: Reefs are impacted by multiple stressors besides just COTS (e.g. bleaching, pollution, cyclones). Environmental data can help disentangle the relative impacts of COTS versus other stressors.

- Inform management: Understanding environmental influences can guide more effective management actions, like identifying areas most vulnerable to outbreaks based on environmental conditions.

- Improve efficacy of sampling: Key environmental variables could be used to help identify locations that disproportionally increase variance in statistical inference. More of these locations could be sampled to reduce uncertainty.

The report highlights several parameters that are “high need” that would most contribute to achieving these outcomes and could be collected at relatively low-cost using water column profiling with a multiparameter sensor cage. These include temperature, salinity, and chlorophyll-a, which are crucial water quality indicators that may influence COTS dynamics. Additionally, monitoring algal cell numbers through discrete water sampling is considered a high need and low cost parameter. Several parameters are listed as "medium need," many of which can be obtained at low cost through the same water column profiling methods, such as turbidity, dissolved oxygen, and pH. Discrete water sampling for parameters like total suspended sediments, dissolved and total organic nitrogen and carbon can also provide valuable medium need data at relatively low cost. For parameters with potentially higher costs, such as monitoring zooplankton composition, CDOM, and continuous bioacoustics profiling, the need is listed as medium. While these data could provide insights into water quality, remote sensing applications, and COTS life cycles, the associated costs may need to be carefully weighed against the potential benefits.

A comprehensive monitoring program could obtain a substantial amount of high and medium need data related to water quality and potential COTS outbreak drivers through relatively low-cost methods like water column profiling and basic water sampling. Where it makes sense in terms of time and cost to collect this data at baseline sites, it should be done. However, more specialised and potentially costlier techniques could be selectively employed based on specific research priorities and resource availability. Marrying the collection of this environmental covariate data with a program like eReefs may be a cost-effective option and ensure data collected is fed into the model to reduce the uncertainty for unsampled locations.

4.4. Monitoring data to inform management and science questions

In light of our findings, we consider the four monitoring purposes and recommend the minimum changes need to improve the COTS Control Program’s ability to answer key questions.

4.4.1. Day to day management

COTS and coral cover data are required at both the site and individual reef scales to answer these questions, most of which are high priority for the COTS Control Program. The existing monitoring tools (manta tow, cull dives and RHIS) and programs (COTS Control, LTMP and RJFMP) provide adequate data to answer most of the day-to-day management questions. However, coral cover estimates required to inform decisions around effort deployment are not adequately provided by current methods. RHIS data shows extremely high variability, with coefficients of variation exceeding 30% at most reefs, making it unsuitable for reliable trend detection or management decisions. While manta tow provides more reliable reef-level estimates, it lacks the precision needed for detailed coral outcome assessments**.**

The tactical decision-making process could be significantly enhanced by increasing the spatial and temporal intensity of the data collection efforts according to a suitable statistical monitoring design. Additionally, the introduction of advanced measurement tools such as ReefScan could improve the accuracy of coral cover estimates at both site and reef levels, thereby overcoming known issues of variability (observer or inherent) in manta tows and RHIS.

Minimum changes recommended:

- Discontinue or significantly reduce the frequency of RHIS in the program as it is adding limited value to the COTS Control Program as it stands.
- Transitioning from manta tow to ReefScan (when it becomes available) for coral estimation could improve coral cover accuracy at both site and reef scales by reducing observer variability and providing continuous rather than categorical data. Integrating data from various monitoring programs requires ensuring measurement comparability across tools and observers and so a period of tool calibration will be essential. *CCIP-D-02* (Lawrence et al. 2025) trialled deployment of manta tow and ReefScan simultaneously, and this would be a cost-effective way to undertake tool calibration during a transition period.

To meet all objectives:

- Answering questions around coral composition at reefs where COTS are present would require the introduction of the 50 m point intercept transects (as per AIMS transect surveys) that are conducted alongside SALAD surveys at some reefs. Utilising photos and machine learning models as done by the AIMS LTMP program could be explored, but this methodology was not something that was identified at the start of this project. In addition, this objective is a lower priority than most others in this group of objectives.

4.4.2. Strategic planning

The highest priority questions around strategic planning relate to directly measuring and tracking COTS densities, culling efforts, and changes in reef condition due to management actions. Whilst the routine monitoring program, consisting of manta tows and cull dives at target sites, is well-suited to quantify the area of culled reefs over time, we note that it is not generalisable to sites and reefs beyond the sample. This is reflected in the bias demonstrated via the simulation study. Further, it faces limitations in accurately assessing COTS demographics across the GBR and detecting changes in reef condition attributable to culling efforts. Incorporating baseline monitoring according to a statistical monitoring design, and measurements with eDNA and SALAD surveys, could significantly improve the ability to track COTS densities, particularly at low levels, as well as measure the impacts of management interventions across varying environmental conditions. Some baseline reefs could be routinely monitored (annually), while others could be monitored opportunistically but selected a-priori based on the sample design. The benefit of this approach is that the opportunistic data is unbiased and can be used in answering many of the monitoring objectives.

For moderate priority questions, such as understanding COTS persistence outside outbreaks, monitoring spawning-related density changes, and detecting outbreak origins, the existing programs like routine monitoring and LTMP provide some insights but are constrained by their reliance on manta tows, which are unsuitable for measuring low COTS densities. eDNA and SALAD are recommended as complementary methods to enhance early outbreak detection and monitoring of COTS population dynamics. Assessing coral cover status is a moderate priority that could benefit from integrating ReefScan to improve spatial coverage and consistency. While LTMP offers valuable long-term coral cover data representing major environmental gradients, bioregions and zoning, it does not cover the full range of environmental parameters (including temperature, salinity, primary productivity, depth and sediment cover) (Mellin et al. 2020). Addressing questions about outbreak connectivity between regions would require a combination of these enhanced monitoring approaches across the different management areas.

Minimum changes recommended:

- Establish baseline monitoring at reefs across the GBR to contrast the effects of COTS management actions on reef condition. The reefs should be selected using an appropriate sample design, such as a spatially balanced cluster design. A set of 60–80 baseline reefs should be routinely monitored (annually). Additional reefs could be monitored opportunistically but selected a-priori based on the sample design for additional spatial coverage. Deploying ReefScan and eDNA sampling at these reefs would provide coral cover estimates and facilitate detection of COTS at low densities.

To meet all objectives:

- Answering questions around COTS population demographics, prior to culling, would be enhanced through the use of SALAD surveys or a similar equivalent that is not reliant on scooters. e.g. a small dive team. However, like the other visual survey methods there are limitations around detectability of juvenile COTS.

- Collecting eDNA both within and outside spawning season would provide the capability to estimate how COTS densities change during the spawning season, however this is a medium priority for the program.

4.4.3. Outcomes of management

Across the set of monitoring questions, this group generally have high priority but are less able to be answered using the existing data. The highest priority questions relate to quantifying the impacts of the COTS Control Program, both in terms of suppressing COTS across the GBR and enhancing overall reef resilience. The existing routine monitoring provides some insight into COTS densities at managed sites, but the potential lack of generalisability limits spatial scope. Further, the existing data collection is unable to robustly measure coral composition, or attribute changes to management actions with a high degree of certainty. Establishing widespread baseline monitoring at reefs, incorporating methods like SALAD surveys for coral composition data and eDNA for early COTS detection, could significantly improve the ability to evaluate program effectiveness in reducing regional COTS numbers and promoting resilience. Integrating ReefScan technology and monitoring of environmental covariates may additionally increase the accuracy and strategic value of data on culling effort requirements to reach sustainable COTS densities.

Moderate priority monitoring questions include understanding COTS dynamics outside of outbreaks and monitoring unmanaged reefs. While routine manta tows offer some relevant data (including COTS scars), their constraints in measuring and tracking changes in low COTS densities hinder insights into outbreak origins and COTS persistence patterns. eDNA monitoring emerges as a recommended tool to overcome this limitation. Continued LTMP monitoring can provide long-term context on coral cover trends at a subset of reefs. Lower priorities like detecting management impacts on coral health may warrant targeted small-scale studies if evidence arises.

Minimum changes recommended:

- Establish baseline monitoring at reefs across the GBR to determine whether the program is suppressing COTS numbers across the GBR and region levels and the impact on reef resilience. The reefs should be selected using an appropriate sample design, such as a spatially balanced cluster design. Some baseline reefs could be routinely monitored (annually), while others could be monitored opportunistically but selected a-priori based on the sample design. Deploying ReefScan and eDNA sampling at these reefs would provide coral cover estimates and facilitate detection of COTS at low densities. Until ReefScan can accurately detect COTS, manta tow would need to be deployed at these sites to distinguish higher COTS densities.

- Monitoring on reefs that were previously managed for COTS outbreaks usually stops once they leave the target list. For scientific understanding, it would be worthwhile to continue monitoring a proportion of these reefs to understand how culled sites behave in the very long term. These reefs could be a subset of the statistically chosen set for monitoring.

To meet all objectives:

- The point intercept transects conducted with SALAD surveys provide quantitative estimates of coral composition data alongside the COTS density data (albeit at shorter transects). While the AIMS LTMP program capture coral cover and composition, their transects are only in one habitat type per reef.

- Supplementing manta tow with ReefScan may improve the speed and accuracy of decisions around ecological thresholds in the future.

4.4.4. Science and knowledge gaps to inform COTS management

This is a diverse set of monitoring questions with the highest priorities revolving around understanding the key drivers, timing, locations, and progression patterns of primary COTS outbreaks across the GBR. The existing routine monitoring via manta tows and culling plays an important role by accumulating COTS density and distribution data over time. However, it is inherently limited by the lack of generalisability to other reefs and times, and also in its inability to detect the crucial early changes in low-density COTS populations that precede and signal emerging outbreaks. To comprehensively address these highest priorities, integrating eDNA monitoring and SALAD surveys at statistically chosen baseline reefs is recommended. Their ability to robustly track COTS densities at very low levels would provide invaluable advanced warning, allow for earlier outbreak detection, and when collected alongside environmental variables would enable modelling of environmental factors driving initiation events. Deployment of these methods across the GBR's diverse environments, complemented by the long-term contextual data from LTMP, could significantly improve understanding of outbreak progression patterns and high-risk areas.

For moderate priorities like elucidating COTS aggregation behaviours, the emerging ReefScan technology shows significant promise when combined with intermittent SALAD surveys.

Minimum changes recommended:

- Monitoring potential drivers of COTS outbreaks that are low cost in terms of resources would contribute to the collection of data that is crucial for understanding the underlying mechanisms of outbreaks and developing effective management strategies. These should be collected at all baseline monitoring reefs, chosen from a statistical monitoring design, but also at COTS control sites when it does not consume a large number of resources to do so.

To meet all objectives:

- Delineating the initiation box is a high priority for the program. eDNA and SALAD are both suited to monitoring COTS at low densities and so could be used to achieve this, although the exercise may be resource intensive. Sampling should occur at sites chosen by a suitable statistical design to guard against unintended bias.

4.5. Statistical designs for baseline monitoring

For data that generalises beyond the reefs that are directly culled, a statistically robust monitoring design is essential. The monitoring design simulations provided valuable insight into the performance of various sampling strategies for estimating average coral cover and COTS densities across the GBR. Using two different simulation models helped to demonstrate the choices around sample frame, inclusion probabilities and sample sizes. It is important to keep in mind that, these are just alternate models of a ‘reality’. We expect the statistical designs to perform similarly in terms of potential bias and relative uncertainty, even if these simulations don’t replicate the ‘truth’. However, the absolute variance in the estimates is likely to be higher in reality as we would expect more variability in the COTS and coral estimates than may be simulated by models.

4.5.1. Random sampling

The random sampling design, which is used as a baseline comparison of "best-yet-unrealistic-practice", demonstrated that increasing the number of monitored reefs leads to decreased variability in the estimates, with diminishing returns beyond a certain number of reefs. This finding is consistent with statistical sampling theory, where larger sample sizes generally result in more precise estimates. Notably, monitoring 50 to 70 randomly selected reefs across the GBR provides the ability to detect a COTS outbreak even if a relatively small proportion of the reefs are experiencing outbreaks. For example, if 5% of the reefs have a COTS outbreak, then monitoring 50 random reefs will detect a severe outbreak with a probability of approximately 75%, increasing significantly to above 90% for 100 reefs monitored. Monitoring 50 reefs also provides reasonable estimates of the status and trend of both COTS and coral across the GBR and the individual Regions. Given that the simulation was based on simulated (not real) data, we cannot say the exact number of sampled reefs that would give the equivalent result for a real monitoring program – except that 50 is likely to be a lower bound. The sample sizes are also based on answering the questions at the whole of GBR level and so reporting with equivalent uncertainty bounds at smaller spatial scales, e.g. Region, would require higher sample sizes.

4.5.2. Clustered sampling

The clustered random sampling design results showed that increasing the number of clusters (while keeping the total number of sampled reefs the same) decreased the variability of the estimates, similar to increasing the number of randomly sampled reefs in the random design. The clustered design with 16 clusters of 3 reefs (48 reefs total) only increased the uncertainty slightly compared to sampling 50 random reefs, suggesting that clustering reefs can be an efficient sampling strategy without sacrificing precision. In general, it is most statistically efficient to try to have more clusters of fewer reefs, but this needs to be balanced against the logistical issues of travel time and ease of trip planning (Foster et al. 2024). The main advantage of the clustered design is potential logistical and cost efficiency. By sampling reefs in close geographic proximity (clusters), travel time and expenses can be reduced compared to sampling completely random and potentially widely dispersed reefs. Spatially balanced cluster designs are a relatively new concept (Foster et al. 2024) and have not previously been utilised in the GBR.

4.5.3. Zone or Region or Reef Size-based sampling

When the designs were based on spreading the samples throughout different groups of reefs, (i.e. Green vs other zones, Region-based or reef size-based) the simulation study showed increased variance in the metrics. These designs are similar to stratified sampling, but do not enforce exact numbers within each stratum for each sample randomisation. All scenarios were unbiased but exhibited increased variability at the GBR level compared to random sampling. These designs would only be the best choice if providing estimates by Management zones, Regions or reef size is more important than providing estimates that are representative of trends at the GBR level.

4.5.4. Priority and Target reef sampling

Biased results were obtained in the simulation study when surveying only Priority and Target reefs. There was a noticeable difference between the estimated average coral cover and COTS density from monitoring only Priority reefs compared to the average over the entire GBR. These findings highlight the potential implications of limiting the sample frame to a subset of reefs in the monitoring program. By focusing solely on Priority or Target reefs, the trends in COTS densities and coral cover on non-Priority or non-Target reefs may not be accurately captured, potentially leading to a biased representation of the overall dynamics across the entire GBR. Some of the monitoring questions relate to COTS and coral status of reefs beyond the Priority reefs and so this potential bias is an important consideration. In contrast, sampling designs that consider all reefs for potential inclusion, even those with a low probability of being sampled, provide unbiased estimates of the temporal trends in COTS and coral cover. Additionally, the effective sample frame for the Priority and Target reef designs changes annually, further compounding the potential for biased estimates when using a restricted set of reefs for monitoring. The sample frames for the other sampling scenarios considered in this simulation study remained consistent over time and did not suffer from this issue.

4.5.5. COTS risk sampling

The COTS Risk Sampling monitoring scenario leveraged existing knowledge on the habitat preferences and risk factors associated with COTS outbreaks to inform the reef selection process for monitoring. By utilising the ensemble output which quantified COTS risk for individual reefs based on multiple environmental, water quality, connectivity, and spatial predictors (Matthews et al. 2020), inclusion probabilities were assigned to each reef in the GBR. Reefs with higher predicted risk were given a higher probability of being included in the monitoring sample, while still maintaining the potential for lower risk reefs to be represented.

We would expect the estimates based on this sampling method to be approximately unbiased, however this was not the case for the COTS estimates from CoCoNet. Further investigation revealed that a subset of 205 reefs were assigned a zero COTS risk by the Matthews et al. (2020) model due to missing data, effectively excluding them from the sample frame. However, these reefs exhibited non-zero COTS densities in the CoCoNet simulations, leading to an underestimation of the overall COTS density when they were excluded from the sample. By removing these zero-risk reefs from the sample frame, the COTS density estimates from CoCoNet would become unbiased, aligning with the accurate estimates observed for coral cover and the ReefMod-GBR model. This result highlights the need to carefully consider the sample frame and assigned probabilities. Should the COTS risk model ever be updated and zero risk reefs later have some risk assigned to them, the sample frame effectively changes. One reason we expect the models and the risk layer may differ is that there was insufficient data in the North to estimate COTS risk at the time.

Compared to the Random Sampling design with 50 reefs, the COTS Risk Sampling scenario exhibited increased variability in the coral cover estimates but similar or slightly lower variability for COTS density estimates. This trade-off between precision and potential bias highlights the importance of carefully evaluating the underlying assumptions and limitations of risk models used to inform monitoring designs. However, in a real-world deployment, with the 'true' COTS densities being reflected better by the risk layer, then it is expected that the variance should be slightly reduced. The concern of adopting this approach though is assuming that relationship in an ever-changing environment.

4.5.6. LTMP-based sampling

The results for the LTMP-based sampling design, which mimics the current LTMP but with a reduced number of 50 reefs to be comparable to the other scenarios, were difficult to interpret. When sampling across these reefs was simulated, CoCoNet exhibited consistent overestimation of coral cover and underestimation of COTS densities at the GBR scale. While the ReefMod-GBR estimates were closer to the model-simulated GBR-wide values, it is concerning both models showed different estimated trends in the COTS and coral cover compared to the simulated truth. Further investigation revealed that this discrepancy was primarily driven by differences in the representation of COTS densities across regions, with better agreement in the North and Central regions where LTMP sampling is more concentrated. The LTMP dataset adds huge value to the estimates of coral cover across the GBR due to the consistency in the sites monitored and the high-level of training provided to the divers. However, the results here show that the LTMP data may not necessarily provide statistically unbiased status or trend results at the GBR-scale, that are needed to answer some of the COTS Control Program's key objectives.

4.5.7. Monitoring design summary

Overall, the simulations highlight the trade-offs between sampling effort, logistical constraints, and the precision and accuracy of estimates. While random sampling provides a robust baseline, alternative designs such as clustered sampling may offer practical advantages without significantly compromising estimation quality.

4.6. Recommendations for implementation

The COTS Control Program requires three distinct but complementary monitoring approaches to address different information needs and management objectives. Each serves specific purposes and operates at different spatial and temporal scales to support tactical decision-making, strategic planning, and early outbreak detection.

4.6.1. Routine surveillance

Routine surveillance should continue to focus on supporting immediate culling decisions and operational efficiency at Priority and Target reefs selected annually through the IPM process. This surveillance provides the tactical information needed for day-to-day management decisions about where to deploy effort and when to stop culling individual reefs. The current approach of conducting manta tow surveys before, during, and after culling operations should be maintained, with timing dictated by IPM protocols.

However, our research has demonstrated that RHIS surveys should be discontinued from routine surveillance operations. Our analysis revealed that RHIS data shows coefficients of variation exceeding 30% at most reefs, making it unsuitable for the tactical decision-making that routine surveillance is designed to support. The effort currently allocated to RHIS could be better directed toward baseline monitoring or early warning surveillance activities.

When operationally feasible, routine surveillance vessels could contribute to baseline monitoring (see below) by surveying pre-identified cluster reefs located within their operational areas, providing cost-effective augmentation of the baseline program without compromising tactical surveillance needs.

As ReefScan technology becomes operationally reliable, it should initially complement and potentially replace manta tow surveys for routine surveillance. Our analysis indicates that ReefScan's concurrent collection of COTS and coral data on identical transects will significantly improve the program's ability to assess management effectiveness by directly linking culling efforts to coral outcomes.

4.6.2. Baseline Monitoring

Baseline monitoring represents the foundation for strategic planning and management effectiveness assessment, providing unbiased, GBR-wide data through a statistically designed cluster sampling approach. This monitoring will address questions that require representative data across the entire GBR, including trends in coral cover and COTS densities and assessment of management effectiveness.

The baseline monitoring program should adopt a spatially balanced cluster design approach with clusters and reefs-within-clusters chosen randomly. This approach performed well in the simulation and has the additional benefit of managing logistical constraints over a completely randomised design. A comprehensive master list of reef clusters should be established with substantial oversampling to allow for exclusion of clusters deemed unfeasible for safety or accessibility reasons. For each cluster selected for annual monitoring, the first three accessible reefs from the cluster list should be monitored, and these same three reefs must be revisited each subsequent year to maintain temporal consistency for trend detection. If one of the originally selected reefs becomes inaccessible, the next reef on the cluster list can be substituted, but this substitution should be permanent - the replacement reef should then be monitored in all subsequent years. Additional reefs within a cluster are available for opportunistic sampling but should not replace the core annual monitoring reefs. It is essential that reef selection be based solely on accessibility and safety considerations, not on prior expectations about COTS or coral status, to maintain statistical rigour. Conducting monitoring during a fixed time each year would reduce data noise and make the trends and patterns easier to identify.

The program should conduct annual monitoring at 16–20 clusters of three to four reefs each year, representing the minimum base level of baseline monitoring required. Additional sampling can be conducted on clusters outside the annually monitored set, following the master list order, with clusters 21–30 targeted for optional sampling in early years and progressing further down the list over time to gradually build spatial coverage.

For baseline monitoring methods, manta tow surveys should serve as the primary data collection tool, transitioning to ReefScan when it becomes operationally reliable. eDNA sampling should be implemented at all baseline sites to ensure detection of changes in low COTS densities that may be missed by visual surveys alone. Enhanced monitoring using SALAD surveys could be deployed at selected baseline sites where detailed coral-COTS relationship data is needed to address specific management effectiveness questions. Environmental covariate collection should be implemented at selected baseline sites to support research into outbreak drivers, though this requires substantial resource commitment and should be prioritised based on available capacity.

Resource allocation for baseline monitoring should involve discussions with the Reef Authority and RJFMP, with initial discussions indicating RJFMP may be able to contribute up to 30 days annually toward baseline monitoring, facilitating monitoring of approximately 9–12 clusters. Given RJFMP's expertise, training consistency, and standardised staff, maximising their contribution to baseline monitoring is preferable to minimise observer bias. Additional baseline monitoring should be completed by COTS Control vessels when their schedules permit, typically contributing one to two clusters per region annually, though this introduces some risk of observer bias that must be managed through standardised monitoring protocols.

4.6.3. Early warning monitoring

Early warning monitoring should complement baseline monitoring by providing systematic, repeated monitoring at high-risk locations to detect emerging outbreaks before they reach damaging densities. This represents a structured monitoring program distinct from ad hoc surveillance activities that respond to current intelligence about potential outbreak locations. While opportunistic surveillance based on reports or observations will continue to play a role in outbreak response, early warning monitoring involves planned, repeated visits to the same strategically selected reefs to build temporal datasets for early outbreak detection. Some reefs in the initiation area, the Southern tip of the Swains and reefs with consistently high connectivity identified through CCIP-R-05 (Choukroun et al. 2025) would be good candidates to consider.

eDNA sampling should serve as the primary method for early warning surveillance due to its capability for detecting COTS at low densities that might be missed by visual surveys. SALAD surveys should provide secondary support for detailed aggregation mapping and size structure assessment when needed. It is crucial to recognise that data collected through early warning monitoring will be inherently biased due to the targeted site selection approach. While this effort enhances the program's ability to swiftly identify and respond to emerging outbreaks, the resulting data should not be integrated with baseline monitoring datasets for broader GBR-wide analyses or assessments. The baseline monitoring data, collected through unbiased cluster design, must remain the foundation for strategic planning and management effectiveness evaluation. Detailed protocols for implementing early warning surveillance are provided in CCIP-D-03 and CCIP-P-04 project reports (Uthicke et al. 2025, Pratchett et al. 2025).

4.7. Project outputs

The main outputs of this project are:

- An evaluation of the effectiveness of nine different monitoring designs using simulations from CoCoNet and ReefMod-GBR.
- A synthesis of relative (not absolute) costs and benefits of undertaking monitoring of parameters that fill gaps in knowledge of outbreak drivers.
- Candidate monitoring designs to address various objectives.
- Recommendations on monitoring designs for future implementation.

5. RESEARCH SYNERGIES AND NEXT STEPS

This project has synergies with several other CCIP projects:

- The companion project *CCIP-D-02 Tool Comparison* (Lawrence et al. 2025) provides a calibration of the sampling tools and associated estimates of uncertainty. These outputs were directly incorporated into the *CCIP-D-01* project by considering the ability of each tool to collect data to answer the monitoring objectives. Having a thorough understanding of both the qualitative and quantitative differences between the sampling tools was imperative to the monitoring recommendations.

- The monitoring simulation exercise relied on outputs from both CoCoNet and ReefMod (*CCIP-R-04 Regional modelling* Skinner et al. 2025). The availability of these reef community models meant that we were able to simulate coral and COTS populations that may reflect realistic GBR scenarios rather than having to undertake a more theoretical statistical exercise that may be harder to interpret. The future collection of baseline monitoring data would in turn provide a valuable data source for improvements to these models.

- The results and learnings from the individual monitoring tools projects *CCIP-D-03 Operationalising eDNA monitoring* (Uthicke et al. 2025), *CCIP-D-04 The COTS Surveillance System* (Bainbridge et al. 2025) and *CCIP-P-04 Pre-outbreak monitoring* (Pratchett et al. 2025), were all important in the development of a comprehensive multi-tool monitoring plan.

The insights generated by this project, enriched by these collaborations, will lead to improved detection and monitoring capabilities for the COTS Control Program. If implemented, the monitoring recommendations will enhance the quality of information available to the program for informed decision-making. Notably, the statistical design recommendations are purposefully robust, ensuring that the collected data is unbiased and can be utilised by any other monitoring program in the future, such as the Reef Restoration and Adaption Program (RRAP) and the Reef Integrated Monitoring and Reporting Program (RIMReP). We developed a spatially balanced cluster methodology for the GBR that allows reefs to be clustered while maintaining good statistical monitoring properties. This is a novel methodology in the reef space and may be useful in the future for monitoring (beyond COTS) as it will cater better for trip logistics compared to a standard spatially balanced design and provides more robust data for decision making than hand selecting reefs.

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

1. Further consideration of the ReefScan technology

There were some delays to the development of the ReefScan technology. Throughout this report we have considered the technology in a theoretical sense i.e. how we expect the technology to operate. Once the technology is developed, implemented in the field and data collected, it would be pertinent to revisit the potential contributions to the monitoring program and reassess how the metrics from ReefScan compare to those from more established methods such as manta tow. This will be particularly important when reef habitat includes a steep wall, which may be difficult for ReefScan to obtain clear imagery. A further challenge with this technology in a monitoring sense will be to develop protocols around how to ensure the robustness of long-term trends when the technology may be continually developed.

2. Further research to understand why some reefs are not vulnerable to COTS outbreaks

By examining the characteristics of reefs that have not experienced outbreaks, researchers may uncover specific biological, ecological, or environmental factors that provide protection against these events. These factors could include the presence of natural predators, specific coral species compositions, or local environmental conditions. The baseline monitoring data will be very valuable in contributing to this understanding.

6. MANAGEMENT IMPLICATIONS AND IMPACT

Our findings can be summarised as a set of general recommendations for future monitoring of COTS and coral across the GBR:

- Adopt a statistically robust sampling design for baseline monitoring: The simulations clearly demonstrate the importance of implementing a well-designed sampling strategy to obtain unbiased and precise estimates of COTS densities and coral cover across the GBR. A random sampling approach, potentially with spatially balanced clustering for logistical efficiency, is recommended as a robust baseline. The baseline monitoring program should implement 16–20 clusters of three reefs each to be monitored annually, with additional clusters monitored opportunistically following the master list order. The reefs should be selected at the outset of the program through a master sample approach that provides a comprehensive list of potential monitoring clusters. This design ensures that the annually monitored clusters provide the temporal consistency essential for trend detection, while the opportunistic clusters gradually build spatial coverage across the GBR. Having a known probability of selection for the opportunistic reefs increases the utility and value of the monitoring data collected.

- Expand the sample frame: Limiting monitoring efforts to a subset of priority or target reefs can lead to biased estimates that do not accurately represent the entire GBR. It is crucial to consider all reefs for potential inclusion in the baseline monitoring program, even if some have a lower probability of selection based on risk factors or other criteria. This does not prevent the inclusion of other reefs from being monitored for specific purposes, such as early outbreak detection. However, the data from such reefs would need to be analysed carefully when answering some monitoring objectives, as they are purposefully biased.

- Integrate emerging technologies: Incorporating emerging tools like eDNA sampling, ReefScan, and SALAD surveys into the monitoring program can enhance detection sensitivity, spatial coverage, and data robustness. However, continued rigorous evaluation and comparison with established methodologies are necessary to ensure their efficacy and suitability for specific applications as they become integrated.

- Maintain a base level of monitoring: Even when regions of the GBR are not experiencing severe outbreaks, it is essential to have a minimum level of baseline monitoring to detect early warning signs, track changes in COTS densities outside of outbreaks, and understand long-term trends and patterns. An annual baseline monitoring program would serve this purpose.

- Collect environmental covariates: Monitoring environmental variables, such as water quality parameters (e.g. temperature, salinity, chlorophyll-a), in addition to COTS densities and coral cover, can provide valuable insights into potential drivers, improve predictive models, and inform management strategies. In the short-term, we recommend collecting those that are low cost (time and money) to collect alongside baseline monitoring or using ships of opportunity. In the long-term a good avenue for collection could potentially be integrating with eReefs.

- Adopt an adaptive management approach for routine surveillance and resource allocation: A flexible approach that allows for the adjustment of the balance between monitoring and culling efforts based on ongoing data and outbreak status is recommended for routine surveillance operations. The baseline monitoring program (16–20 clusters annually) must maintain consistency regardless of outbreak status to ensure statistical validity and trend detection capability. However, for routine surveillance at Priority/Target reefs, during periods of low outbreak activity across a region, monitoring emphasis could be increased with the ability to rapidly shift resources toward intensive culling when early warning signs are detected or outbreaks emerge. This is similar to what currently occurs through the IPM process, where if manta tow surveys do not trigger action at a cull site, monitoring continues at other sites and reefs rather than deploying culling effort.

- Regularly review and update monitoring strategies: As new information, technologies, and modelling approaches become available, it is essential to regularly review and update the monitoring strategies to ensure they remain effective and aligned with the latest scientific understanding and management objectives. This comes with the caveat that it is essential to consider any changes of design or tools, on the utility of resulting data for a broad range of monitoring objectives.

The findings and recommendations from this project have significant implications for various entry points within the COTS management framework. These include:

- COTS Strategic Management Framework: The proposed monitoring designs, particularly the baseline monitoring approach, directly contribute to the strategic planning and evaluation components of the COTS management framework. The improved data collection and analysis facilitated by the recommended designs will enable better assessment of management outcomes and inform future strategic decision-making.

- Annual Reef Prioritisation Process: Integrating the recommended baseline monitoring approach can provide a more comprehensive understanding of COTS dynamics across the GBR, potentially influencing the reef prioritisation outcomes.

- Integrated Pest Management Framework: The monitoring recommendations, particularly the integration of emerging tools like eDNA and SALAD surveys, align with the principles of an IPM approach. Early detection of COTS outbreaks and improved understanding of outbreak drivers, facilitated by the proposed monitoring designs, can enhance the effectiveness of management interventions.

- On-water Operations and Data Collection: The project directly addresses the need for a dedicated monitoring program to support on-water operations and data collection for the COTS Control Program. Implementing the recommended monitoring designs, including the integration of novel tools like ReefScan, eDNA, and SALAD surveys, will improve the quality and breadth of data collected during on-water operations.

In summary, the research conducted in this project contributes to achieving the overarching outcomes and impacts identified in the CCIP Research Impact Plan. The improved detection and monitoring capabilities facilitated by the recommended monitoring designs directly address the outcome of improved detection and monitoring. Furthermore, the enhanced understanding of COTS dynamics and the potential for more effective operational responses enabled by the proposed monitoring approaches support the outcomes of more efficient and effective operational responses, as well as more accurate prediction of outbreaks. Ultimately, these outcomes contribute to the overarching impact of suppressing and preventing COTS outbreaks, protecting coral cover across the GBR, and benefiting Traditional Owners, the tourism industry, and the broader community.

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8. DATA ACCESSIBILITY

The data generated for the simulations is stored on the CSIRO Data Access Portal (https://doi.org/10.25919/14ks-er54). The collection contains 4 files of 500 simulations:

- coconet_coral_df.csv (simulated coral data from CoCoNet)
- coconet_cots_df.csv (simulated COTS data from CoCoNet)
- reefmod_coral_df.csv (simulated coral data from ReefMod)
- reefmod_cots_df.csv (simulated COTS data from ReefMod)

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APPENDIX A – COTS MONITORING AND SURVEILLANCE INFORMATION NEEDS

Identifying why monitoring and surveillance data is needed is a crucial step that guides the monitoring design and process. The project team identified four broad categories of monitoring purposes to address the overarching data needs of the COTS Control Program, scientific community and other relevant stakeholders. The overarching purposes relate to:

1. Day to day management: What monitoring data do we need to collect to ensure that cull operations are effective and efficient on a daily to weekly basis?

2. Strategic planning: What monitoring data do we need to make effective management decisions about resources 6–12 months ahead?

3. Outcomes of management: What monitoring data do we need to assess the effectiveness of COTS program management?

4. Science and knowledge gaps: What monitoring data do we need to answer key science and knowledge gaps regarding COTS outbreaks?

The types of questions that fall under each of these categories, as identified throughout the project, are listed below.

1. Day to day management

- Where should the COTS Control Program cull effort be deployed?
- Where are the highest densities of the largest COTS?
- Where is the most coral to be 'saved' i.e. highest density reefs and/or regions?
- Where should we look for COTS and why (biology)? Patches within a reef or reefs?
- Where on the reef are the COTS that would be most readily managed?
- What is the dominant coral type at reefs with COTS?
- When should we stop culling individual reefs?

Summary of data needed to address the purpose:

The day-to-day management questions rely largely on estimates of the status of both COTS (density; size) and coral (density; type; conydition) at a fine spatial and temporal scale (within reef and within management action timeframes).

2. Strategic planning

- When to switch some of the control effort from culling to monitoring?
- Where are the highest priority areas for COTS management?
- How do COTS persist outside of outbreaks?
- What is the status of coral cover and composition across the GBR?
- What are the COTS densities and demographics across the reef?
- Do we need long term indicator sites (inner, central and outer reefs) to tease out specific disturbances?
- What data do we need to measure number of unique reefs/hectares surveyed per year, hectares of unique reef culled per year, hectares of reef sites that have been culled more than once a year, coral cover and their assemblages?
- Do we need to increase monitoring effort during spawning season?

Summary of data needed to address the purpose:

The strategic planning questions rely largely on estimates of the status and trend of both COTS (density; size) and coral (density; type; condition) at a broader spatial scale (reef/region) and at 6–12 monthly temporal scales (e.g. for voyage planning).

3. Outcomes of management

- How does reef condition (as measured by RIMReP indicators e.g. coral cover, COTS density) change due to COTS management actions?
- Do we need more extensive coral monitoring at COTS sites to evaluate impact of COTS management?
- Where is best to evaluate impact? Do we need reference sites?
- Are we protecting the cultural values of the reef?
- Are we suppressing COTS numbers?
- Are we boosting reef resilience?
- Has the density of COTS decreased to sustainable levels after control effort?
- How is coral cover influenced by COTS management? For example, do the control activities cause damage/disease?

Summary of data needed to address the purpose:

The outcomes of management questions rely largely on estimates of the status and trend of both COTS (density; size) and coral (density; type; condition) at a range of spatial scales (within reef/reef/region) and at locations where any potential effect of management actions are likely to be seen (and reference sites too).

4. Science and knowledge gaps

- What causes primary COTS outbreaks?
  - Water quality?
  - Natural causes?
  - Reduction in predators?
- When and where are outbreaks most likely to occur?
- Where is the initiation box?
- What is the progression along the coast?
- What are the conditions for a primary outbreak?
- What knowledge do Traditional Owners have about COTS outbreaks and what knowledge can scientists share with Traditional Owners to help improve these knowledge gaps?

Summary of data needed to address the purpose:

The science and knowledge gap questions are varied, each requiring very specific data to adequately address any given knowledge gap. However, data pertaining to status and trend of COTS and coral at various spatial scales and temporal resolutions will be beneficial to allow potential environmental drivers to be analysed alongside COTS and coral data.

APPENDIX B - SUMMARY OF EXISTING COTS AND CORAL MONITORING PROGRAMS IN THE GBR

Below is a summary of the relevant COTS and coral monitoring programs in the GBR.

Australian Institute of Marine Science (AIMS) LTMP monitoring

The AIMS Long-term Monitoring Program (LTMP) dates back to the mid-1980s. It provides data both at reef and within reef scale on COTS, coral and fish. It is designed to detect changes in reef communities at a subregional scale, including inshore, mid-shelf and outer shelf reefs (Australian Institute of Marine Science 2022). The LTMP conduct broadscale manta tow reef surveys of COTS populations and coral cover, intensive photographic surveys of benthic organisms on fixed 50 m transects and intensive visual counts of reef fish, juvenile corals, COTS, coral-eating snails (*Drupella sp.)* and coral disease and bleaching. There are 93 representative reefs that are routinely monitored annually as part of the program. Along with the RJFMP COTS Response Program, the LTMP delivers critically important reconnaissance of COTS outbreak and coral status across the Marine Park. These data are used to inform reef prioritisation and to guide tactical deployment of resources in the COTS Control Program.

Marine Monitoring Program Inshore

The Marine Monitoring Program (MMP) coral program monitors inshore coral reef communities at reefs adjacent to the Wet Tropics, Burdekin, Mackay-Whitsunday and Fitzroy Natural Resource Management regions. Data is collected from 32 reefs monitored at depths of two and five metres. Funding changes through the years have led to some reefs being surveyed every year, but most reefs have been surveyed every second unless a major disturbance event has occurred (for further details see Table 1 of Thompson et al. (2019)). Holding digital still cameras approximately 40 cm above the substrate, the scientists take approximately 40 photographs along a 20 m fixed transect (five transects per site). Percentage cover of corals and other benthic categories are estimated from five points on each image. SCUBA search transects (20 m x 2 m) are also undertaken to document the incidence of disease and other agents of coral mortality, including COTS. The MMP Inshore monitoring data is focused inshore so generally lower COTS risk sites.

The MMP also has a Water Quality program conducted jointly by AIMS and JCU to monitor ambient water quality (including grab sampling and data loggers) to collect a suite of physical, chemical, and biological water quality analytes at 22 sampling locations (Gruber et al. 2024). The water quality measurements include total suspended solids, Secchi disc depth, Chlorophyll-a, particulate and dissolved nutrients.

Eye on the Reef: Reef Health Impact Surveys

Reef Health Impact Surveys (RHIS) surveys are routinely conducted as part of GBRMPA's Eye on the Reef monitoring and assessment program across the GBR. Within circular plots of 5 m radius, snorkel or scuba divers estimate a range of coral health indicators including hard coral cover and the presence and extent of a range of impacts. In the context of the COTS Control Program these surveys are used to estimate coral cover to inform culling effort and augment the data collected via manta tow surveillance. Undertaking the RHIS requires three 10–20 minute surveys at each site. RHIS data are fine-scale and while they represent a fairly accurate measure of conditions at the sample site, Beeden et al. (2014)and Gladish et al. (2020) indicate individual surveys are not indicative at the whole of reef scale. Mellin et al. (2019)provide further support for this observation with analyses showing variation of up to 40% among trained observers in a structured RHIS comparison.

Reef Restoration and Adaption Program

The Reef Restoration and Adaption Program (RRAP) is a program bringing together some of Australia's leading experts on coral reefs to help the GBR resist, adapt and recover from climate change. EcoRRAP is designed to boost the success of RRAP interventions by providing advice on the what, where and when of coral/reef interventions. Under EcoRRAP, a field-testing program was established in 2021 and has successfully continued through 2023 and 2024, with monitoring now expanded to 64 reference reef sites with 352 permanent plots spanning from the Torres Straits to the Southern end of the GBR, significantly expanding from the original 19 reefs across 7 reef clusters. All sites are visited and surveyed annually, and if massive bleaching events occur, further surveys may occur. The Reference Reef sites will provide critical baseline datasets to support decision makers in determining how, why and where to deploy coral interventions. The Reference sites are research sites, chosen to cover a range of environmental gradients (e.g. flow, light, temperature, productivity) with a strong emphasis on coral demography. At each site a range of monitoring activities are being conducted (some annually and others one-off), ranging from estimating coral larvae settlement, juvenile coral densities, fish community structure and diversity to oceanographic monitoring, now enhanced with cutting-edge 4D photogrammetry techniques that allow scientists to track reef dynamics over time with millimetre-level precision.

While the data collected at these sites includes photogrammetry and video imagery of coral and COTS, COTS monitoring is not the primary purpose of monitoring these sites and so except for Lizard Island they are generally located North or South of the initiation box. Many of the sites are already monitored through the LTMP and MMP programs, however, it is the span of ecological and biophysical monitoring attributes that may be of interest to the COTS Control Program. The monitoring at the EcoRRAP reference sites is an excellent demonstration of how multiple monitoring methods can be employed at key sites to generate a detailed baseline of essential data (environmental variation, biological diversity and macroalgal dynamics) that can be used to investigate knowledge gaps.

Reef Joint Field Management Program (RJFMP) COTS Response

The RJFMP undertake both RHIS and manta tow surveys that provide valuable data to the COTS Control Program. These surveys provide good spatial coverage building our knowledge of the Reef, but do not include long-term fixed site monitoring and as such will contribute to the monitoring design by providing information about the historical distribution of COTS and coral cover rather than being considered as legacy sites.

Integrated Monitoring and Reporting (IMR) Fish monitoring

The IMR Fish monitoring project is an integrated reef fish monitoring program for species of recreational, commercial, bio-cultural and ecological significance in the GBR. The IMR monitoring program is currently being designed under Reef Trust Partnership funded research, however it builds on long-term legacy datasets collected by JCU, AIMS and others. Legacy fish and benthic community underwater visual census (UVC) data for inshore GBR reefs extends back to the late 1990's, while baseline inter-reefal baited remote underwater video (BRUV) data was established in the early 2000s.

Table A 1 Summary of relevant data collected under existing or planned GBR monitoring programs.

	COTS density	COTS size	Coral density	Coral type	Coral Condition	Other	Comments
AIMS LTMP monitoring	Yes, Reef-scale	Yes	Yes, Reef-scale + fine-scale	Yes, fine-scale	Yes	Fish counts	Combination of manta tow, photo transects and SCUBA methods giving data at a variety of scales
MMP Inshore	Yes, Reef-scale	Yes	Yes, Reef-scale + fine-scale	Yes	Yes	Water quality	Inshore reefs selection of reefs across water quality gradients
Eye on the reef RHIS	Yes, Site-scale	No	Yes, Site-scale	Yes	Yes		RHIS are point-based surveys with high spatio-temporal variation and observer bias. May still provide valuable data if the RHIS site replication is adequate.
RRAP	Yes	No	Yes, fine-scale	Yes	Yes		The Reference sites are being considered research sites, not long-term monitoring sites. They will be monitored annually for up to 4 years under RRAP.
RJFMP COTS Response	Yes	Yes	Yes	Yes	Yes		Manta tow and RHIS are used to provide broad scale reconnaissance of COTS outbreak and coral status across the Reef.
IMR Fish monitoring	Yes	Yes	Yes	Yes	Yes	Fish monitoring	Some benthic data will be collected including coral and COTS. This program builds upon legacy monitoring programs conducted by JCU and AIMS, however it is still in the design phase.

APPENDIX C – RHIS FOR MONITORING CORAL IN THE COTS CONTROL PROGRAM

Motivation

Many of the objectives for monitoring that were identified in the early stages of the project require coral measurements at sites being managed by the COTS Control Program. Many of these questions fall under a group of questions we could summarise as “measuring the outcomes of COTS management”. The questions include:

- How does reef condition across the GBR (as measured by RIMReP indicators e.g. coral cover, COTS density) change due to COTS management actions?
- What is the trend in coral cover at COTS management sites?
- Where is best to evaluate impact? Do we need reference sites?
- How is coral cover influenced by COTS management? For example, do the control activities cause damage/disease?
- What is the coral loss due to COTS?

Currently there are two monitoring techniques used by the Control Program to measure coral: RHIS and manta tow data. Here, we look at the effectiveness of Reef Health Information Surveys (RHIS) data in answering some of these questions.

RHIS data

RHIS are snorkel or scuba dive surveys that collect quantitative and qualitative information on coral cover and factors that may impact coral cover on reefs, including crown-of-thorns starfish, coral bleaching, coral disease, and physical damage (Beeden et al. 2014). Each RHIS survey covers a 5 m radius area, with three RHIS survey locations distributed at roughly equal distances across each site resulting in a total survey area per cull site of 235 m². Each site takes approximately 20 minutes to survey. RHIS data are collected through many monitoring programs across the reef, including the COTS Control Program, the Eye on the Reef program, and the Reef Joint Field Management Program. The two deployment methods of RHIS that are most relevant to the Control Program are:

- **Surveillance RHIS** – permanent GPS marked sites around the perimeter of a reef, conducted approximately twice a year, which was initiated in October 2021. These are fixed locations that are repeatedly surveyed to track changes over time.

- **Cull Site RHIS** – permanent GPS sites within cull sites intended to monitor the decline/recovery of coral during and after culling visits. Each RHIS point is permanently marked with a steel picket to ensure the same area is surveyed in each survey.

We looked at these two datasets separately with a view to get a better understanding of how these surveys perform in terms of estimating coral cover and their statistical power to detect change.

Surveillance RHIS

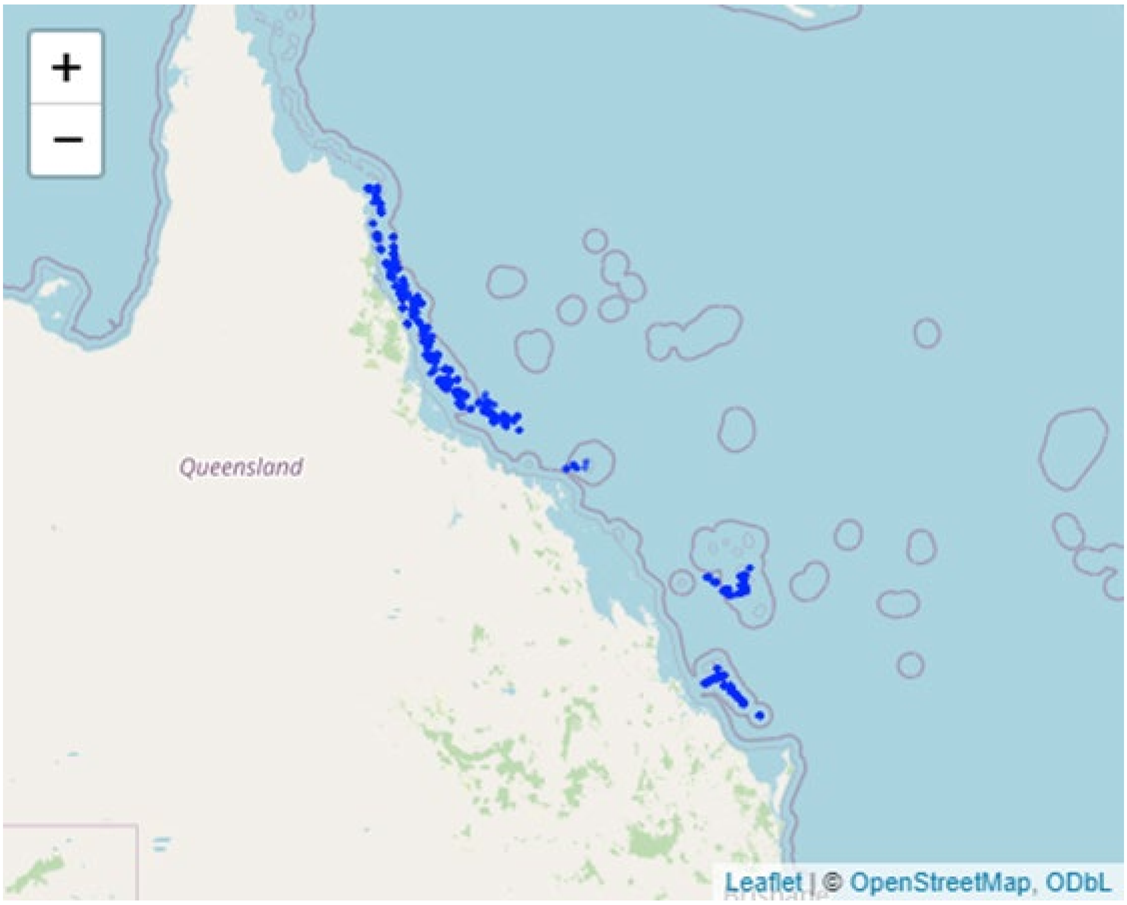

Figure A 1 Distribution of RHIS surveillance data.

Looking at RHIS sites that have at least 25 records (this should be at least three visits for smaller reefs (12 RHIS) and at least two for larger reefs (24 RHIS)). Fitting a linear trend to each reef provided an indication of the variability at the visit/reef level and the trend in the mean and associated 95% confidence intervals. The variability was high but the reef-level trends look reasonable (in line with plausible changes in coral cover). However, most of the reefs here were the bigger ones with more than 12 RHIS per visit (a product of our subsetting to reefs with at least 25 records) so we have removed a lot of the inherent variability in the data and forced a linear trend through time.

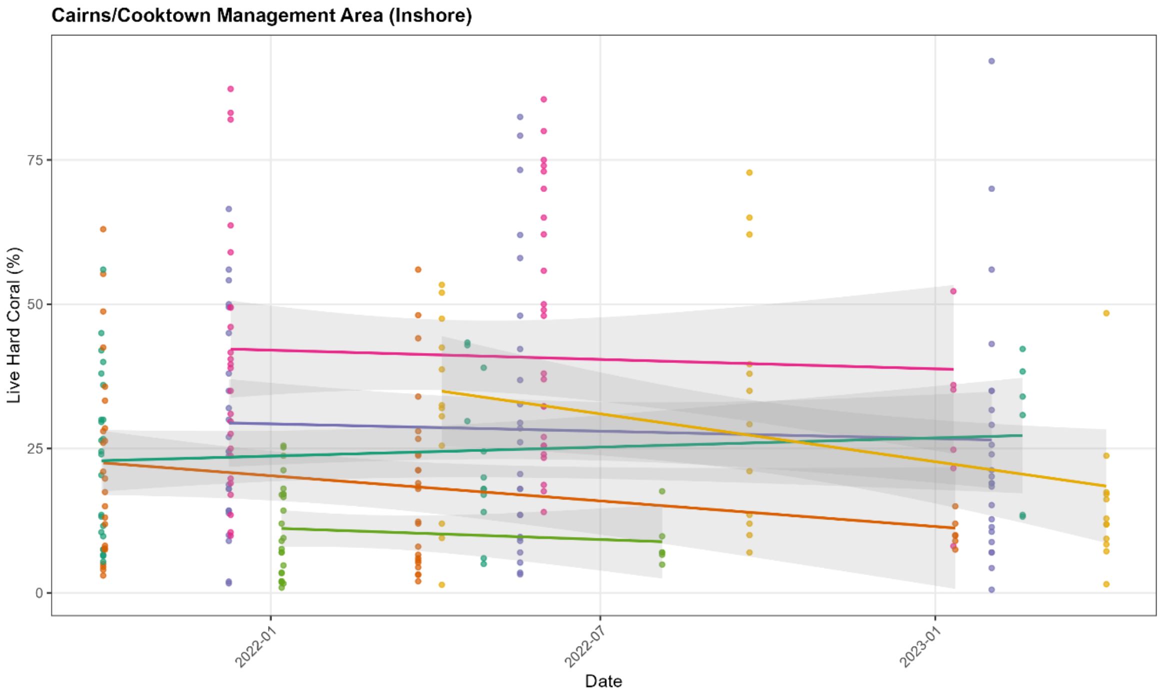

Figure A 2 Estimated linear trends in hard coral cover at reefs in the Cairns/Cooktown Management Area (Inshore) using surveillance RHIS. Different colours are used to represent the RHIS (points) and trend (line) at each reef.

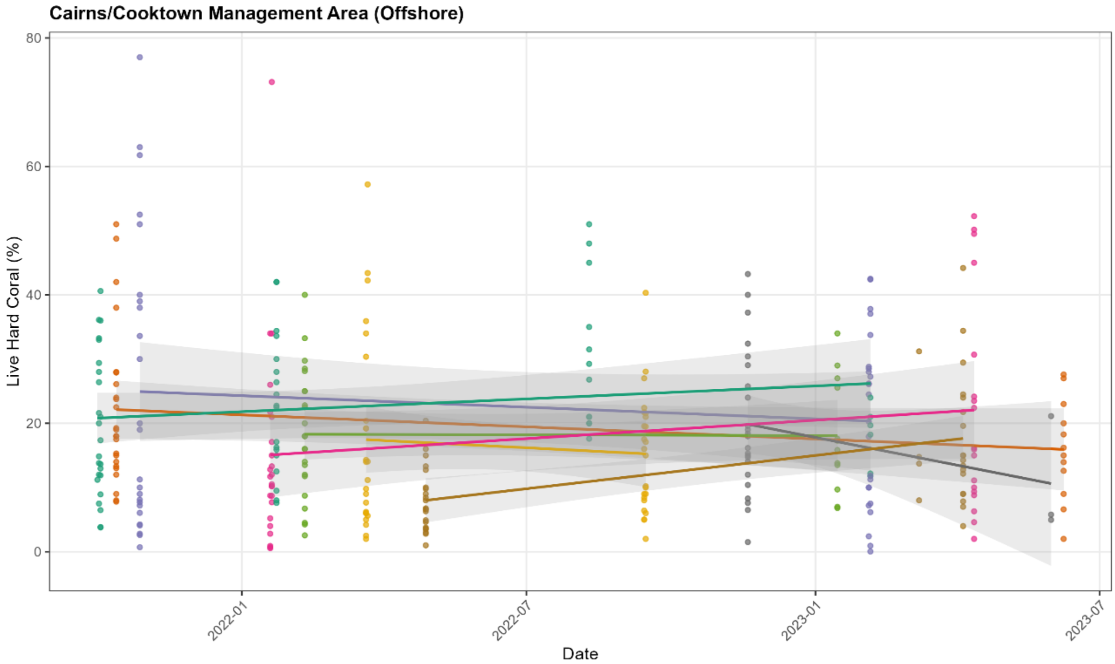

Figure A 3 Estimated linear trends in hard coral cover at reefs in the Cairns/Cooktown Management Area (Offshore) using surveillance RHIS. Different colours are used to represent the RHIS (points) and trend (line) at each reef.

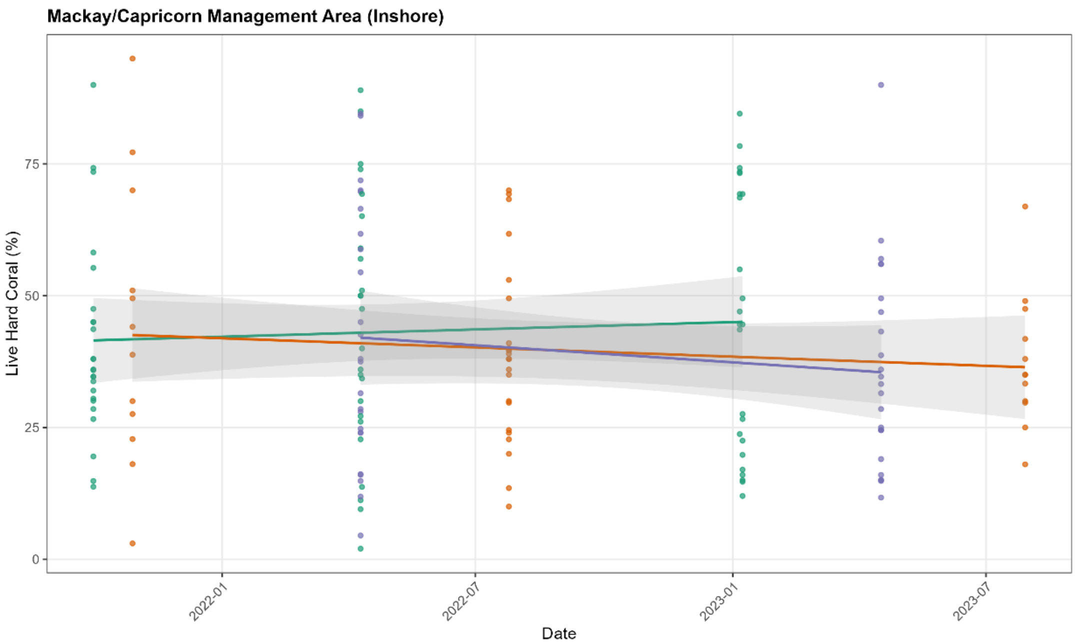

Figure A 4 Estimated linear trends in hard coral cover at reefs in the Mackay/Capricorn Management Area (Inshore) using surveillance RHIS. Different colours are used to represent the RHIS (points) and trend (line) at each reef.

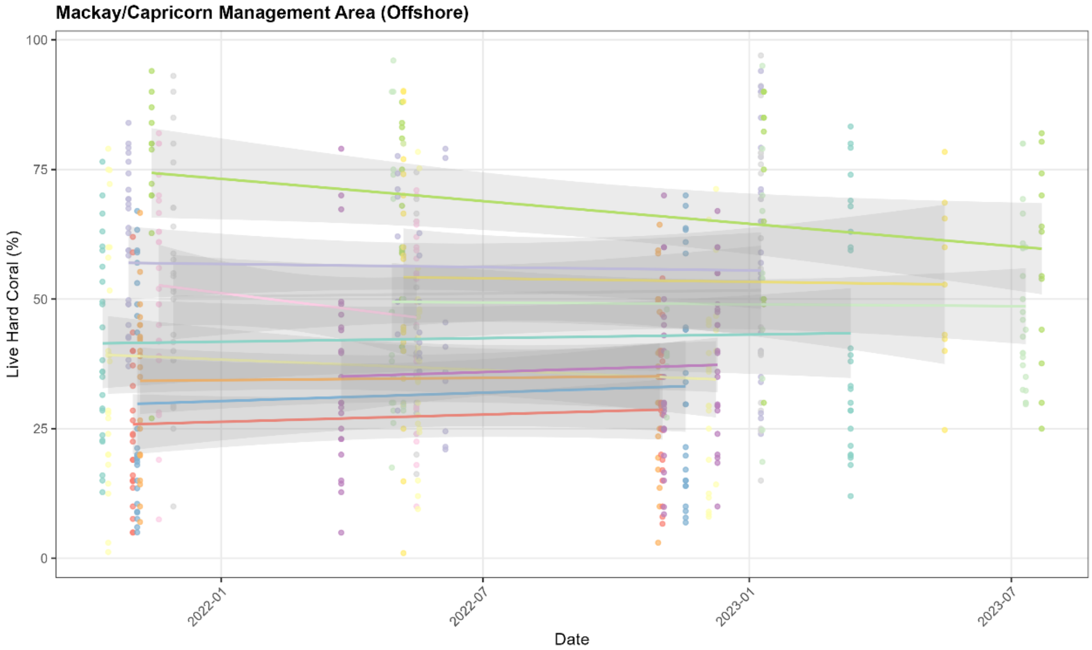

Figure A 5 Estimated linear trends in hard coral cover at reefs in the Mackay/Capricorn Management Area (Offshore) using surveillance RHIS. Each line represents a different reef. Different colours are used to represent the RHIS (points) and trend (line) at each reef.

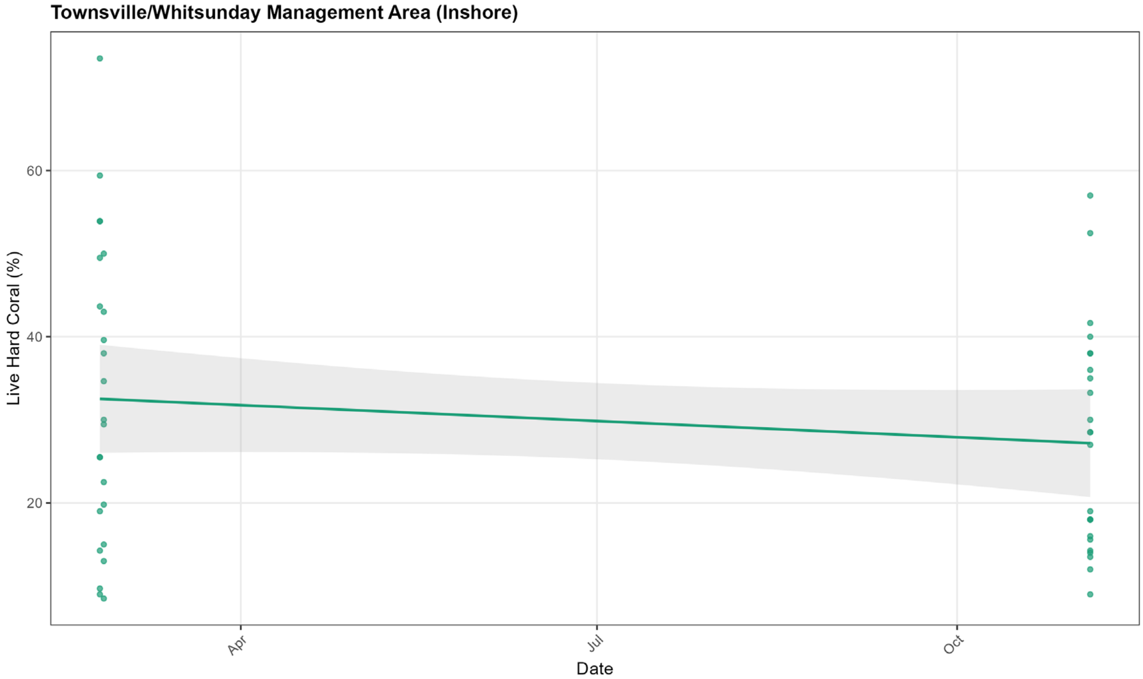

Figure A 6 Estimated linear trends in hard coral cover at reefs in the Townsville/Whitsunday Management Area (Inshore) using surveillance RHIS. Each line represents a different reef.

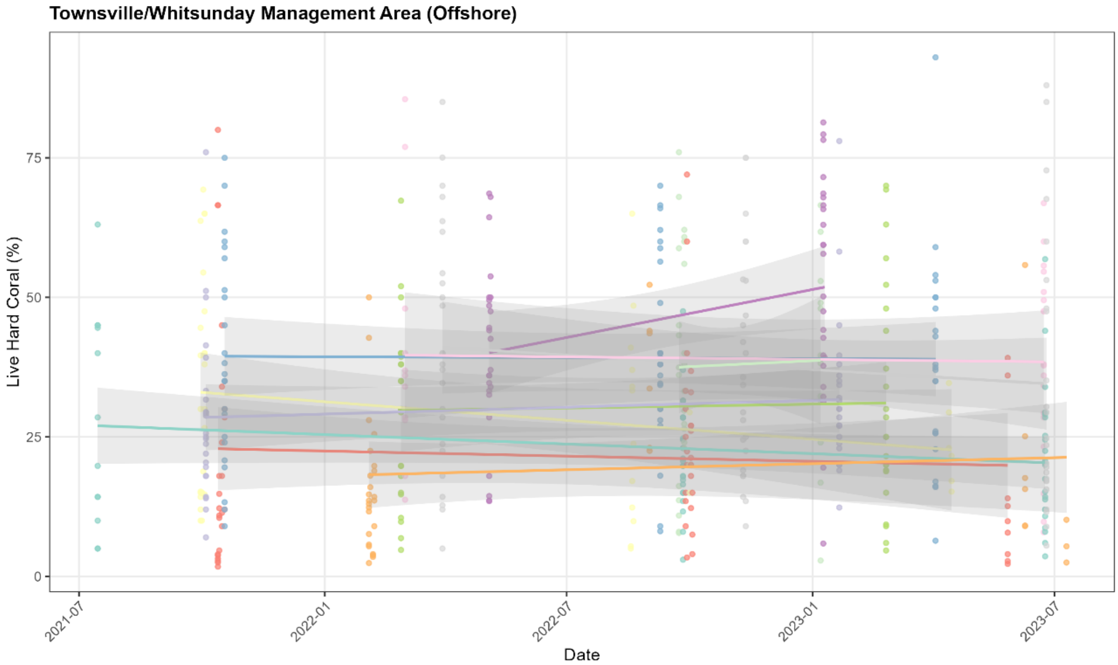

Figure A 7 Estimated linear trends in hard coral cover at reefs in the Townsville/Whitsunday (Offshore) using surveillance RHIS. Each line represents a different reef.

The distribution of the number of RHIS at a reef per visit is shown in **Figure A 8**. Most are the standard 12 or 24 but there were a significant number of occasions where that wasn't the case, perhaps indicating that sometimes the full survey procedure was not completed.

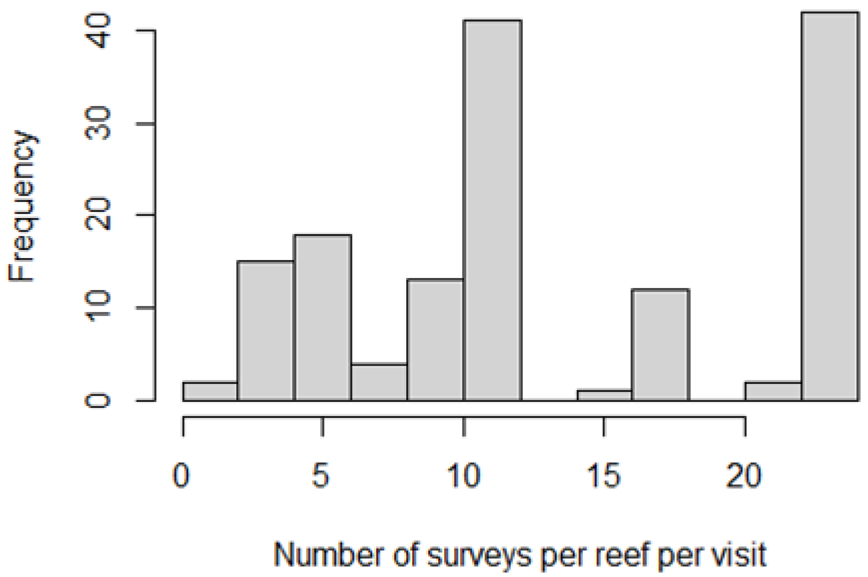

Figure A 8 Number of surveys per reef per visit.

Completing a similar exercise to above, we looked at how much a mean can change through time if we didn’t force the trend through time to be linear (each line represents a reef and the observations are the individual RHIS). We first restricted to reefs with at least 40 RHIS so the plots weren’t overwhelmed with data. You can see that in general the mean hard coral cover fluctuated far more than you would expect in reality. You may expect a large negative drop with a COTS outbreak or other disturbance but not a large positive change within a short time period.

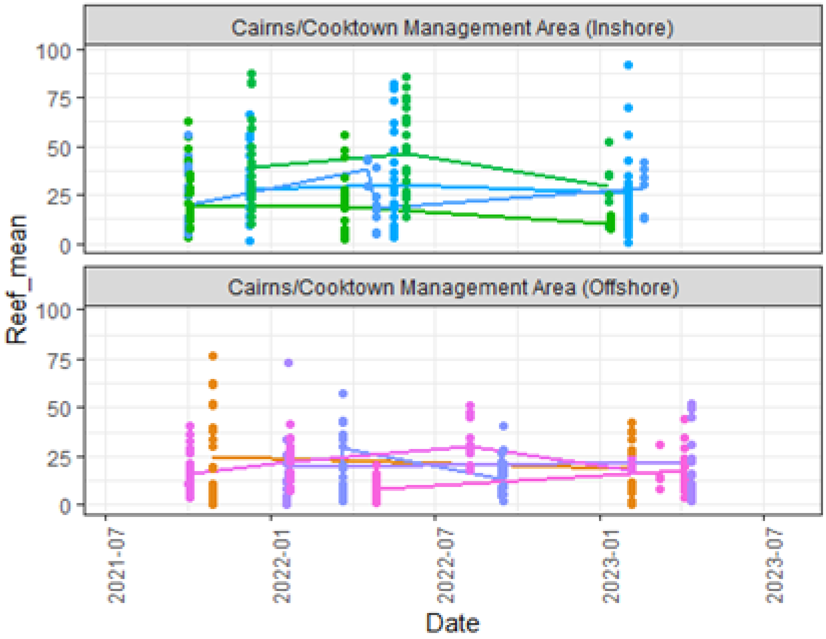

Figure A 9 Mean hard coral cover at reefs with at least 40 RHIS in the Cairns/Cooktown Management Area (Inshore and Offshore) using surveillance RHIS. Each line represents a different reef.

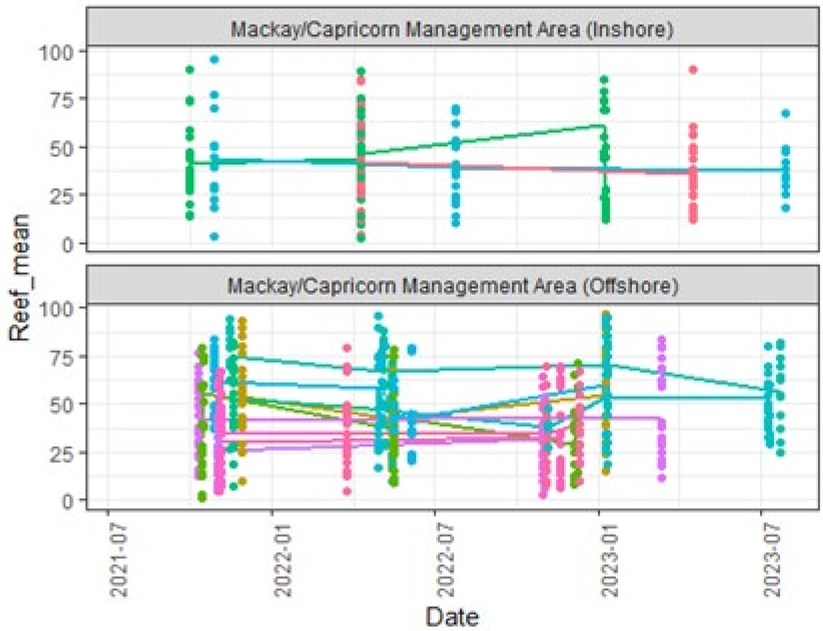

Figure A 10 Mean hard coral cover at reefs with at least 40 RHIS in the Cairns/Cooktown Management Area (Inshore and Offshore) using surveillance RHIS. Each line represents a different reef.

Figure A 11 Mean hard coral cover at reefs with at least 40 RHIS in the Townsville Management Area (Inshore and Offshore) using surveillance RHIS. Each line represents a different reef.

Looking at reefs that have been surveyed irregularly (with less than 40 RHIS), there were some very large changes over very small-time scales.

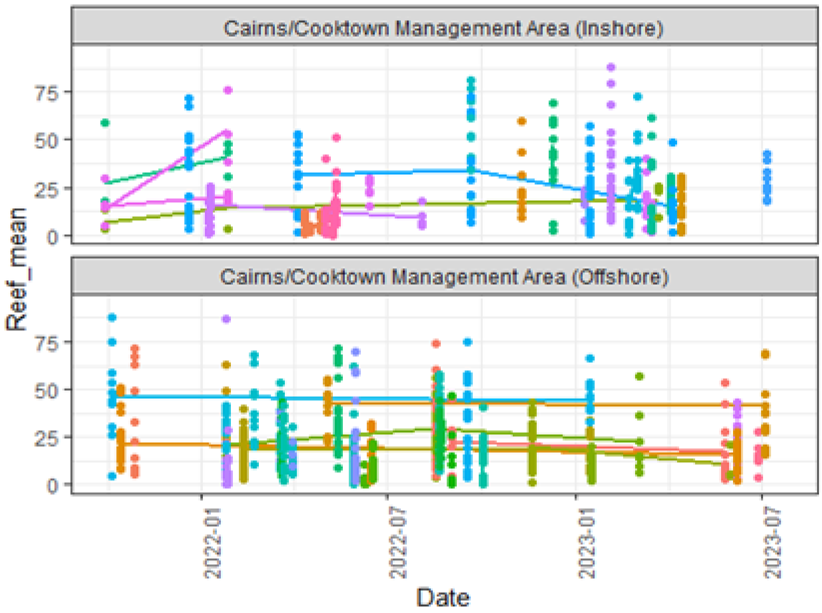

Figure A 12 Mean hard coral cover at reefs with less than 40 RHIS in the Cairns/Cooktown Management Area (Inshore and Offshore) using surveillance RHIS. Each line represents a different reef.

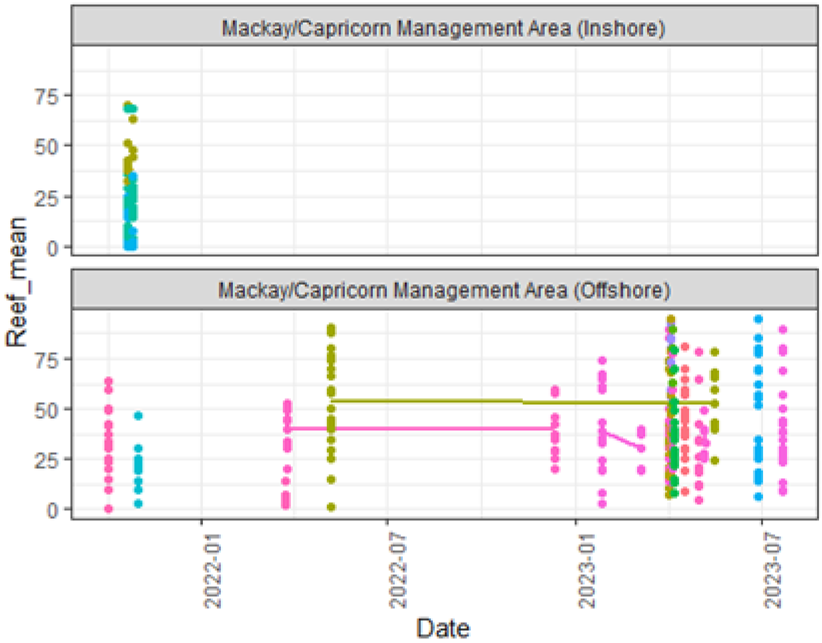

Figure A 13 Mean hard coral cover at reefs with less than 40 RHIS in the Mackay/Capricorn Management Area (Inshore and Offshore) using surveillance RHIS. Each line represents a different reef.

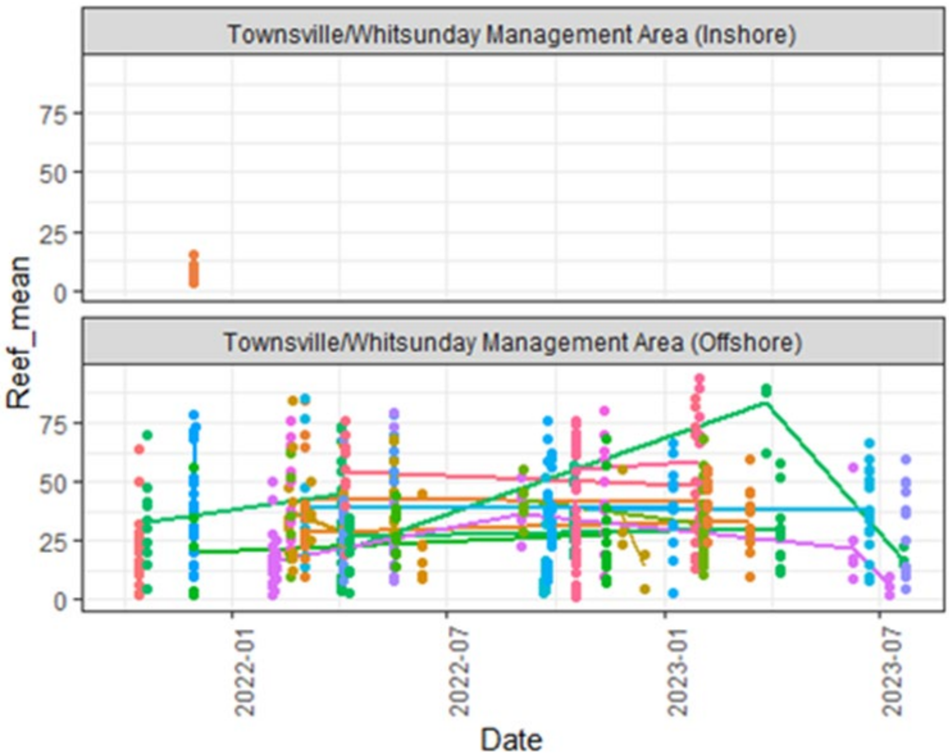

Figure A 14 Mean hard coral cover at reefs with less than 40 RHIS in the Townsville Management Area (Inshore and Offshore) using surveillance RHIS. Each line represents a different reef.

The coefficient of variation (CV) is a statistical measure that expresses the degree of variability in a set of data relative to its mean. It is particularly important when considering the value of monitoring data collected because it provides insights into the precision and reliability of the data. When monitoring environmental variables or ecological parameters, there is inherent variability in the measurements due to various factors such as spatial heterogeneity, temporal fluctuations, and measurement errors. A high coefficient of variation indicates that the data is more dispersed and less consistent, which can impact the ability to detect meaningful patterns or trends. Conversely, a low coefficient of variation suggests that the data is more tightly clustered around the mean, increasing confidence in the observations and conclusions drawn from the monitoring data.

We plotted the CVs at each reef at each point in time. We indicated a line at 30% because a CV of 30% is considered high, but in ecology it would not be uncommon due to the natural variability in what is being measured. Here, the great majority of CVs are greater than 30% with many points far exceeding 30%. CVs that are very large like these suggest that the survey data is not adequate for estimating long term trends due to the very large amount of variability in the data. The variability is likely due to the patchiness of coral at the reef scale not being adequately captured by such small-scale surveys.

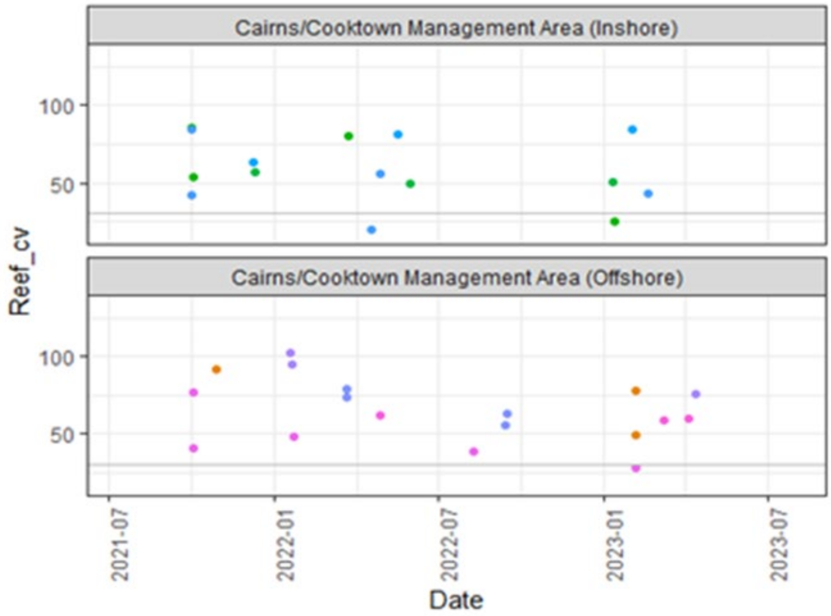

Figure A 15 Coefficient of variations for each visit to a reef in the Cairns/Cooktown Management Area (Inshore and Offshore). The grey dotted line indicates a CV of 30%.

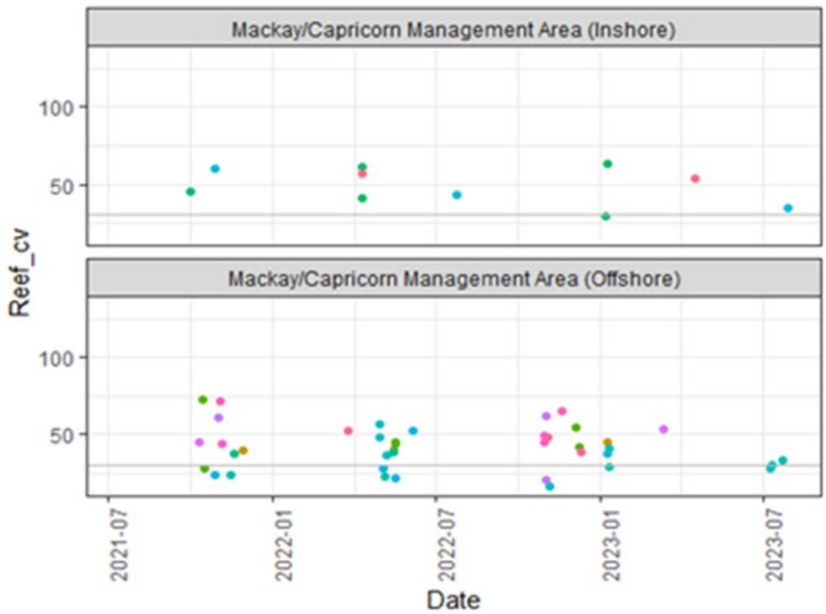

Figure A 16 Coefficient of variations for each visit to a reef in the Mackay/Capricorn Management Area (Inshore and Offshore). The grey dotted line indicates a CV of 30%.

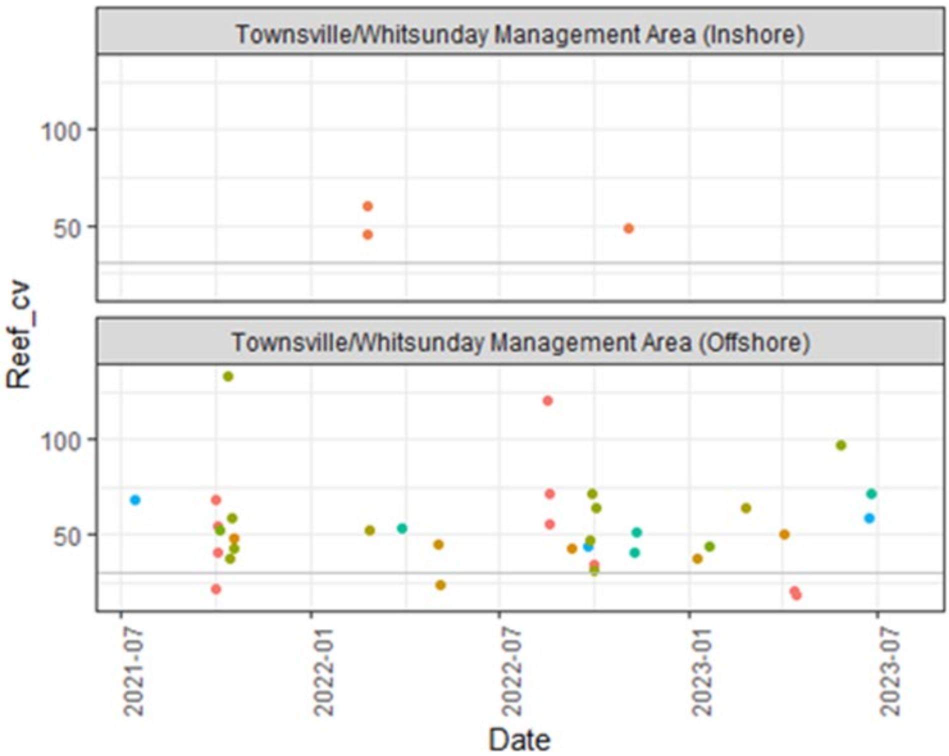

Figure A 17 Coefficient of variations for each visit to a reef in the Townsville/Whitsunday Management Area (Inshore and Offshore). The grey dotted line indicates a CV of 30%.

COTS Site Revisit

We also analysed the RHIS data collected at cull sites before and after culling. If you look at the RHIS data at a reef level, some have had many RHIS completed (**Figure A 18**). These are likely to be reefs that have had many control sites open.

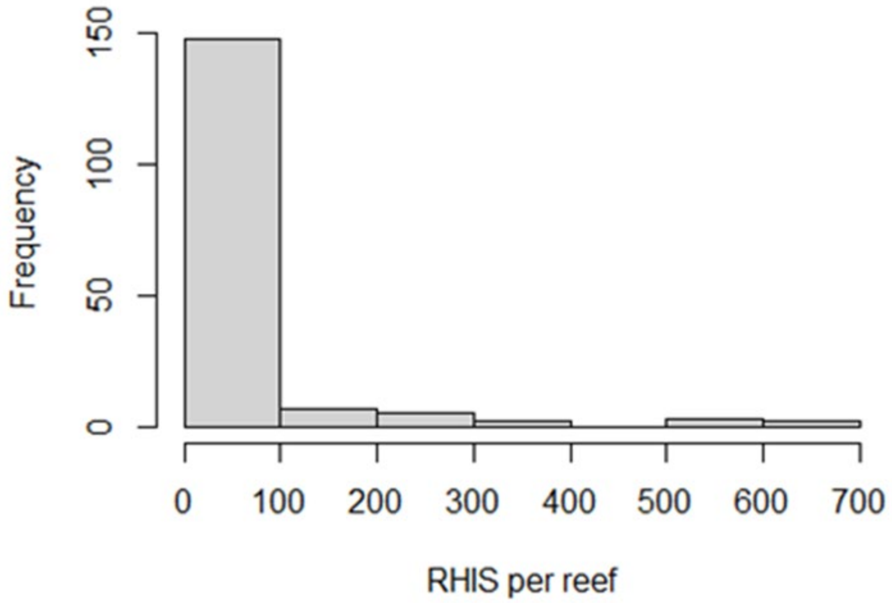

Figure A 18 Number of RHIS per reef in the cull site revisit data.

If we look at the data at the cull site level (**Figure A 19**), you can see most have been surveyed less than ten times.

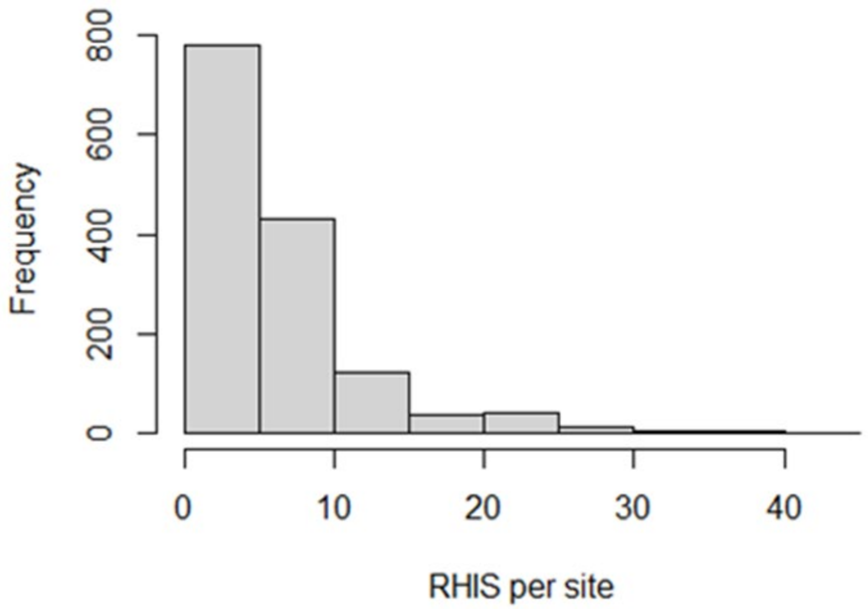

Figure A 19 Number of RHIS per site in the cull site revisit data.

Analysing the hard coral cover and fitting a linear trend to the mean at the site level through time, you can still see that tracking coral cover through time at the site level is not sensible given the huge variability in the data. There are huge changes in mean coral over relatively small timeframes, that realistically could not occur. Note: we only show a subset of the reefs in the Figures. The large increases over short timeframes could be attributed to either inherent randomness/variability or observer bias either of which means that this survey method is not fit for measuring trends in coral as it stands.

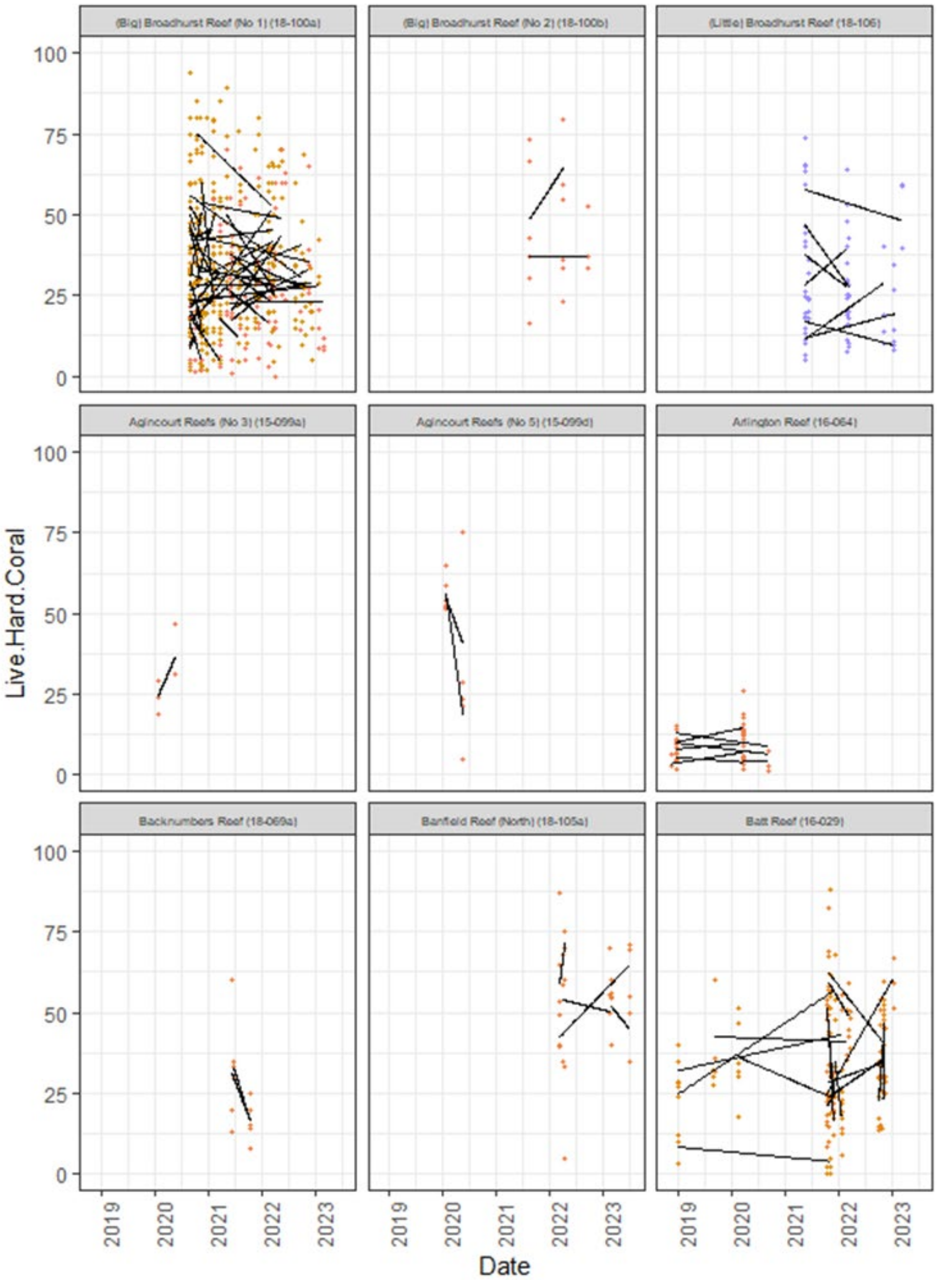

Figure A 20 Mean hard coral cover based on RHIS at cull sites that have been revisited. Each line represents a different site and each point a different RHIS.

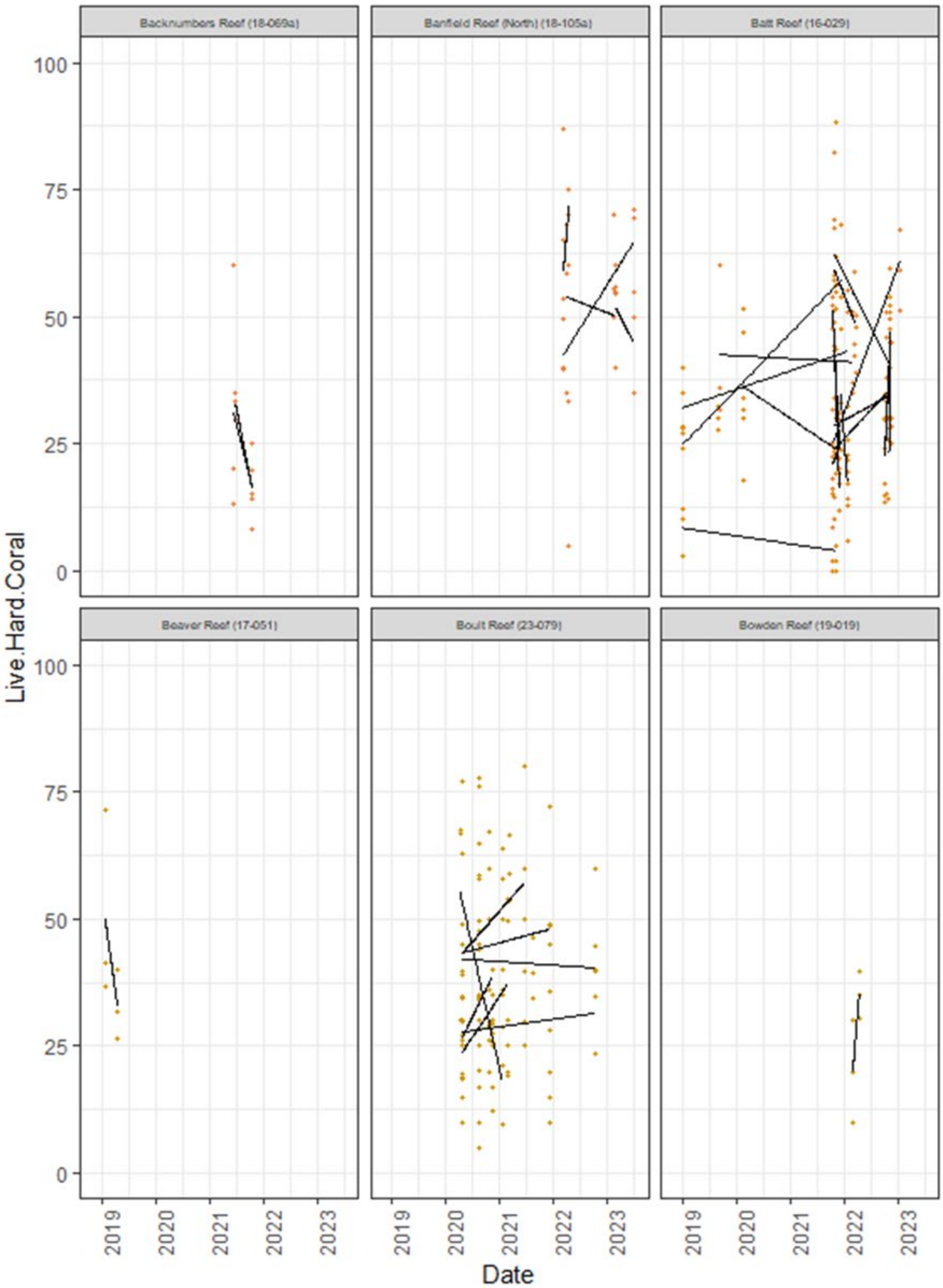

Figure A 21 Mean hard coral cover based on RHIS at cull sites that have been revisited. Each line represents a different site and each point a different RHIS.

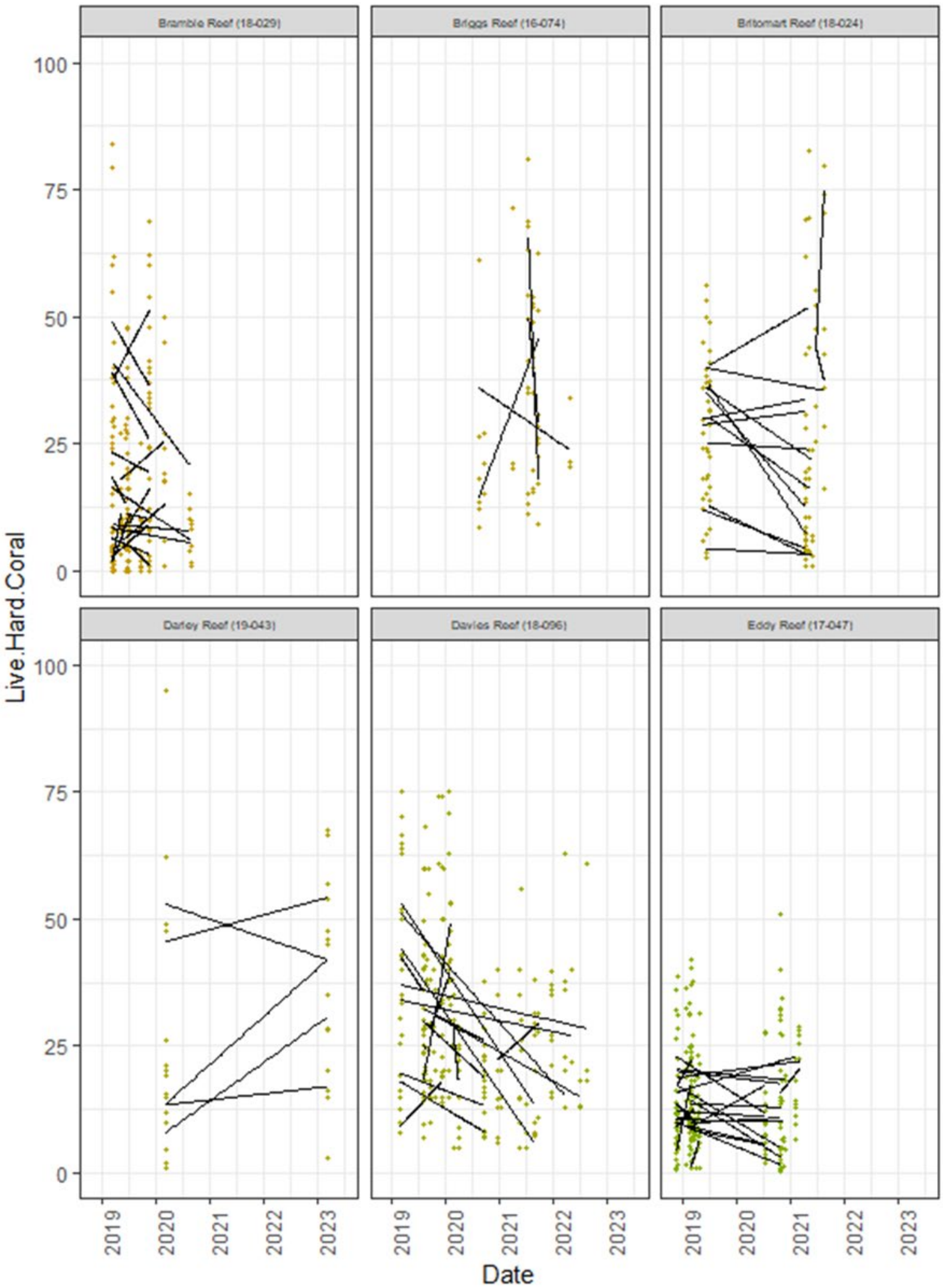

Figure A 22 Mean hard coral cover based on RHIS at cull sites that have been revisited. Each line represents a different site and each point a different RHIS.

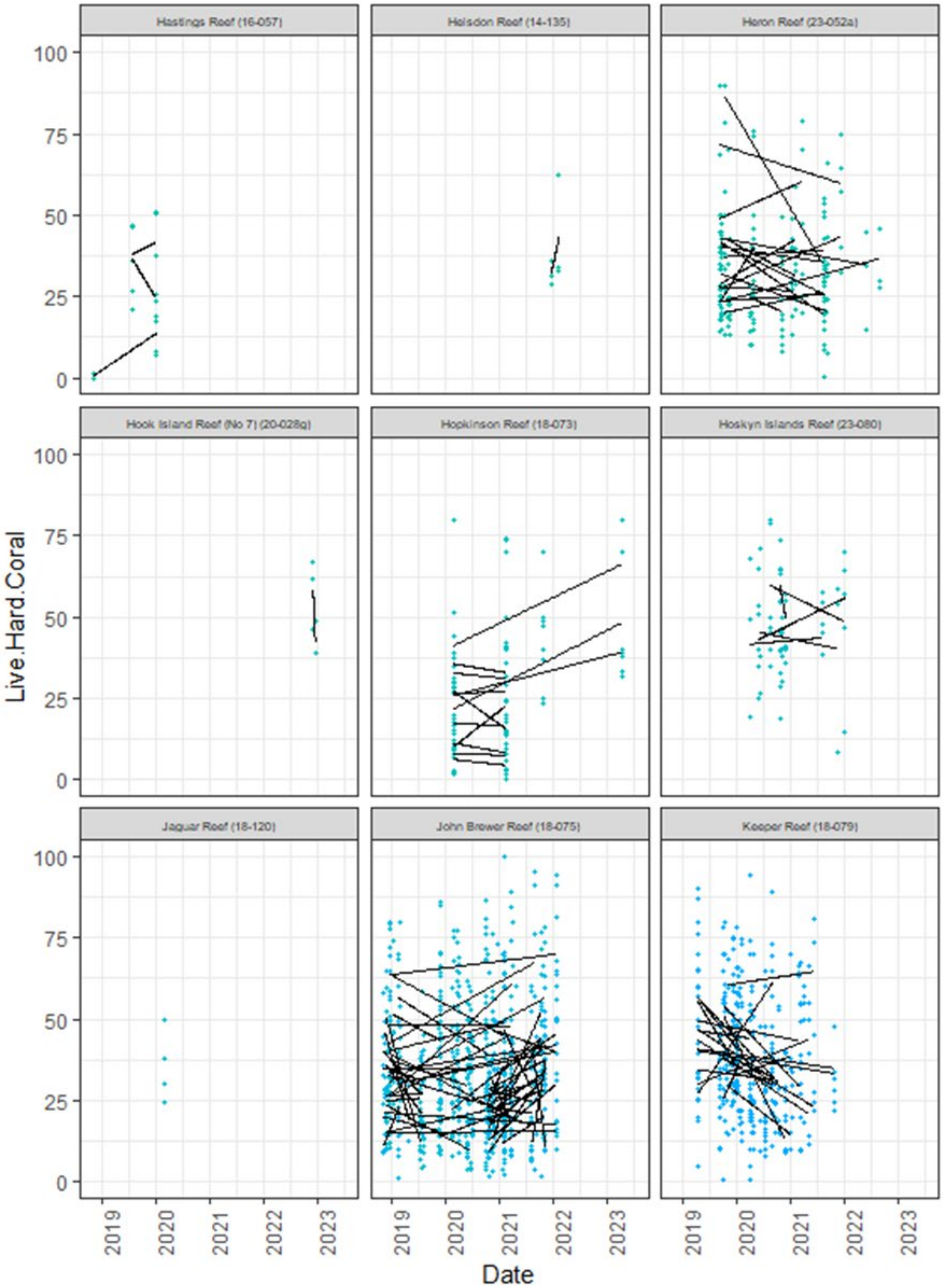

Figure A 23 Mean hard coral cover based on RHIS at cull sites that have been revisited. Each line represents a different site and each point a different RHIS.

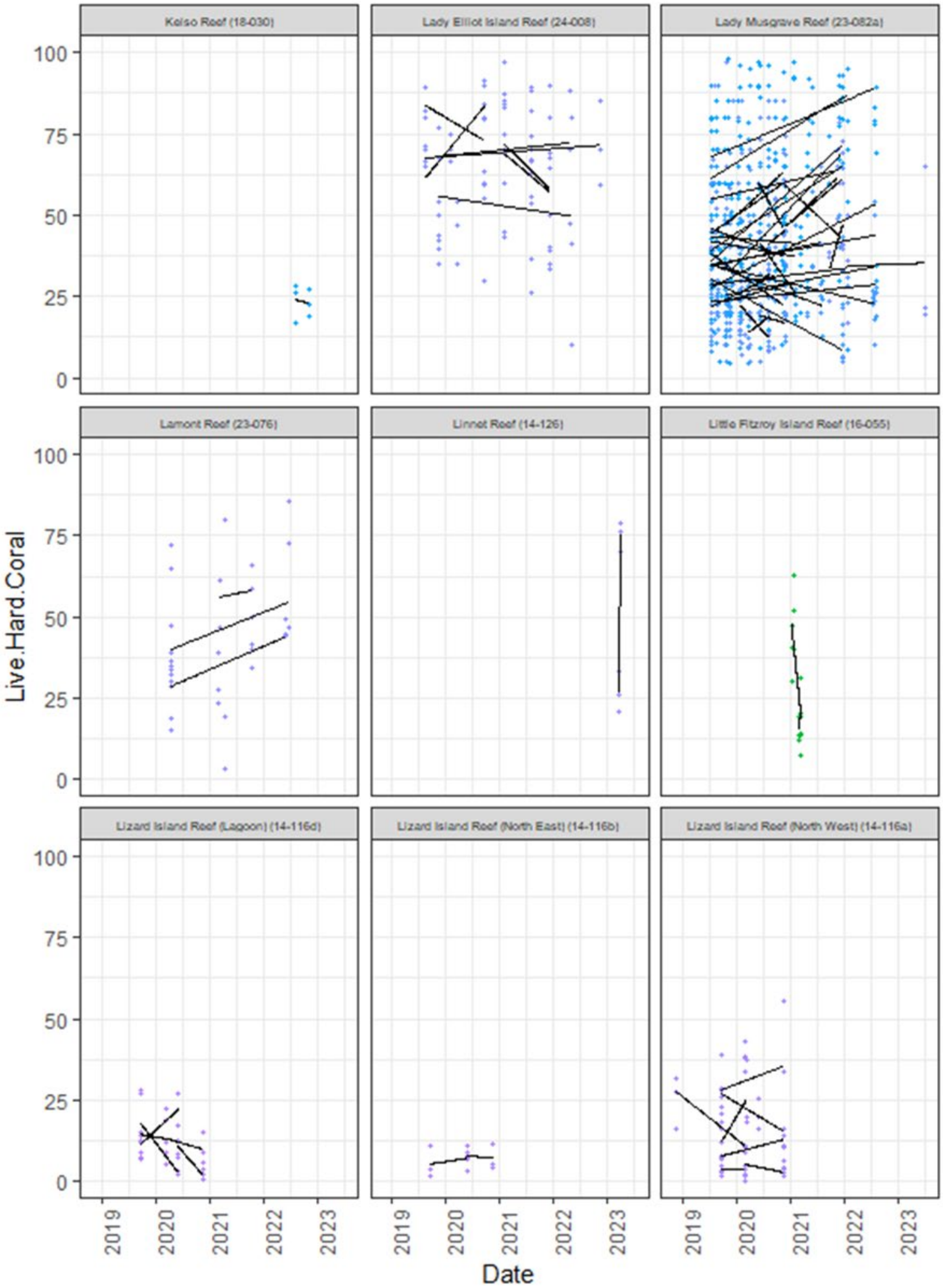

Figure A 24 Mean hard coral cover based on RHIS at cull sites that have been revisited. Each line represents a different site and each point a different RHIS.

If we look at the CVs for this dataset, the values are again very high.

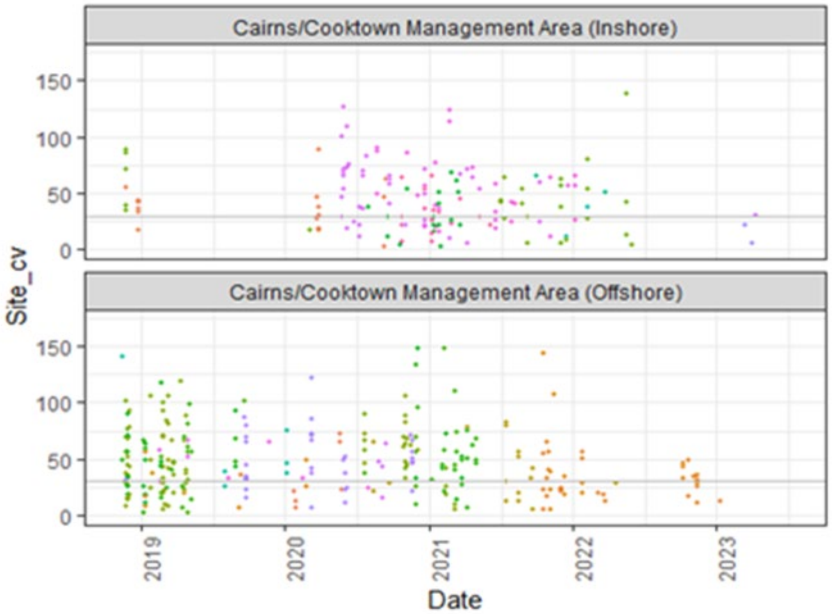

Figure A 25 Coefficient of variations for each visit to a site in the Cairns/Cooktown Management Area (Inshore and Offshore). The grey dotted line indicates a CV of 30%.

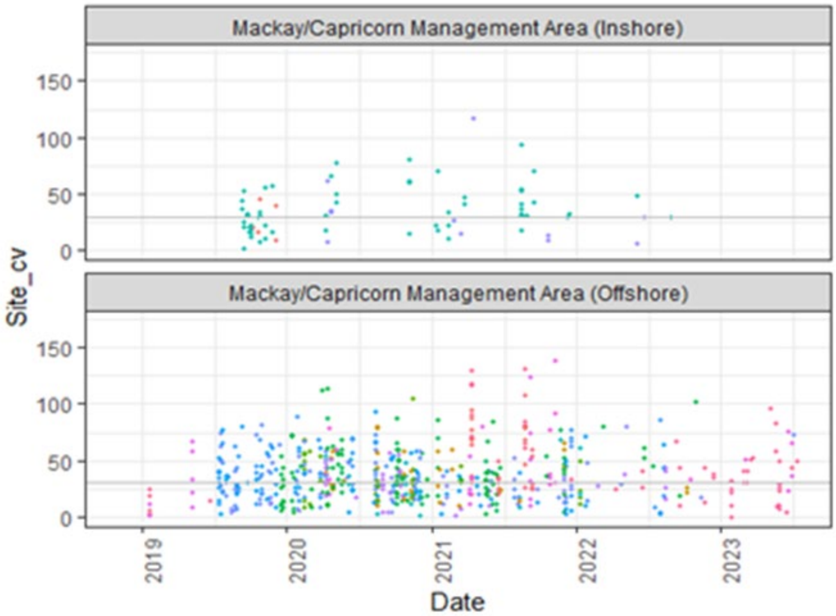

Figure A 26 Coefficient of variations for each visit to a site in the Mackay/Capricorn Management Area (Inshore and Offshore). The grey dotted line indicates a CV of 30%.

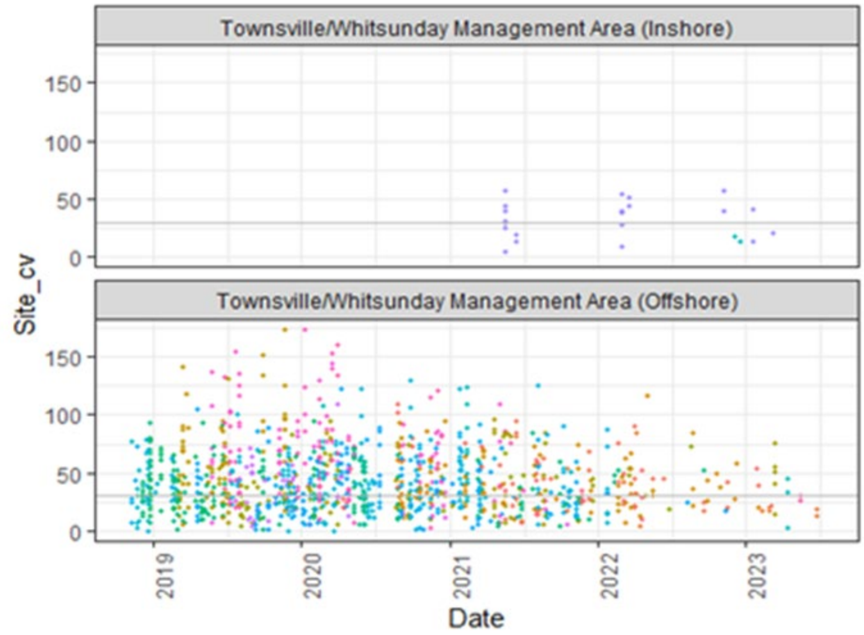

Figure A 27 Coefficient of variations for each visit to a site in the Townsville/Whitsunday Management Area (Inshore and Offshore). The grey dotted line indicates a CV of 30%.

We repeated the linear trend analysis at the cull sites but only on the sites that have at least 20 RHIS in total. Only two management areas have sites with this amount of repeat data. **Figure A 28** shows the trends and in **Figure A 29** we have included the standard errors, which are very wide (Note the confidence intervals would be almost twice as wide).

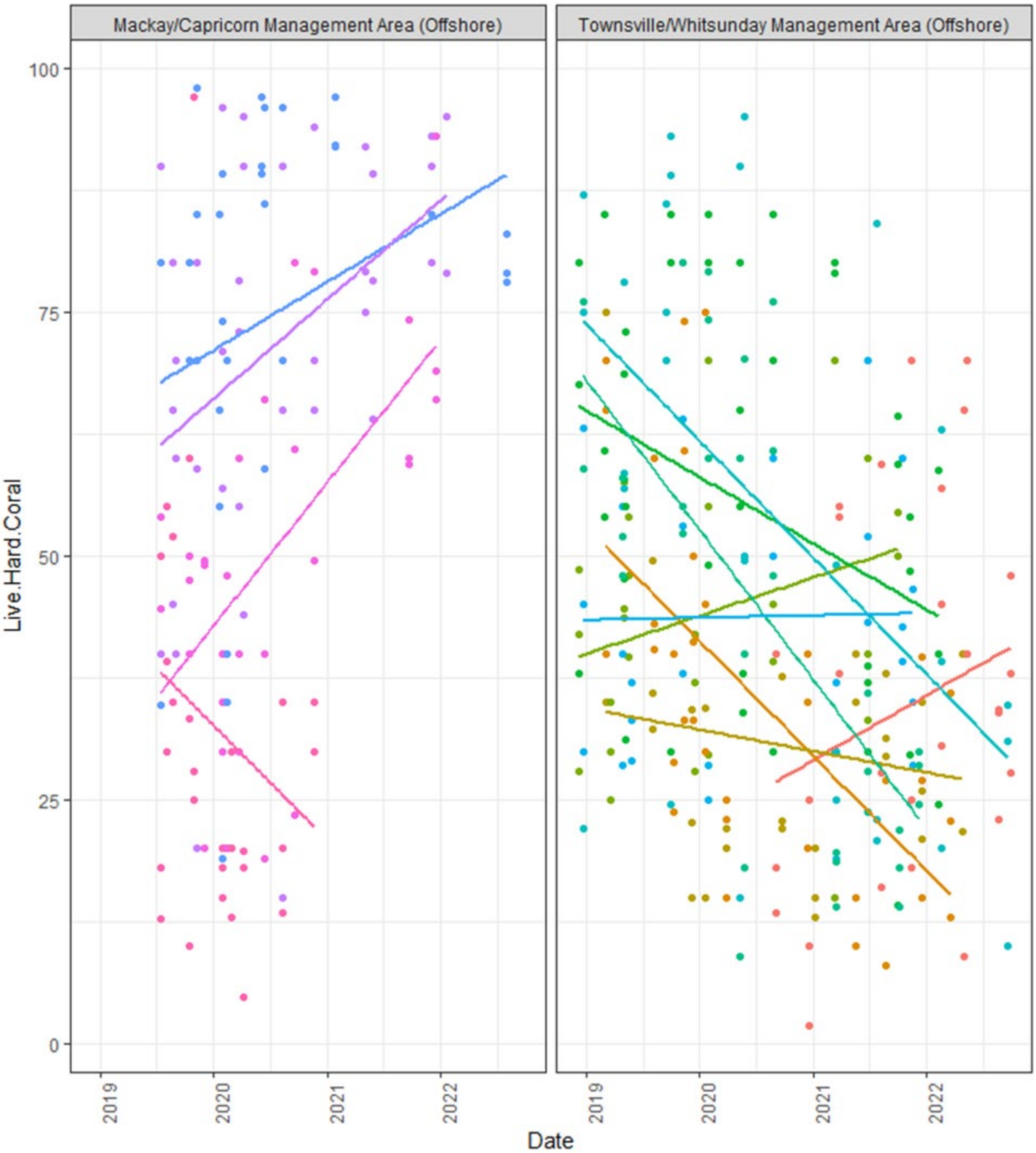

Figure A 28 Linear trend analysis of cull sites that have been revisited frequently.

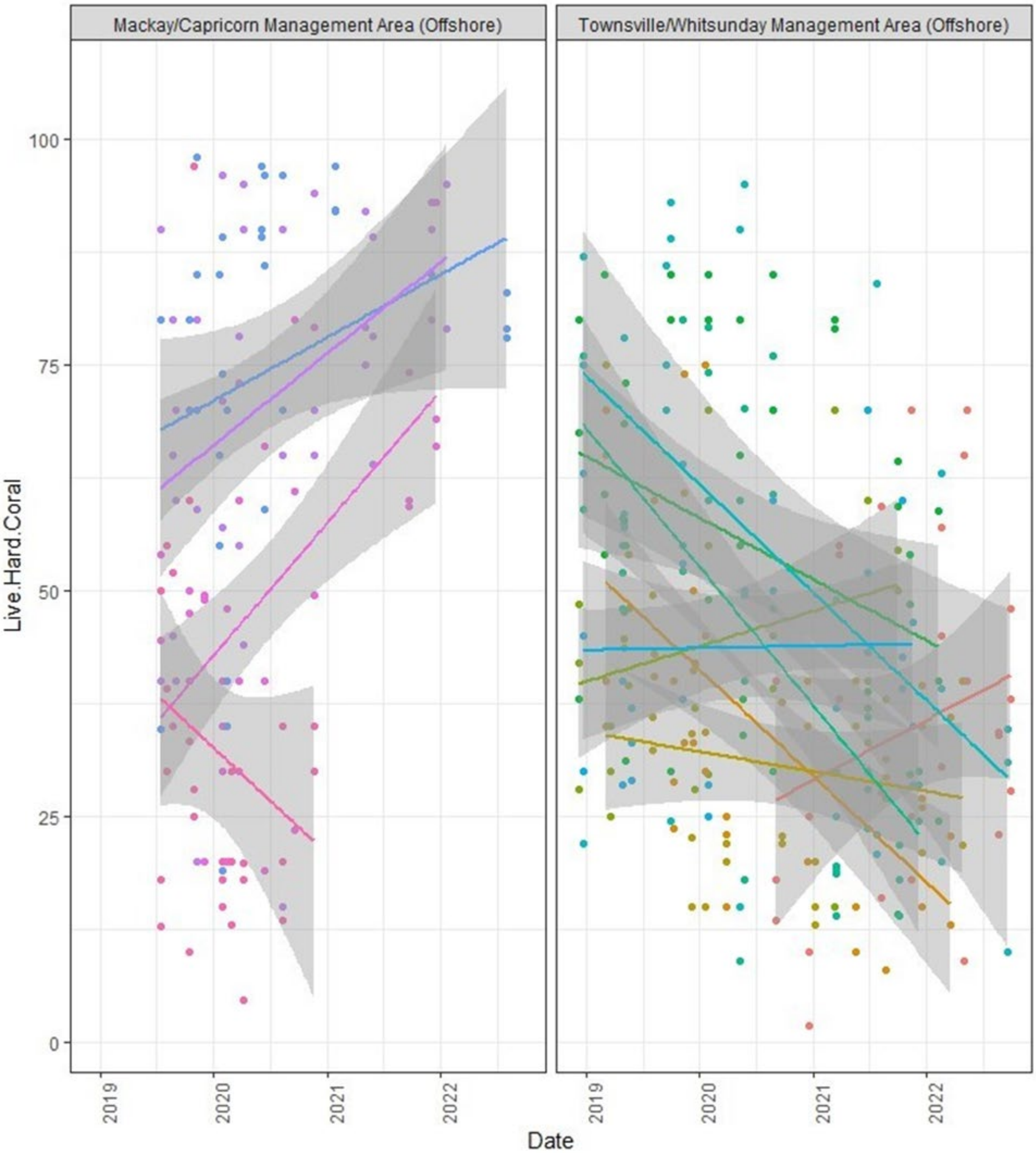

Figure A 29 Linear trend analysis of cull sites that have been revisited frequently, the grey shading indicates one standard error either side of the mean.

Power analysis

A power analysis is essential for determining the appropriate sample size required to detect a meaningful effect or difference in the dataset. Given the varying number of RHIS surveys per reef and the different numbers of visits per reef, a simplified approach was adopted. The analysis focused on the square root-transformed coral data, employing a two-sample, two-sided t-test with a power of 0.8 and a significance level of 0.05.

For reefs with repeated RHIS measurements over time, the mean and standard deviation can exhibit substantial variation. To account for this, the pooled standard deviation for each reef was taken as the median standard deviation across the set of RHIS surveys conducted at that reef. This approach provided a reasonable estimate, although it should be noted that the results were approximate in nature.

The power analysis was initially conducted to detect a 20% change in the mean coral cover (**Figure A 30** and **Figure A 31**). Consequently, for reefs with lower coral cover values, the absolute change being detected was smaller. For instance, a 20% change in a reef with 10% coral cover would correspond to an increase from 10% to 12%, while for a reef with 20% coral cover, the change would be from 20% to 24%. It is important to note that the required sample sizes tend to be higher for reefs with lower coral cover estimates, as the analysis aims to detect smaller absolute changes, and these reefs often exhibit greater variability.

This formal approach acknowledges the inherent complexities and variability in the dataset while providing a realistic framework for conducting the power analysis and determining the appropriate sample sizes required to detect meaningful effects or differences in coral cover. For most sites over 100 RHIS at each reef would be needed at each time point to detect a 20% change in the mean, except those sites with 45% or more coral cover.

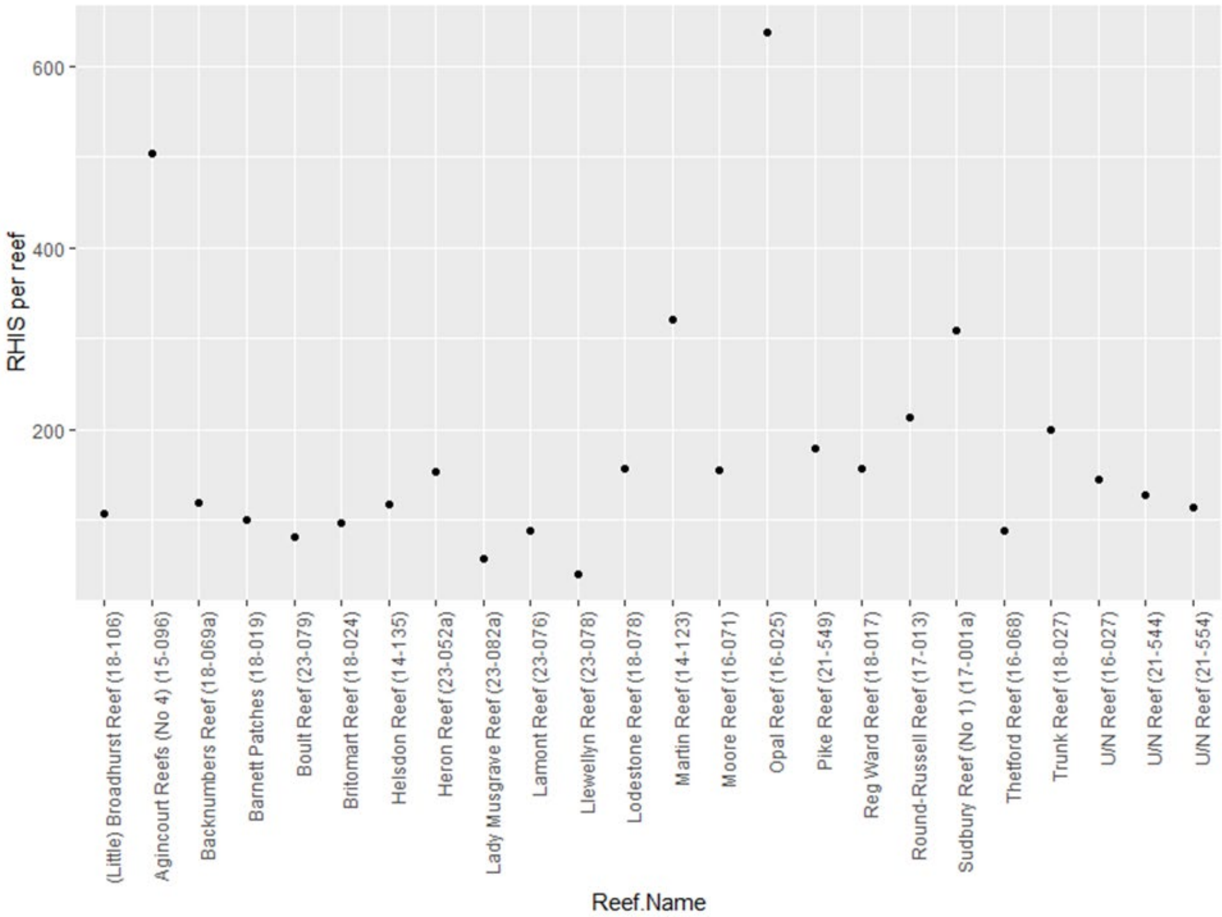

Figure A 30 Estimated number of RHIS per reef needed to detect a 20% relative change in hard coral cover.

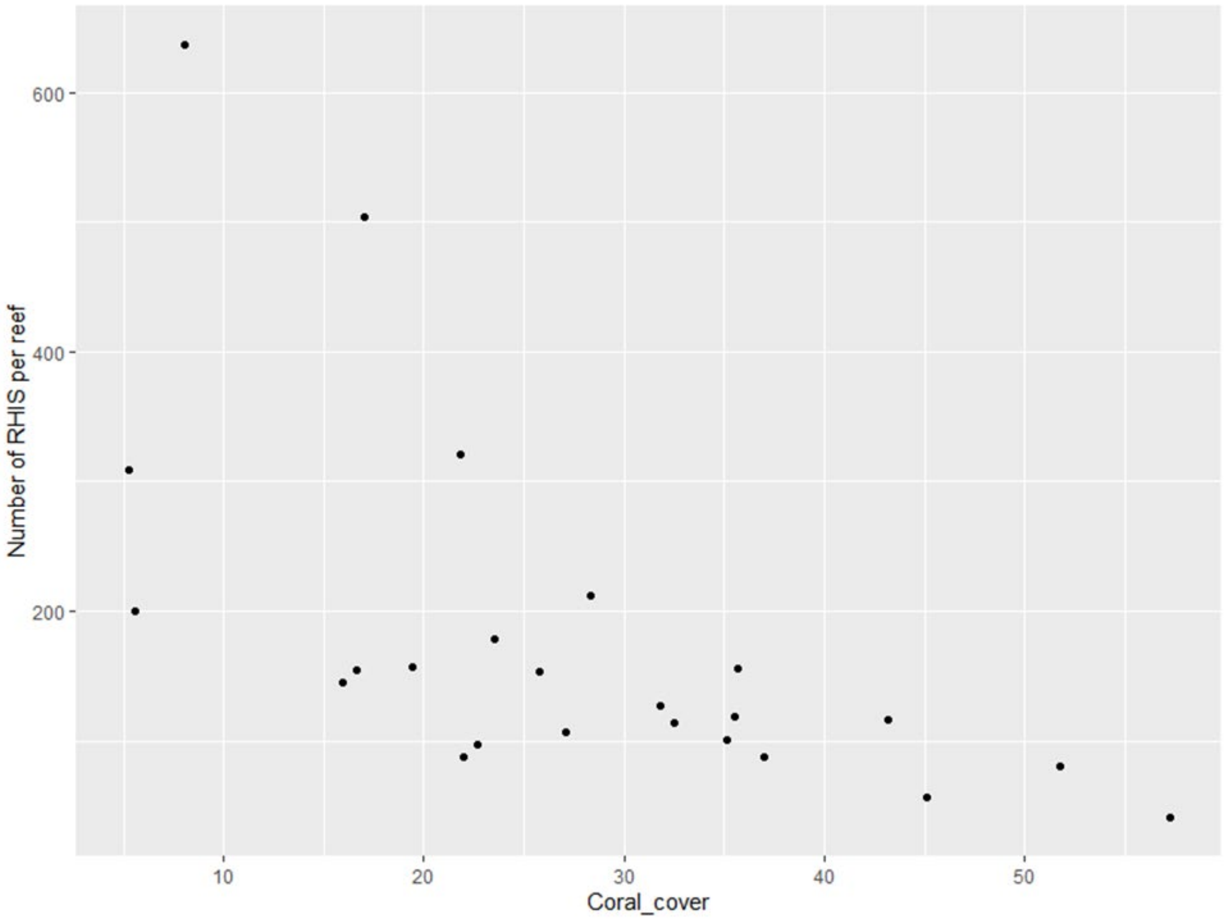

Figure A 31 Estimated number of RHIS per reef needed to detect a 20% relative change plotted against hard coral cover.

The power to detect a 50% change (**Figure A 32** and **Figure A 33**) in the mean of coral cover demonstrates that less samples are required for a greater change. These results show that for higher estimates of coral cover, the larger reefs that have 24 RHIS per sample could reasonably expect to be able to detect a 50% change in mean coral using RHIS surveys e.g. from 30% to 15% or from 40% to 60%. In reality these are very large differences in coral cover that would either be due to disturbance (loss) or take a long time to occur (growth).

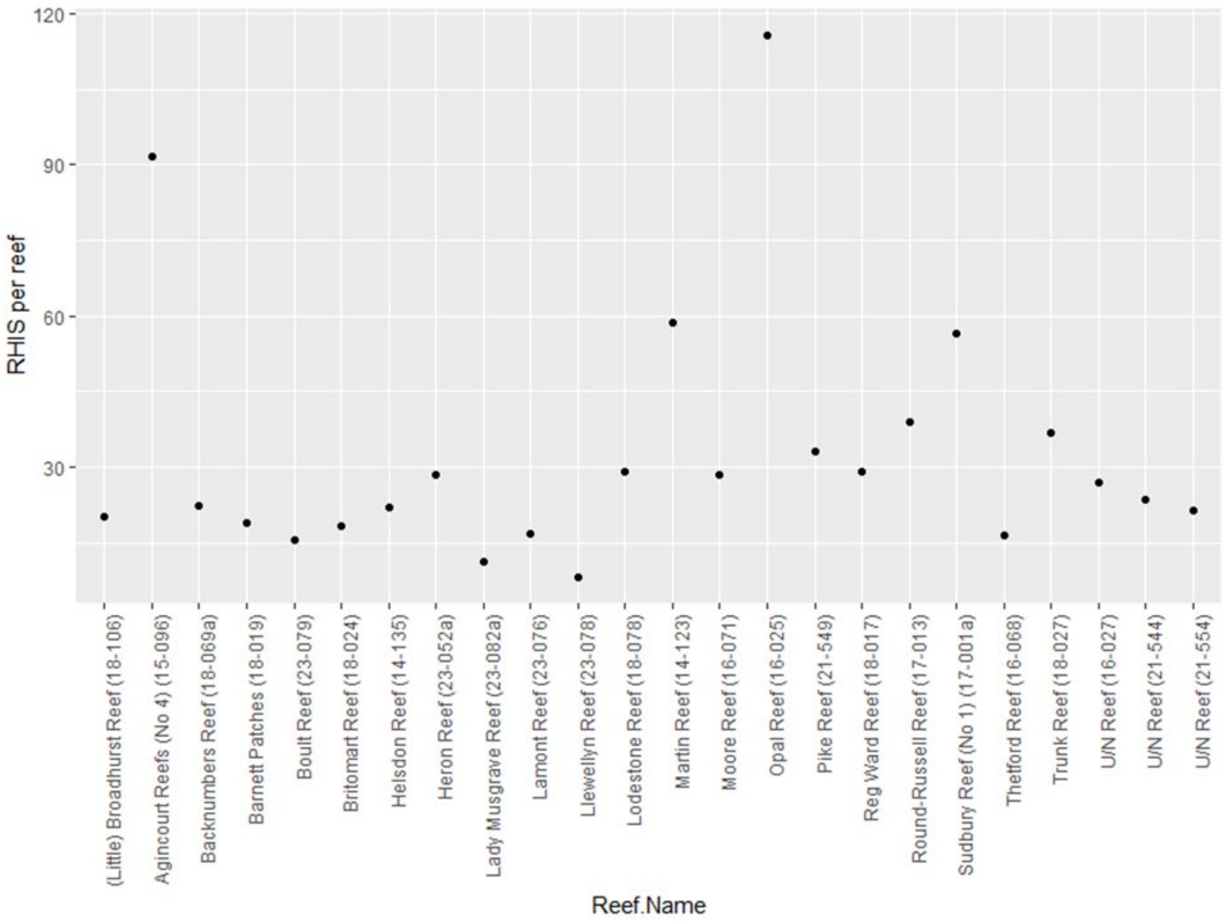

Figure A 32 Estimated number of RHIS per reef needed to detect a 50% relative change in hard coral cover.

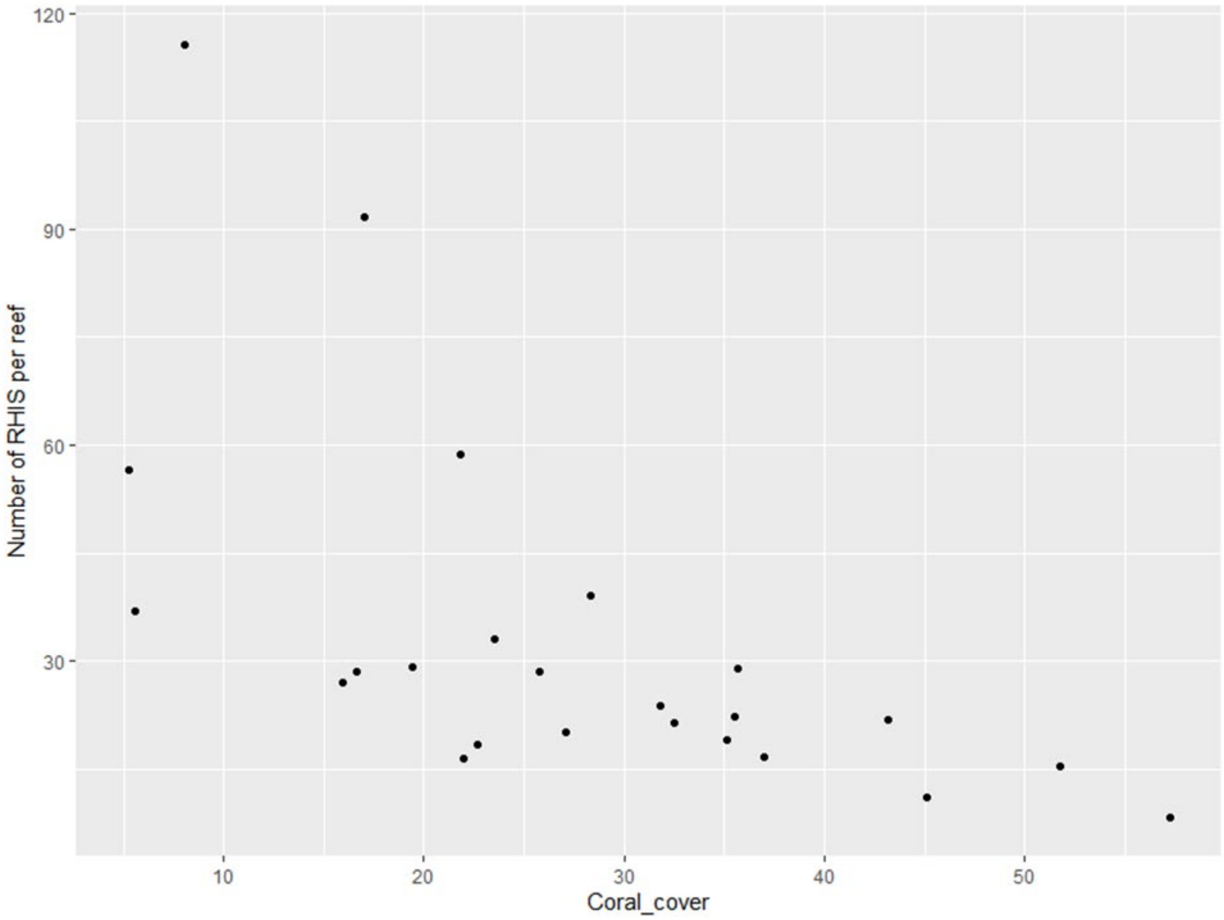

Figure A 33 Estimated number of RHIS per reef needed to detect a 50% relative change plotted against hard coral cover.

The number of samples required to detect a relative change of 20% or 50% might be realistic for mean hard coral cover towards the upper end but as the figures above demonstrate, at the lower end of coral coverage they would not likely be feasible. For this reason, we have also looked at the number of samples required to detect an absolute change in hard coral cover of 5%. Previous power analyses on LTMP data demonstrate that they are likely to be able to detect a 1% change per annum (Schaffelke et al. 2020).

For coral cover above about 15% at least 50 RHIS per visit would need to be undertaken to confidently capture a 5% change in coral cover. Measuring changes from say 50 to 55% would likely require several hundred RHIS per visit.

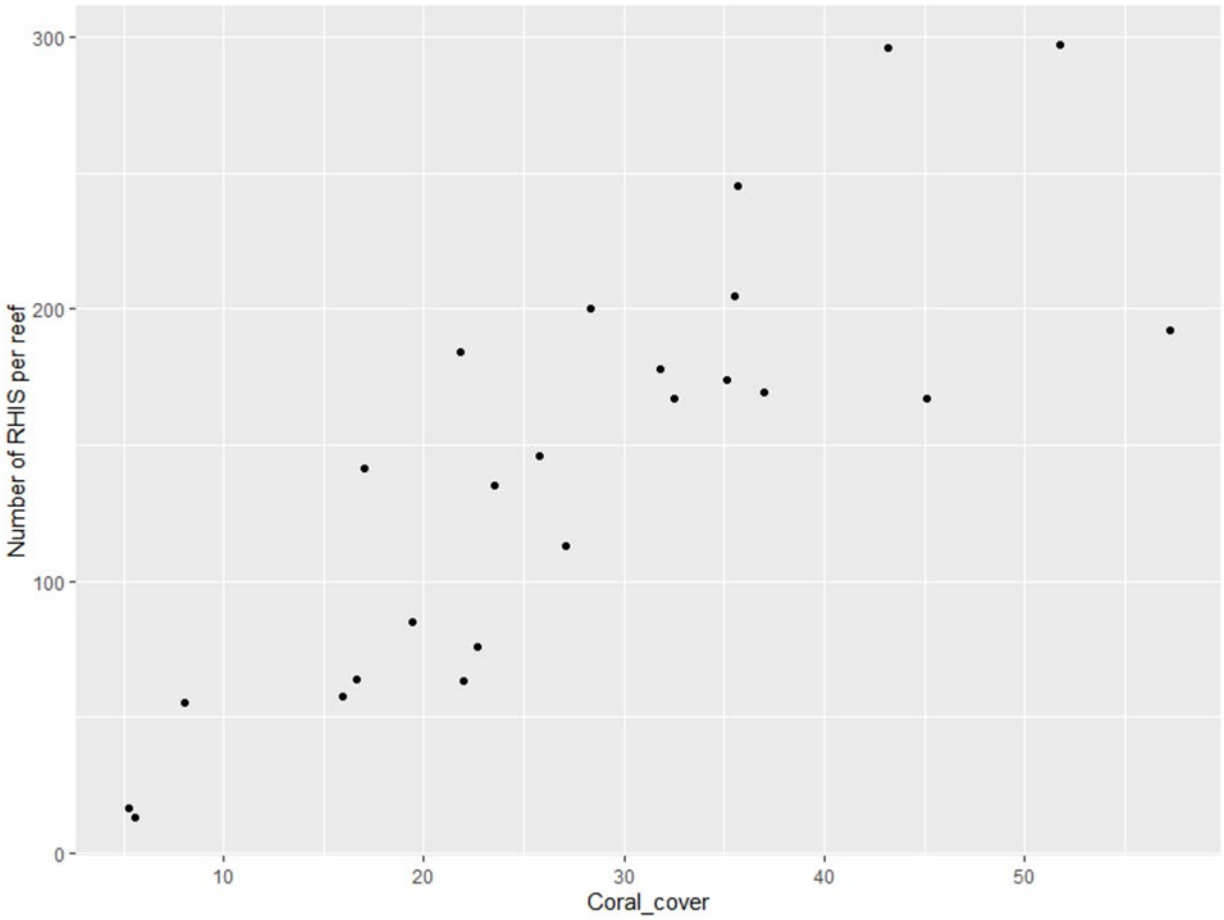

Figure A 34 Estimated number of RHIS per reef needed to detect a 5% absolute change in hard coral cover.

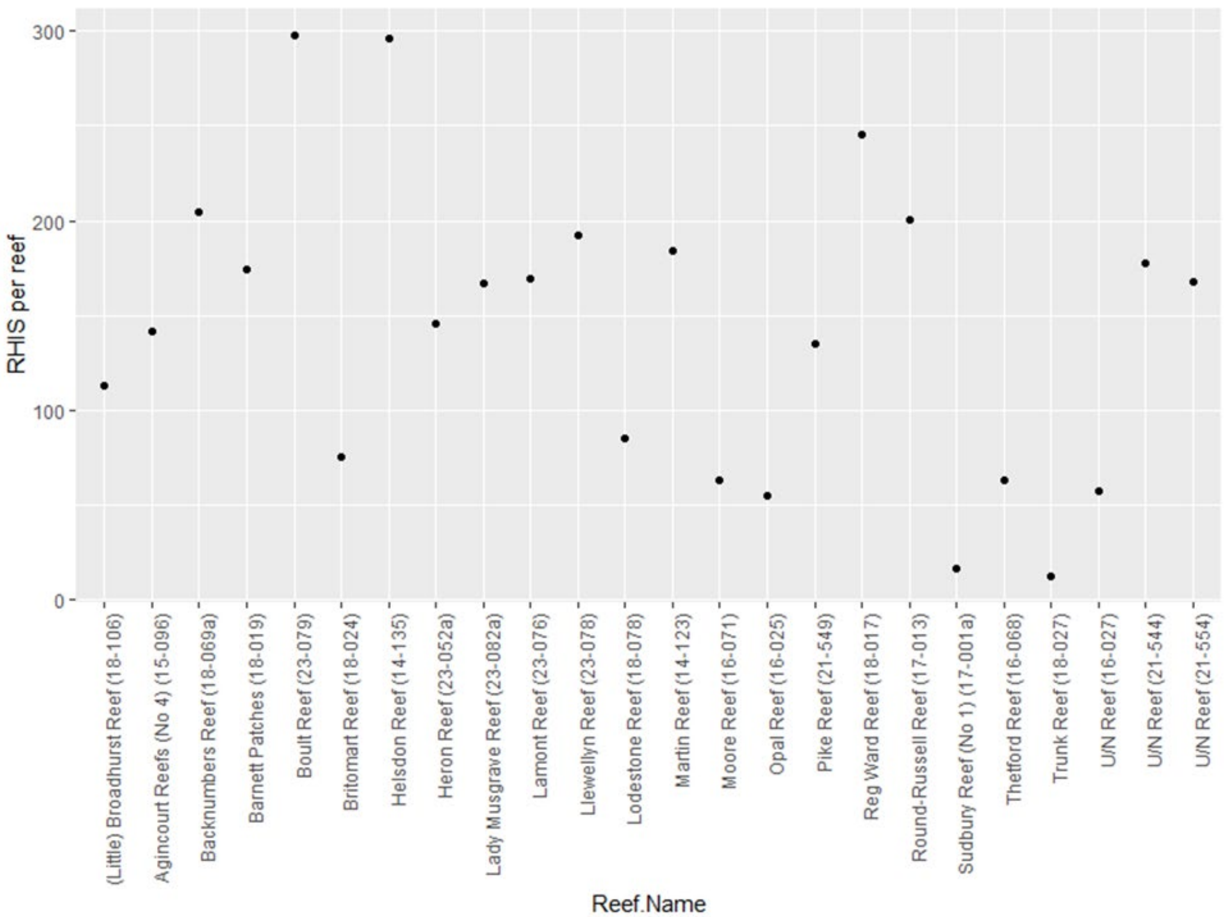

Figure A 35 Estimated number of RHIS per reef needed to detect a 5% absolute change in hard coral cover.

APPENDIX D - SAMPLE DESIGN SIMULATIONS

Methods

Here we provide extra details on the methods for creating and comparing multiple possible statistical designs for measuring COTS and coral across the GBR.

Simulation Models

Simulations were run starting from 1901 but recorded from 2000 through 2020. Adult COTS densities and coral cover were recorded for 3,806 reefs on a yearly basis. The 500 individual CoCoNet simulations and mean of all simulations of estimated average coral cover and COTS densities is shown in **Figure A 36**. Note that only reefs with at least four sites are used in the mean, noting that 95% of priority reefs have at least four sites. However, there are many small reefs, especially in the southern region, that are not included in this mean.

The version of CoCoNet we used has been in development for CCIP, current version 3.0 (noting that version 1 was developed for a generic reef network (Condie et al. 2018), and version 2 framed to the GBR (Condie et al. 2021). CoCoNet v3 has been in active development throughout CCIP, with the version used for our simulations based on the state of CoCoNet in March 2024.

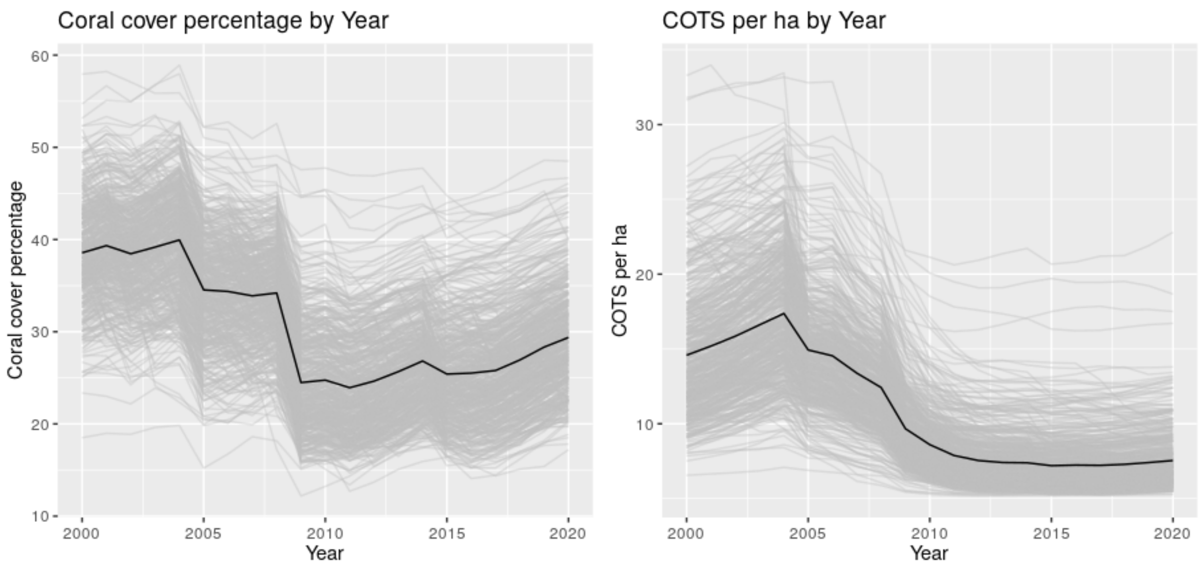

Figure A 36 Time series plots of the 500 CoCoNet simulations showing the mean coral cover percentage (left) and COTS densities per ha (right), of reefs with at least 4 sites. Grey lines indicate individual simulations while black line indicates mean of all simulations.

ReefMod-GBR

Output is generated at 3,806 reefs on a 6-month time step, with hindcast results from winter 2007 through summer 2022. Coral and COTS trajectory dynamics may be forecasted into

2100. For our purposes, we implemented ReefMod-GBR using only the hindcast, averaged to the year level (e.g. 2008–2022). Simulations of ReefMod-GBR were generated using v6.8, available from https://github.com/ymbozec/REEFMOD.6.8_GBR. The 500 individual ReefMod-GBR simulations and mean of all simulations of estimated average coral cover and COTS densities is shown in **Figure A 37**. As with CoCoNet, only reefs with at least four sites as dictated by CoCoNet (for consistency purposes) are used for the mean and will, once again, not include many smaller reefs which are in higher proportion in the southern region.

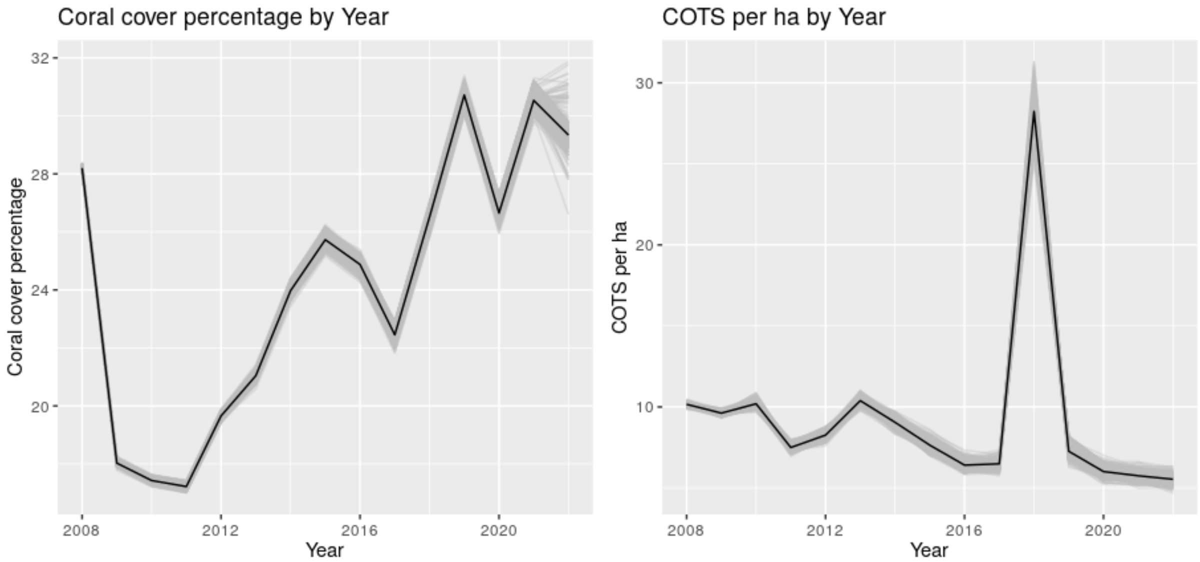

Figure A 37 Time series plots of the 500 ReefMod-GBR simulations showing the mean coral cover percentage (left) and COTS densities per ha (right), of reefs with at least 4 sites. Grey lines indicate individual simulations while black line indicates mean of all simulations.

Monitoring Design

The inclusion probabilities are denoted:

$$\boldsymbol{\pi}^{(s)} \equiv \left(\pi_1^{(s)}, \dots, \pi_N^{(s)}\right)',$$

where $\pi_i^{(s)}$ is the specified inclusion probability of cell *i* and *N* is the number of cells in the raster. These inclusion probabilities $\boldsymbol{\pi}^{(s)}$ are scaled so that they sum to *n*, where *n* is the number of reefs selected to monitor. If sampling clusters of reefs is not specified in the monitoring design, $\boldsymbol{\pi}^{(s)}$ is the final inclusion probability that is used for randomised sampling. For monitoring designs that have a number of samples in close spatial proximity (a cluster), an added step is needed to created working inclusion probabilities $\boldsymbol{\pi}^{(w)}$ for specifying the probability of choosing a given cluster of reefs. We refer the reader to Foster et al. (2023) for details but note that this is all performed within the software (Foster 2021).

After inclusion probabilities have been specified, reefs are sampled using the BAS method of Robertson et al. (2013), Robertson et al. (2017). This was done using the 'MBHdesign' package (Foster 2021) using R v4.2.1 (R Core Team, 2022). Given the irregular shape of the GBR raster which may result in the BAS algorithm being unable to sample a suitable balanced design, the number of samples to consider in the rejection step was significantly increased from the software's default; minimum samples considered in our designs set at 50000*n.*

For each monitoring design, we estimate average coral cover and COTS densities over the entire GBR. Given our method for altering inclusion probabilities will result some reefs being sampled with higher probability than others, resulting in a biased sampling process, our estimator needs to account for the associated probability of inclusion. This is done via the Horvitz-Thompson (HT) estimator (Horvitz & Thompson, 1952). That is, for observation y_i (representing either coral cover or COTS density) from reef *i* in a monitoring design with given set of reefs *S*, where the size of *S* is *n*, then the mean estimated (coral cover or COTS density) value is

$$\hat{\mu} = \frac{1}{|S|} \sum_{i \in S} \frac{y_i}{\pi_i^{(o)}} . (1)$$

where $\pi_i^{(o)}$I is the observed inclusion probability – equal to $\pi_i^{(s)}$ for non-clustered designs and approximating $\pi_i^{(s)}$ for clustered designs. Lastly, 1000 different surveys were randomly chosen for each monitoring design. This enables the estimation of a distribution of possible estimates of average coral cover and COTS density. We compared the resulting average estimate to the true value of the associated sampling frame of the GBR (that is, if only reefs with at least 4 sites as specified by CoCoNet, then the estimated value was only compared the average over reefs with at least 4 sites). Values were taken over the 500 simulations of CoCoNet and ReefMod-GBR.

Table A 2 shows a summary of the monitoring scenarios we considered, with descriptions below. Sites in this case are the number of sites as noted by CoCoNet. The number of sites may differ from that which is actually on a given reef. However, the number of sites is directly correlated with the size of a reef. Note that four sites was chosen as the cutoff for many monitoring designs as 95% of the priority reefs had at least four sites but there are a greater percentage of small reefs across the entire GBR.

Table A 2 List of monitoring scenarios.

Monitoring Design	Number of Reefs Monitored	Min Number of Sites per Reef
Random Reefs	30, 50, 70, and 100	4
Clustered Random Reefs	~50 reefs (5, 10, 16, and 25 clusters)	4
Fishing Intensity	50 reefs, 25 in each zone	4
Region based	50 reefs, ~25% in each control region	4
Priority Reef Based	50 reefs	4
Target Reef Based	50 reefs	4
COTS Risk Layer Based	50 reefs	4

Size Distribution Based	50 Reefs	1
LTMP Reefs Based	50 reefs	1

A Note on Calculating Variability and Bias

Critical to understanding the performance of each sampling design is determining the bias of the estimator and associated uncertainty. Noting that coral cover and COTS outbreaks generally vary from year to year and that CoCoNet and ReefMod-GBR output may be generated on a yearly scale, we calculate the resulting estimates of coral cover and COTS densities through years.

We compare the difference of the estimated coral cover and COTS densities from a monitoring scenario as determined by Equation (1) from the true average coral cover and COTS density for the given model, subject to the frame of reference (e.g. for designs that only incorporate at least four sites in a reef, we compare the resulting estimator to the true average of reefs with at least four sites). Given we have 500 simulations of each model run and 1000 replications of each monitoring design scenario, this difference is calculated as follows (noting some notation is suppressed). Let $\hat{\mu}_{i,j}^{(d)}(t)$be the estimator obtained from Equation (1) for simulation *i*, replication *j*, and design *d* at year *t*. Let $\mu_i(t)$ be the true average of interest for simulation *i* and year *t*. Then the difference is calculated as:

$$\hat{\mu}_{i,j}^{(d)}(t) - \mu_i(t). (2)$$

We can then generate boxplots of all values to determine variability and bias of the estimator. This should be centred around zero. Additionally, we compare average value of the estimator to the true average value. As there are two dimensions of variation, we collapse the simulations into one estimator, obtaining mean values $\bar{\hat{\mu}}_i^{(d)}(t)$ and $\bar{\mu}(t)$, presenting time series plots as a result.

We can then generate boxplots of all values to determine variability and bias of the estimator. This should be centred around zero. Additionally, we compare average value of the estimator to the true average value. As there are two dimensions of variation, we collapse the simulations into one estimator, obtaining mean values and, presenting time series plots as a result.

Results

We present the results of the monitoring designs described in the previous section here. The results of each monitoring design are presented via boxplots and time series plot for each monitoring design scenario. Note that there are several comparisons that may be considered, and what is presented here is not exhaustive. In particular, further investigation could be done at the control region scale. In general, we compare the results of many monitoring designs to that of Random Sampling of 50 reefs.

Random Sampling

Figure A 38 shows boxplots of the distribution of the difference between the estimated coral cover and COTS densities based on random sampling of 30 reefs, while **Figure A 39** shows the results of 50 random reefs, **Figure A 40** for 70 reefs, and **Figure A 41** for 100 reefs. In all these plots the estimator for average coral cover and COTS densities for all years for both CoCoNet and ReefMod-GBR is unbiased. As expected, increasing the number of reefs monitored decreased the variation in the estimated average coral cover and COTS density in all models over years. This decrease diminishes with each increase in reefs monitored. That is, the decrease in variability from 50 reefs to 70 reefs is less than that from 30 to 50. Increased estimates of coral cover or COTS densities do tend to increase variability as would be expected.

Special mention should be made of the estimated average COTS density for ReefMod-GBR in 2018, showing a larger variation than the remaining years. While zero is still within the bounds of the estimator, often the estimated average COTS density is projected lower than the true average. This is due to the heavily skewed distribution of COTS densities at different reefs over this year. Closer inspection shows that on average, 90% of reefs had estimated 0.3 COTS/manta tow, while the maximum ranged from 47 to 167 COTS/manta tow. Comparing to **Figure A 37** the mean COTS density for 2018 is near 0.4 COTS/manta tow. This amount of variation is not seen in any of the other years for ReefMod-GBR. The high skewness of 2018's COTS densities for ReefMod-GBR explains why the results are significantly wider, which becomes less pronounced with increasing number of reefs monitored. Lastly, while the estimator may show high variability in 2018, it is still unbiased, as evidenced by the time series plots in **Figure A 42**, **Figure A 43**, **Figure A 44**, and **Figure A 45**.

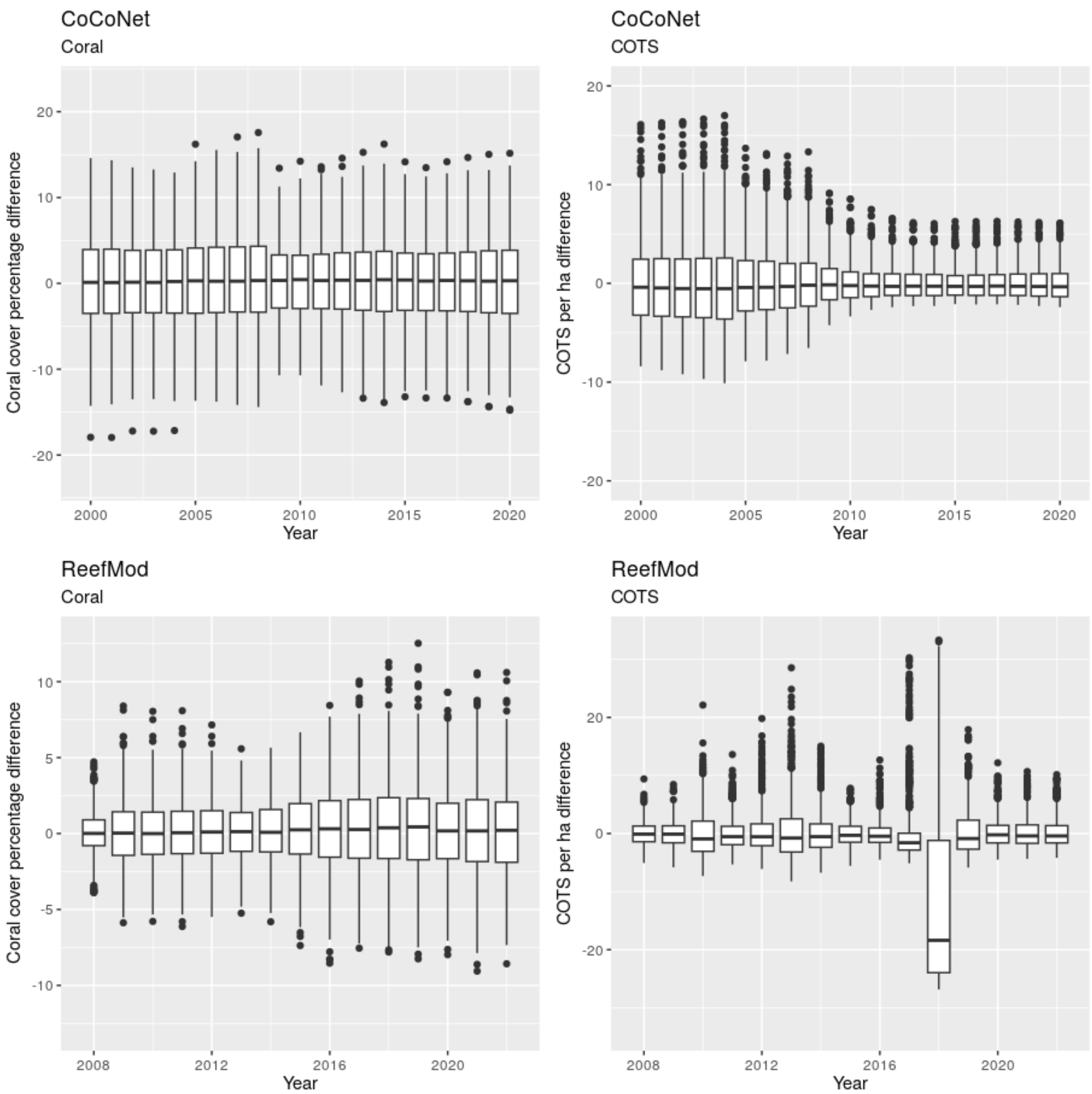

Figure A 38 Results of **Random Monitoring of 30 reefs**. Boxplot showing the difference between estimated total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

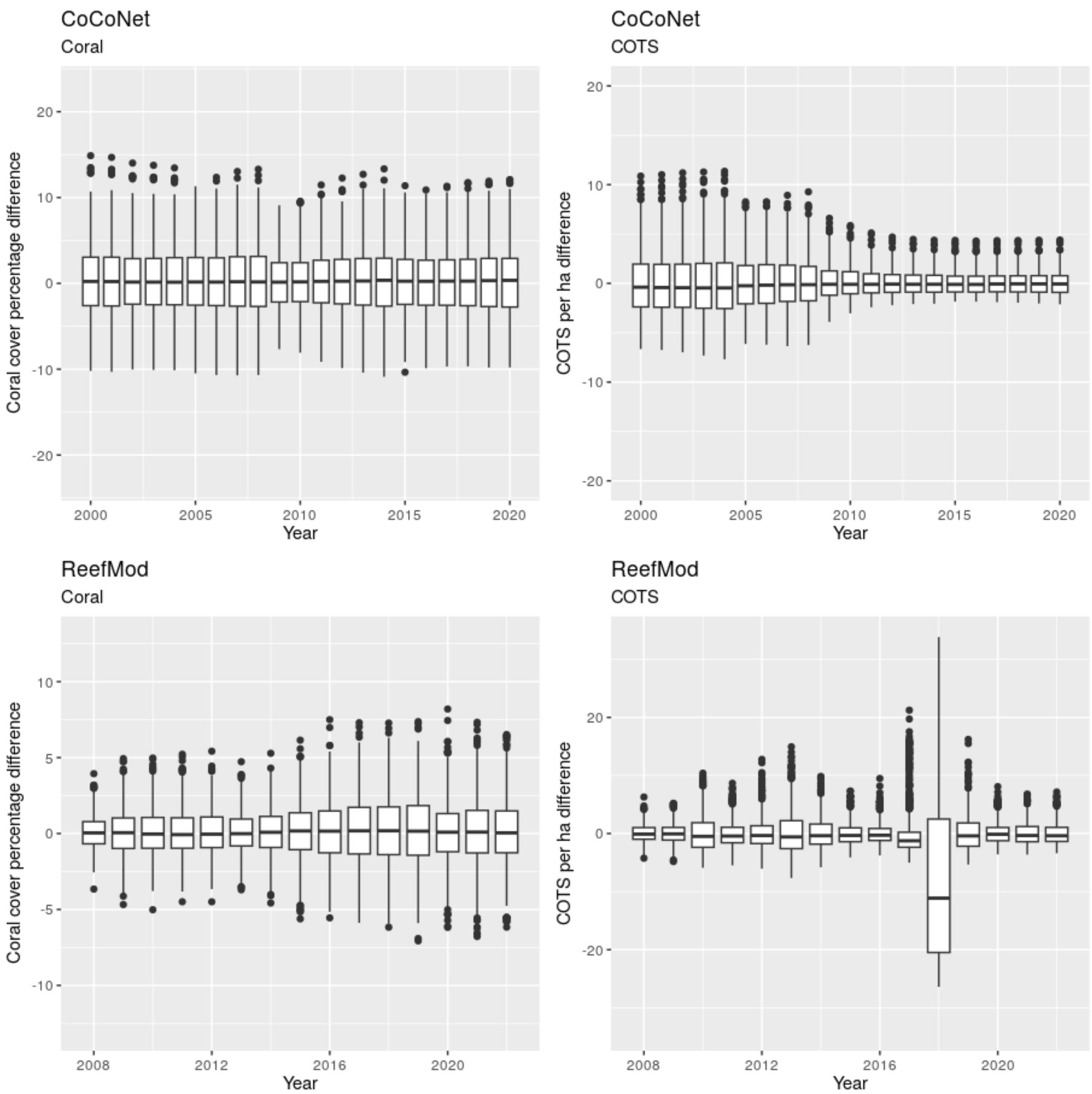

Figure A 39 Results of **Random Monitoring of 50 reefs**. Boxplot showing the difference between estimated total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

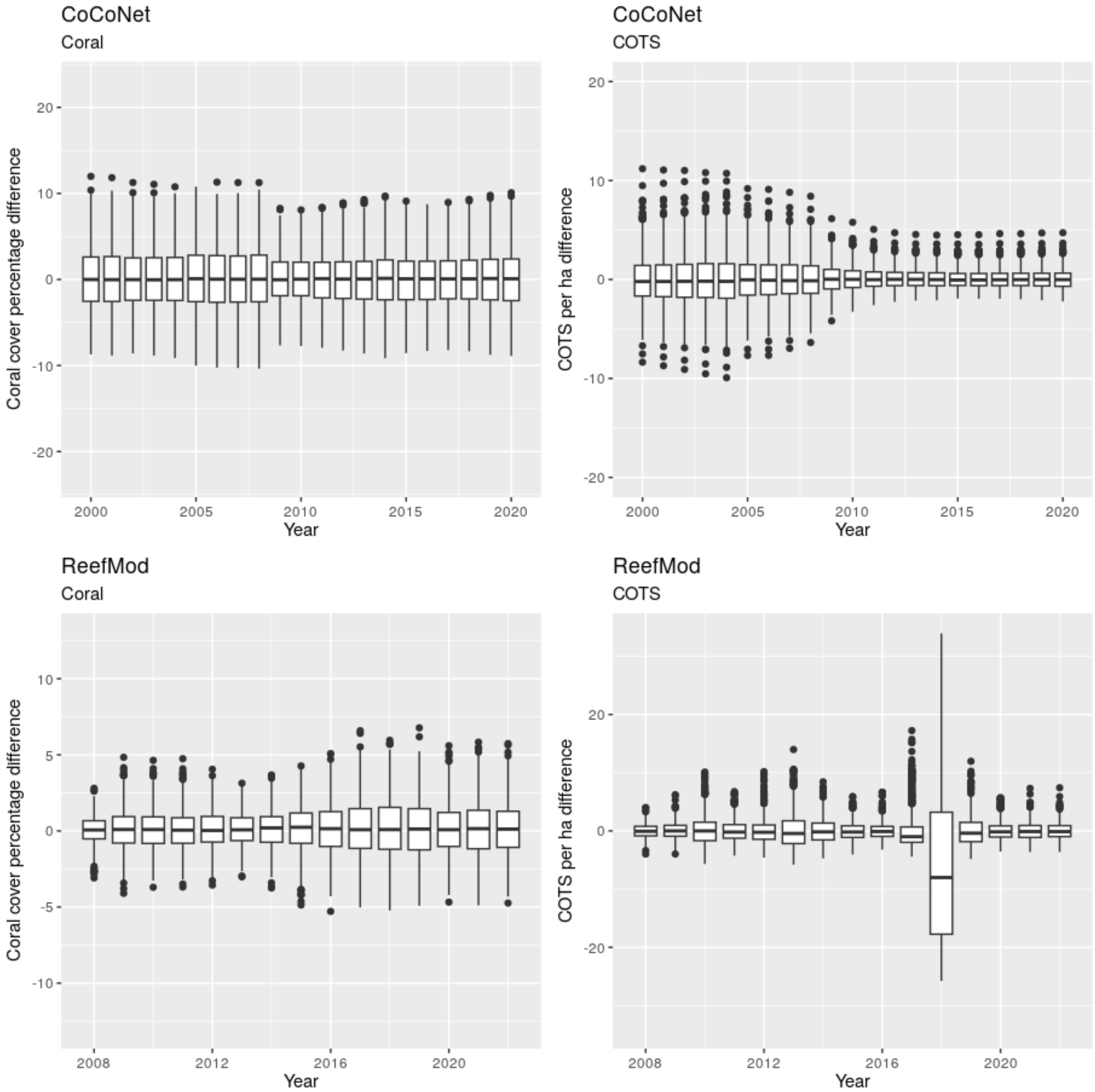

Figure A 40 Results of **Random Monitoring of 70 reefs**. Boxplot showing the difference between estimated total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

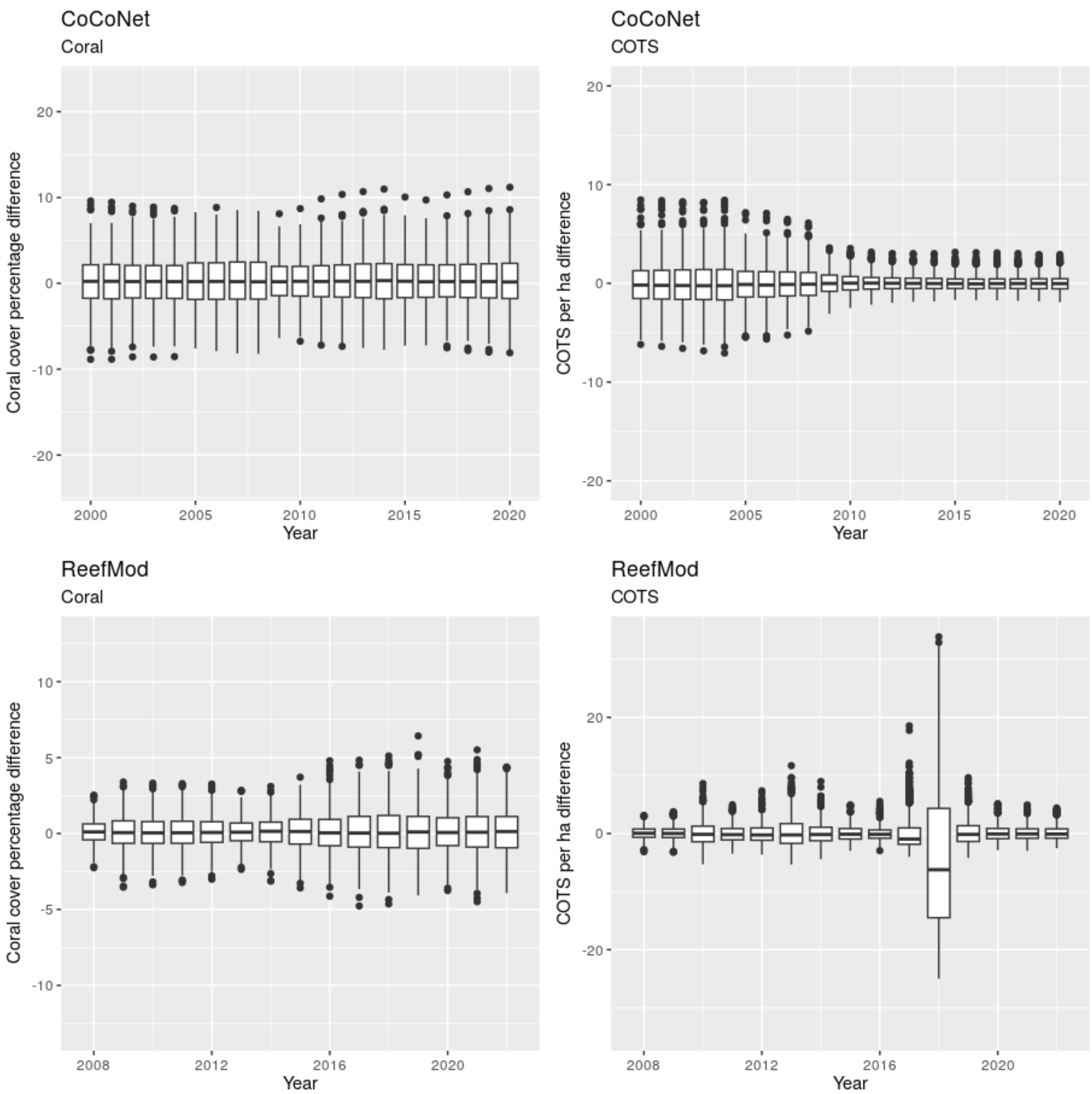

Figure A 41 Results of **Random Monitoring of 100 reefs**. Boxplot showing the difference between estimated total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

Time series plots showing the estimated average coral cover and COTS densities over the GBR are shown in **Figure A 42**, **Figure A 43**, **Figure A 44**, and **Figure A 45** for 30, 50, 70, and 100 reefs, respectively. The mean estimates from the random sampling designs line directly with the true mean coral cover and COTS densities of reefs over the entire GBR with at least 4 sites for both CoCoNet and ReefMod-GBR, with the variability decreasing as the number of reefs monitored increases.

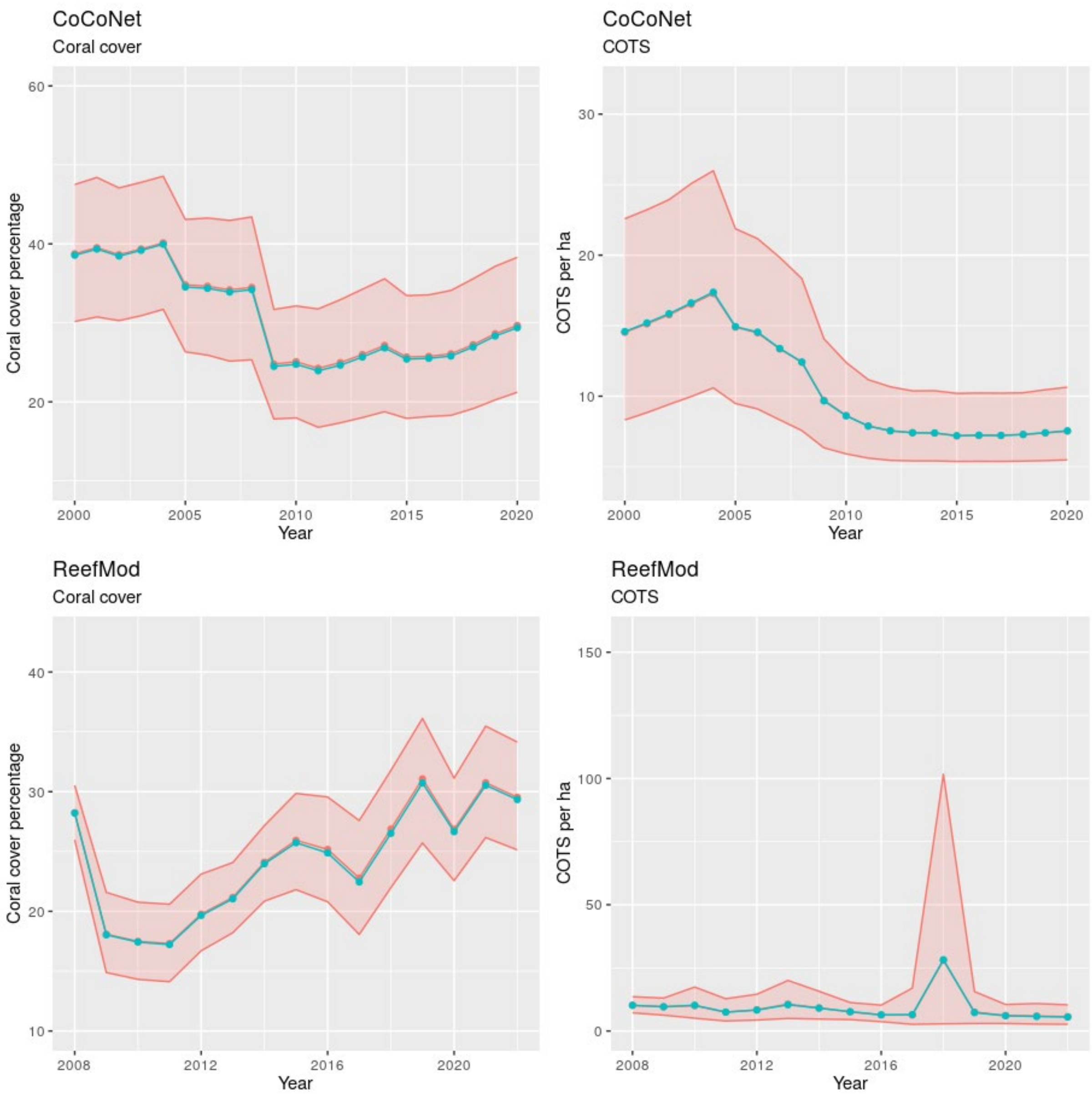

Figure A 42 Time series plots showing estimates (red) and true value (blue) from **Random Reef Monitoring of 30** reefs over years with 95% intervals. Plot shows total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

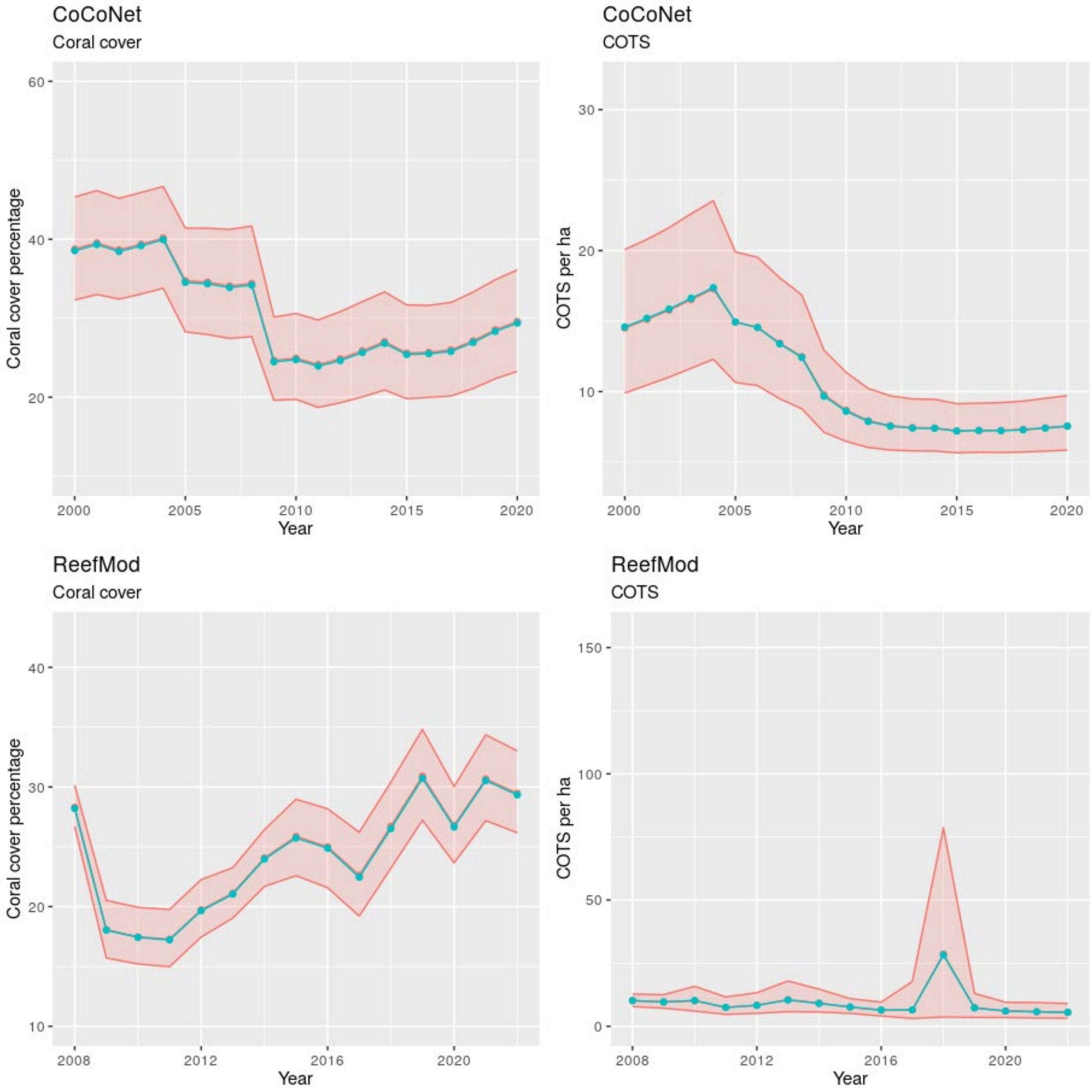

Figure A 43 Time series plots showing estimates (red) and true value (blue) from **Random Reef Monitoring of 50 reefs** over years with 95% intervals. Plot shows total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

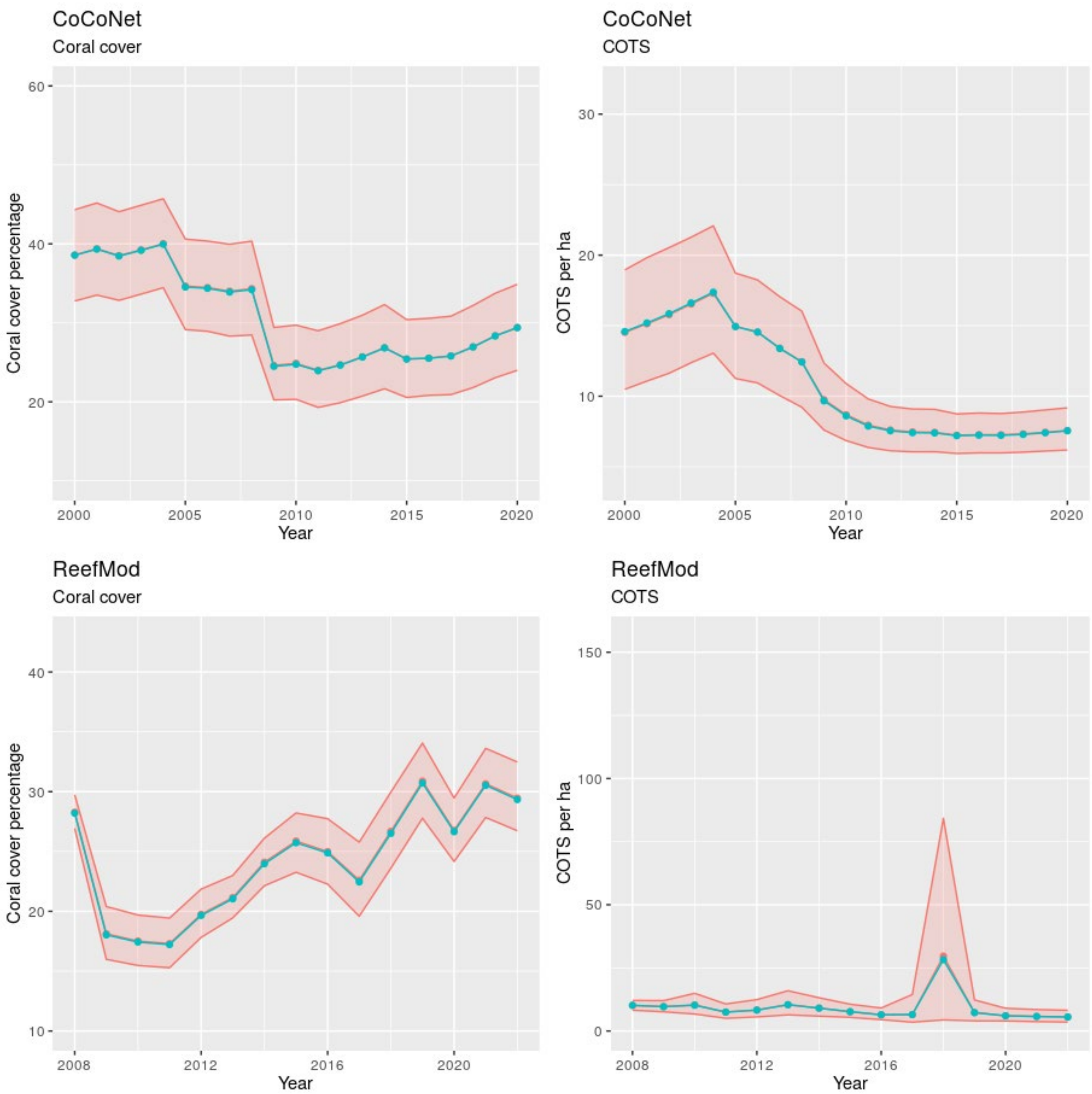

Figure A 44 Time series plots showing estimates (red) and true value (blue) from **Random Reef Monitoring of 70 reefs** over years with 95% intervals. Plot shows total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

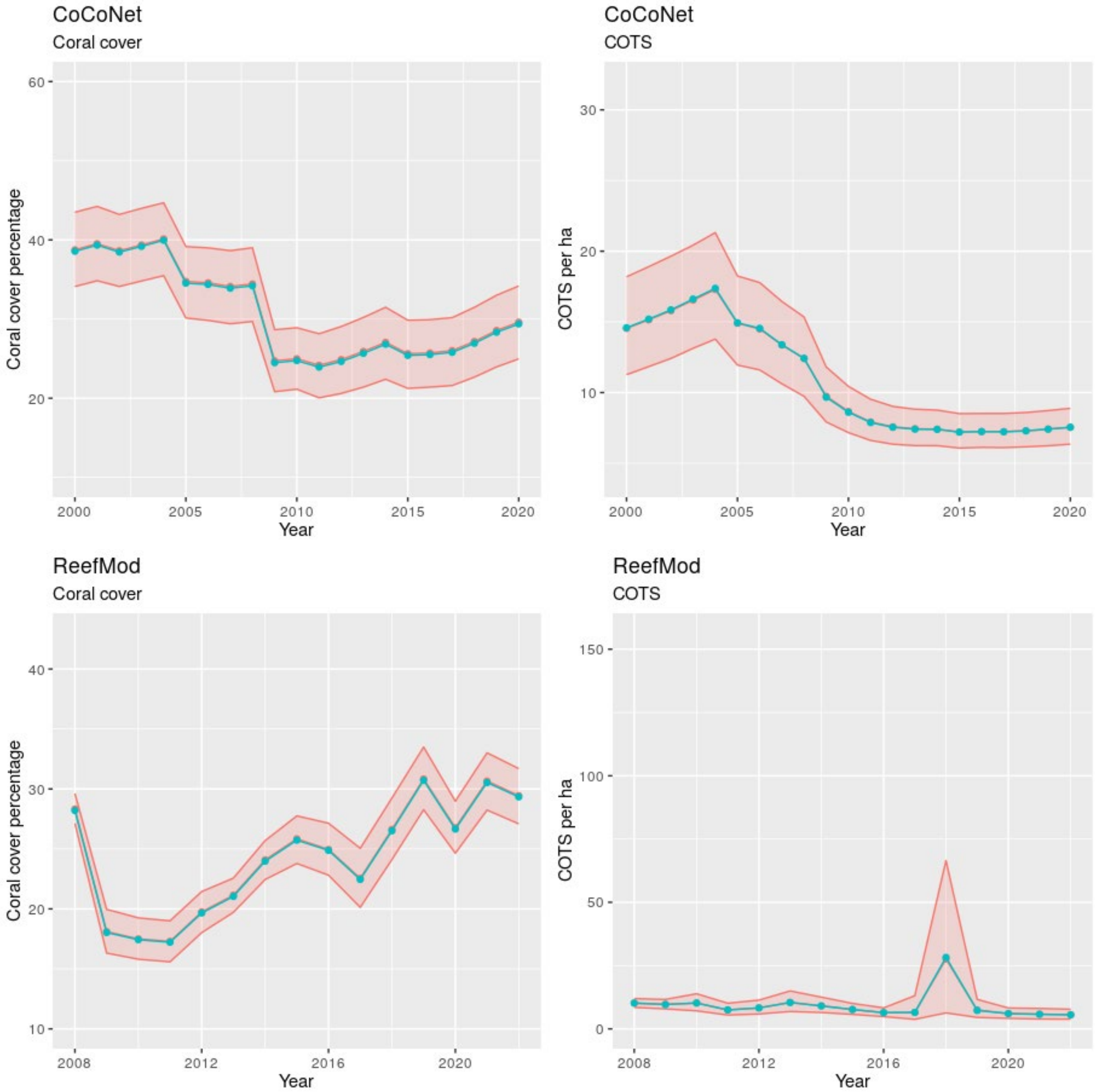

Figure A 45 Time series plots showing estimates (red) and true value (blue) from **Random Reef Monitoring of 100 reefs** over years with 95% intervals. Plot shows total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

Clustered Random Sampling

While sampling random reefs is a general baseline, logistically sampling clusters of reefs is more feasible, given the time it takes to travel to between reefs. In this section we present the results of the Clustered Random Sampling scenario. The cluster radius was set to 25 km.

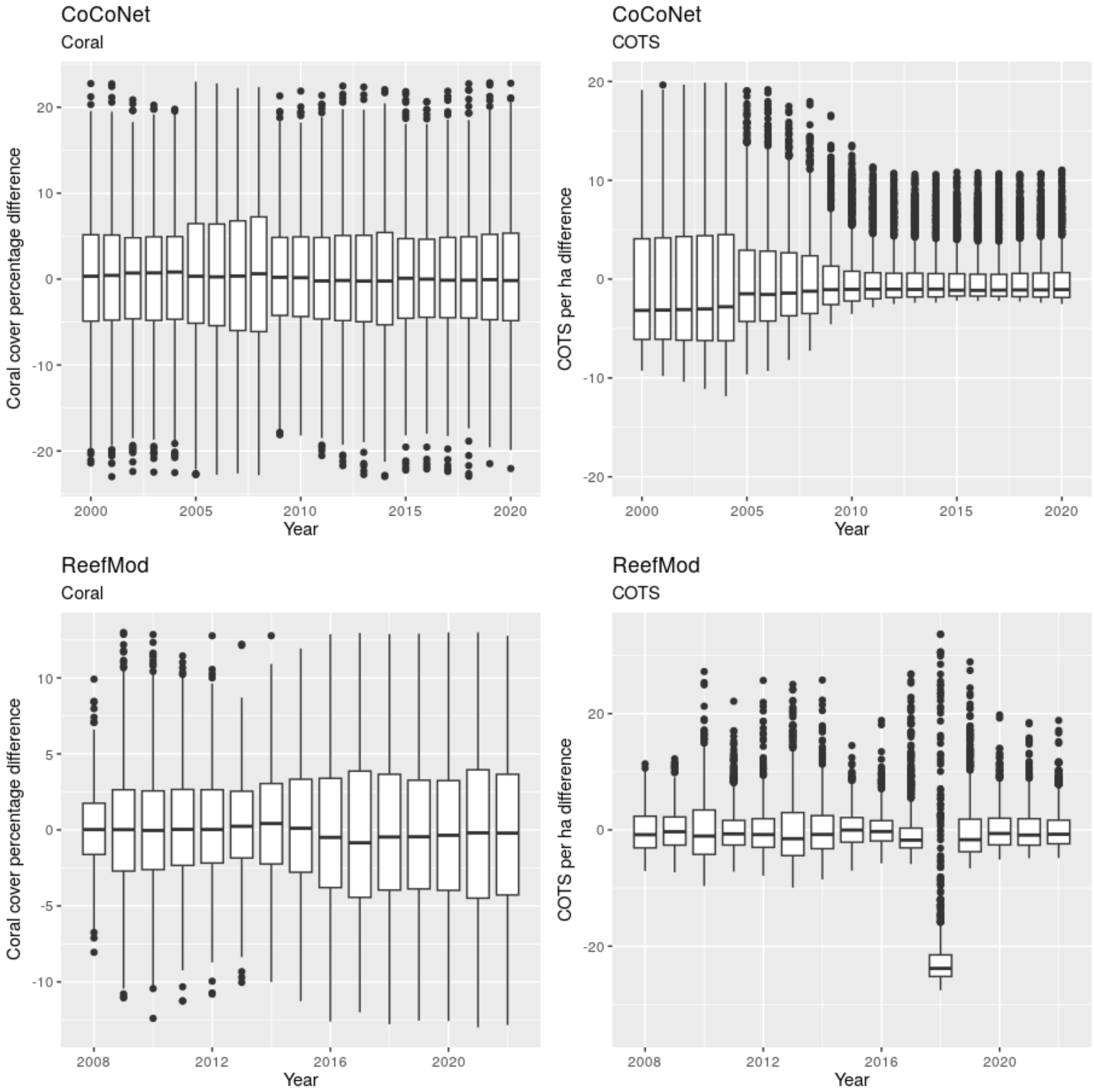

Figure A 46, **Figure A 47**, **Figure A 48**, and **Figure A 49** show boxplots of the difference between 5 clusters of 10 reefs, 10 clusters of 5 reefs, 16 clusters of 3 reefs, and 25 clusters of 2 reefs. As expected, the estimator is unbiased when compared to the same sampling frame, that being the average of reefs with at least 4 sites. Increasing the number of clusters decreased the variability despite the (approximately) same number of reefs being monitored. Further investigation found that increasing the number of reefs per cluster found negligible decrease in variability (not shown). As with the Random Sampling designs, the decrease in variability between 25 and 16 clusters is smaller than that from 16 to 10 and again from 10 to 5 clusters. In this sense, the number of clusters performs in a similar manner to that as the number of reefs in the Random Sampling design. Interestingly, the difference between 16 and 25 clusters appears negligible.

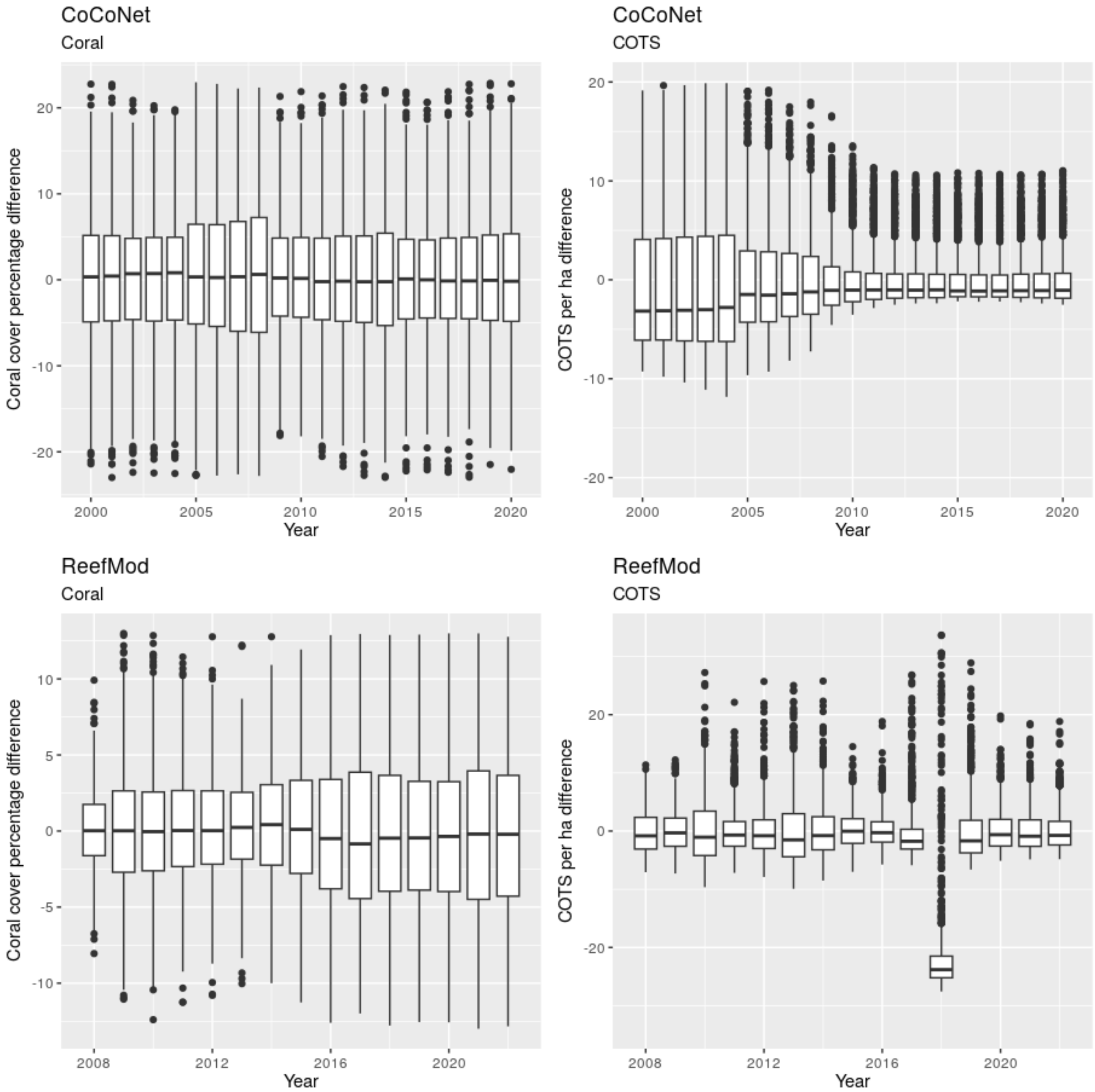

Figure A 46 Results of **Clustered design, 5 clusters of 10 reefs**. Boxplot showing the difference between estimated total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

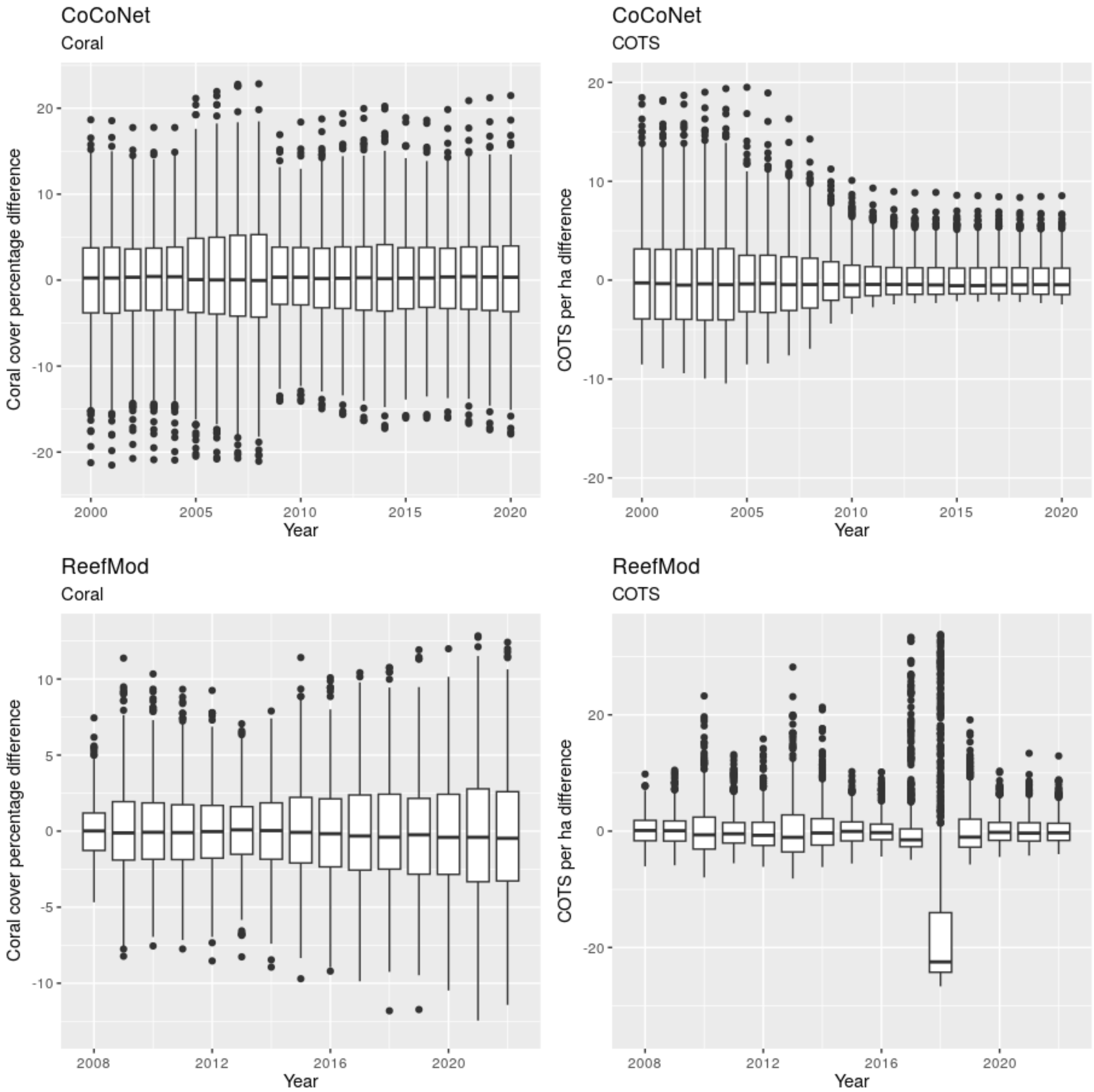

Figure A 47 Results of **Clustered design, 10 clusters of 5 reefs**. Boxplot showing the difference between estimated total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

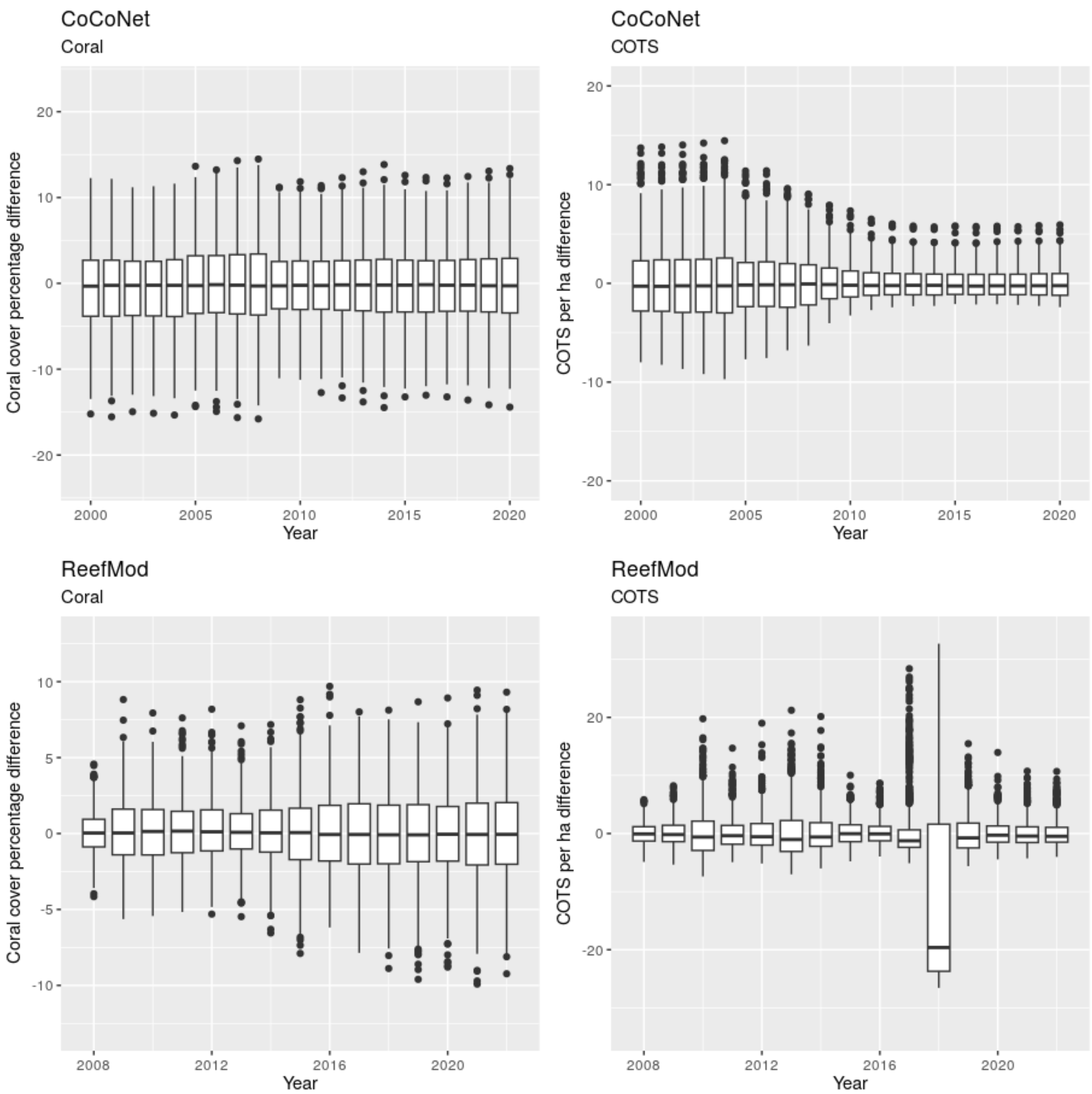

Figure A 48 Results of **Clustered design, 16 clusters of 3 reefs**. Boxplot showing the difference between estimated total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

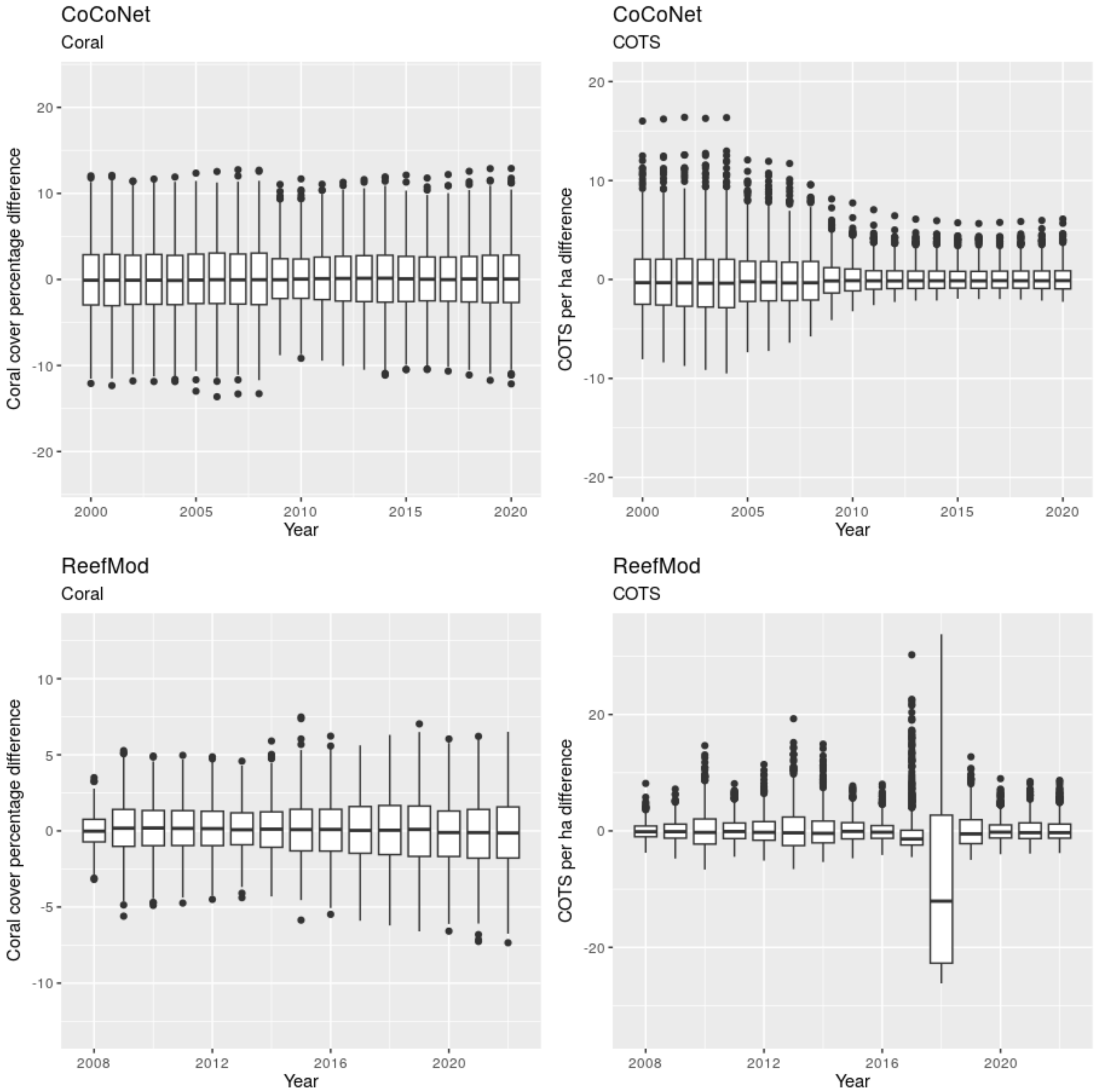

Figure A 49 Results of **Clustered design, 25 clusters of 2 reefs**. Boxplot showing the difference between estimated total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

Figure A 50, **Figure A 51**, **Figure A 52**, and **Figure A 53** show the estimated time series plots comparing the estimated coral cover and COTS densities for Clustered Random Sampling for 5, 10, 16, and 25 clusters. As with the random sampling case, the estimated average matches well with the true average coral cover and COTS density in both simulation models. The decrease in variability is also noticeable similar to that of the boxplots.

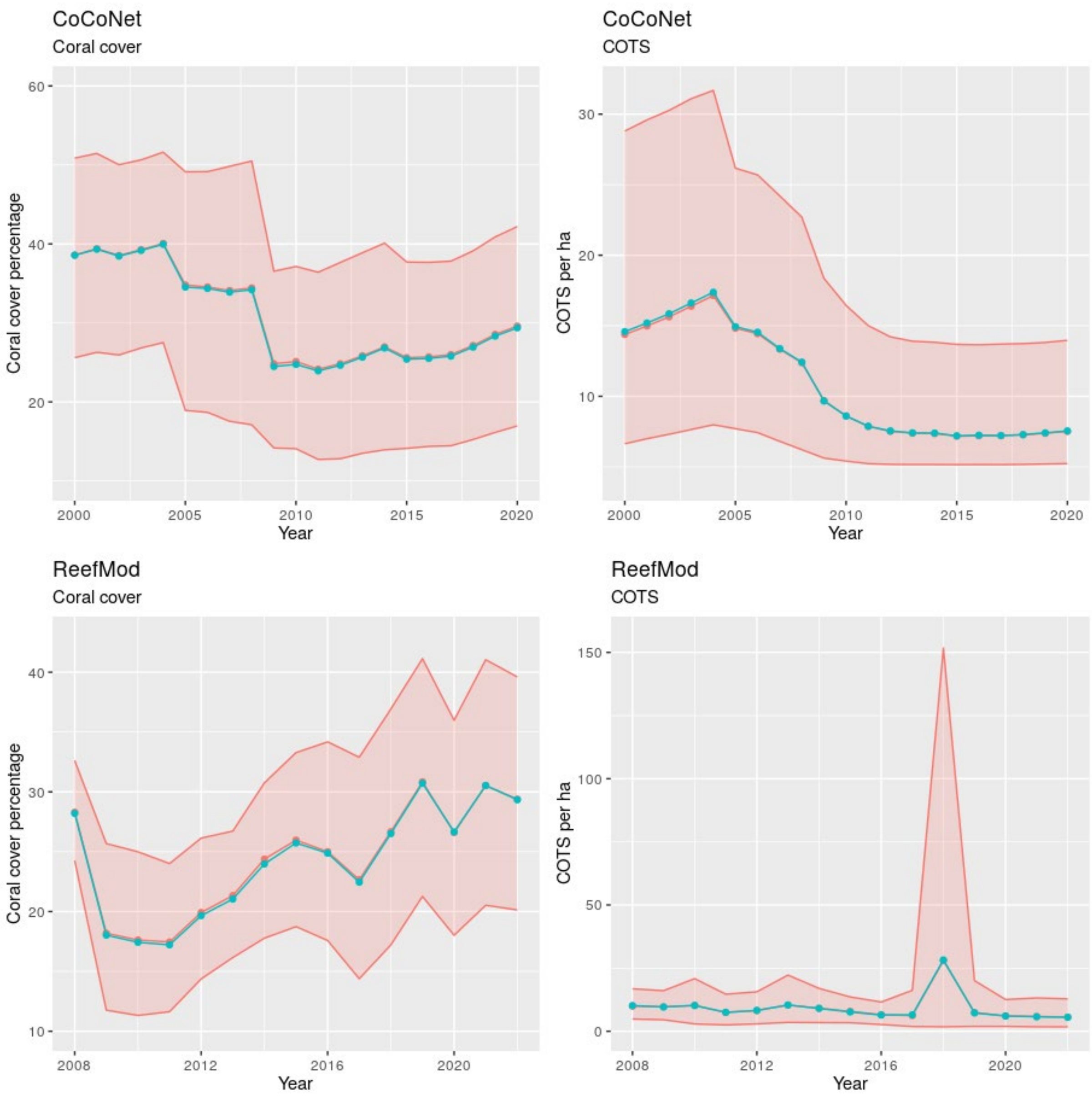

Figure A 50 Time series plots showing estimates (red) and true value (blue) from **Clustered design with 5 clusters of 10 reefs** over years with 95% intervals. Plot shows total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

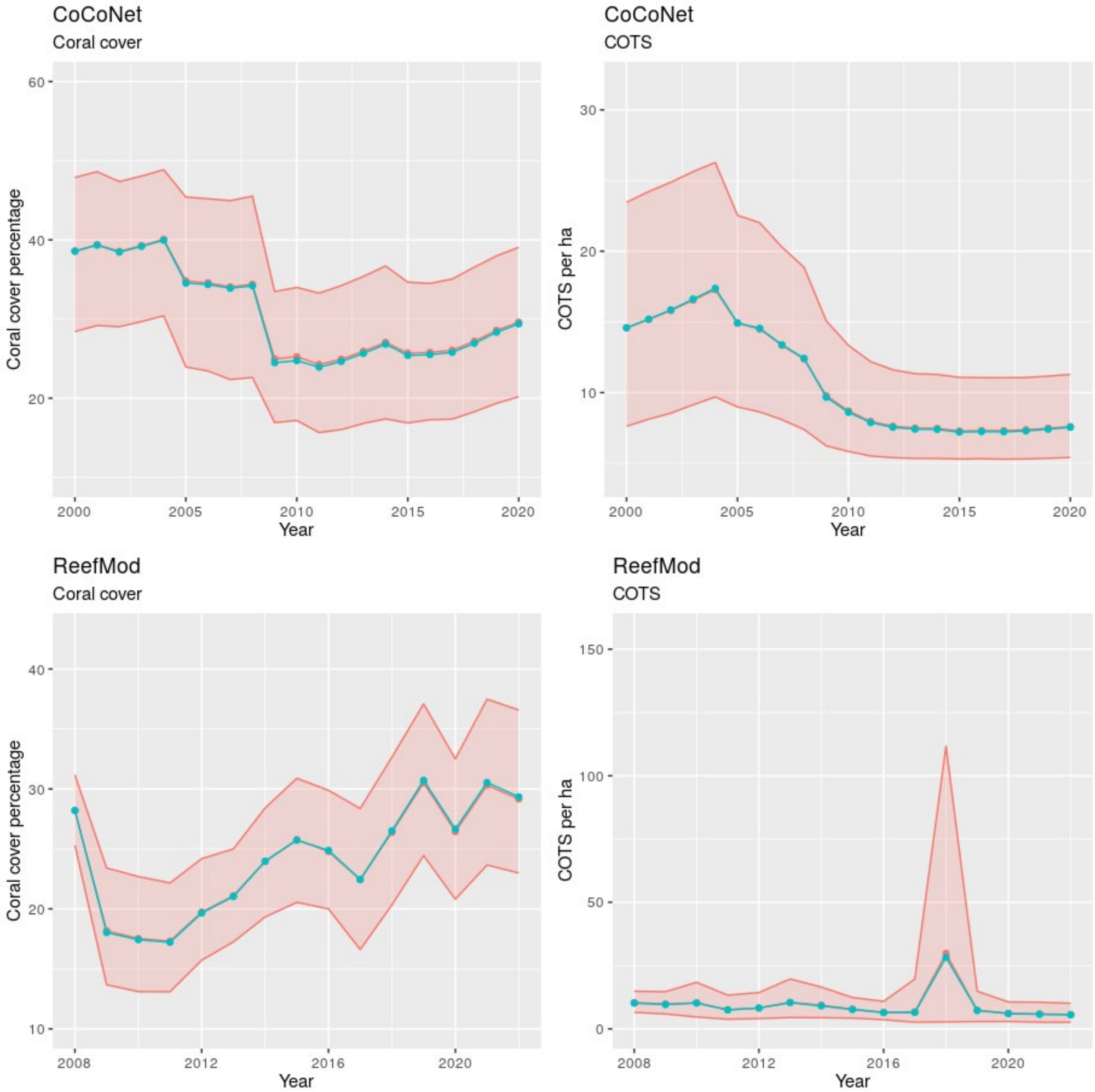

Figure A 51 Time series plots showing estimates (red) and true value (blue) from **Clustered design with 10 clusters of 5 reefs** over years with 95% intervals. Plot shows total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

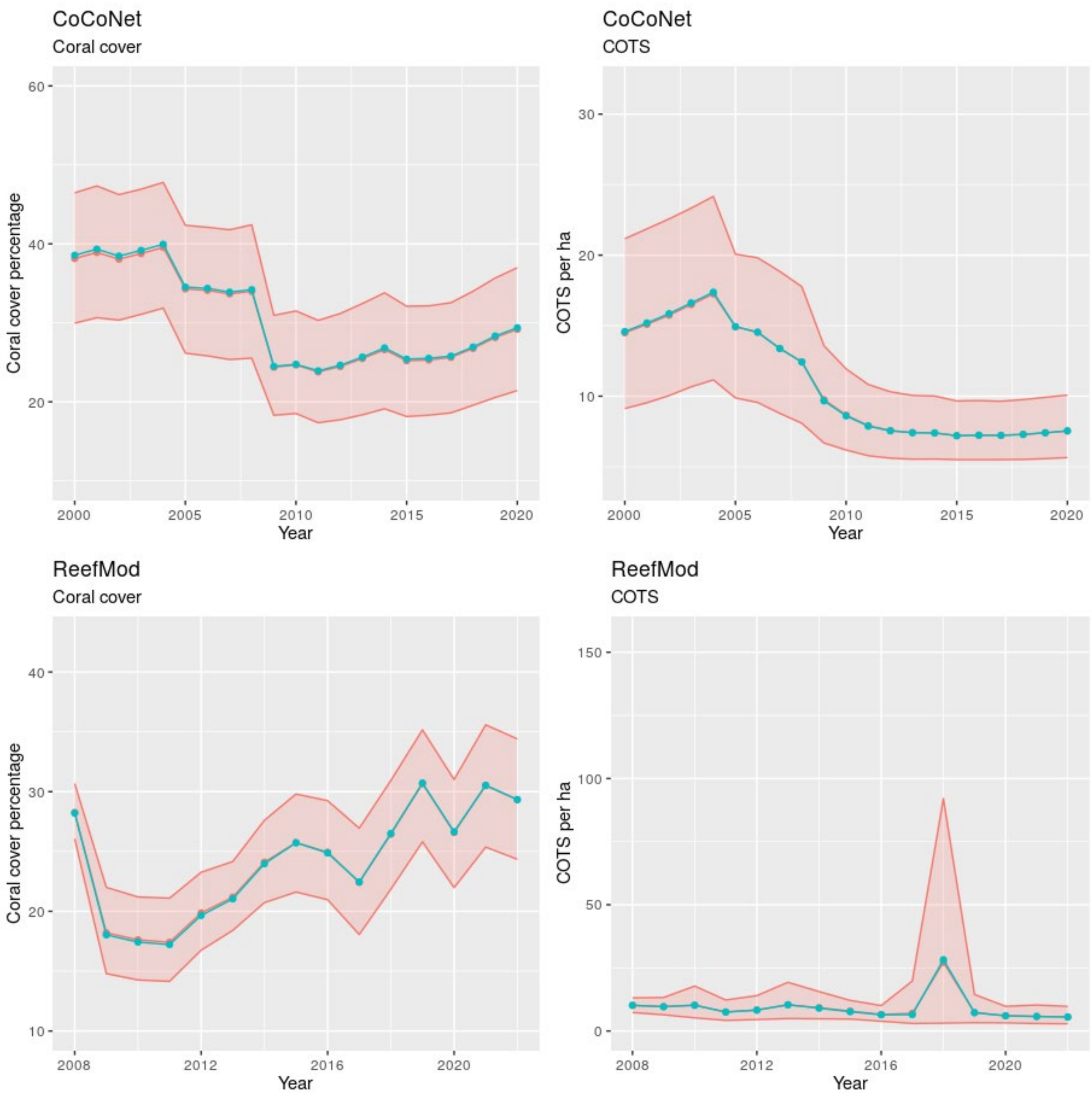

Figure A 52 Time series plots showing estimates (red) and true value (blue) from **Clustered design with 16 clusters of 3 reefs** over years with 95% intervals. Plot shows total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

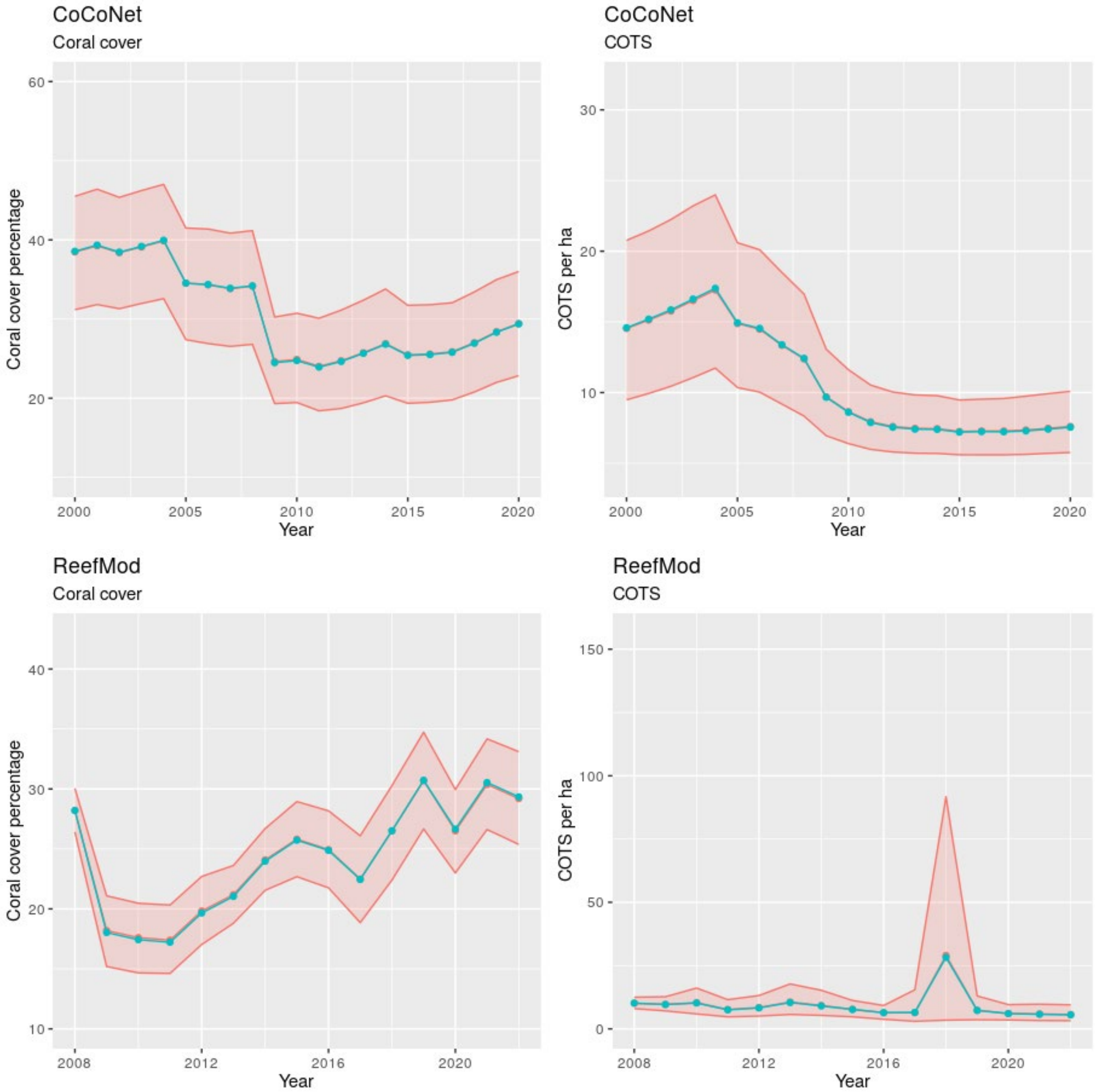

Figure A 53 Time series plots showing estimates (red) and true value (blue) from **Clustered design with 25 clusters of 2 reefs** over years with 95% intervals. Plot shows total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

Fishing Intensity Sampling

Figure A 54 shows the boxplots of the difference in average estimated coral cover and COTS density and true averages while **Figure A 55** shows the time series plots through years of the estimator compared to the true values. The estimators are unbiased, with boxplots covering zero overall years and simulations, and the time series plot shows good agreement between the estimated values and true mean. However, there is an small increase in variation with wider boxplots and larger confidence regions in the time series plots when compared to Random Sampling scenario with 50 reefs (**Figure A 39** and **Figure A 43**), although this increase is small. This may indicate that stratifying a design based on green vs other zones will give a good estimate within each zone at the cost of increased variability at the GBR wide level, though if comparing densities between green and other zones was a key objective of the monitoring program it could still be considered.

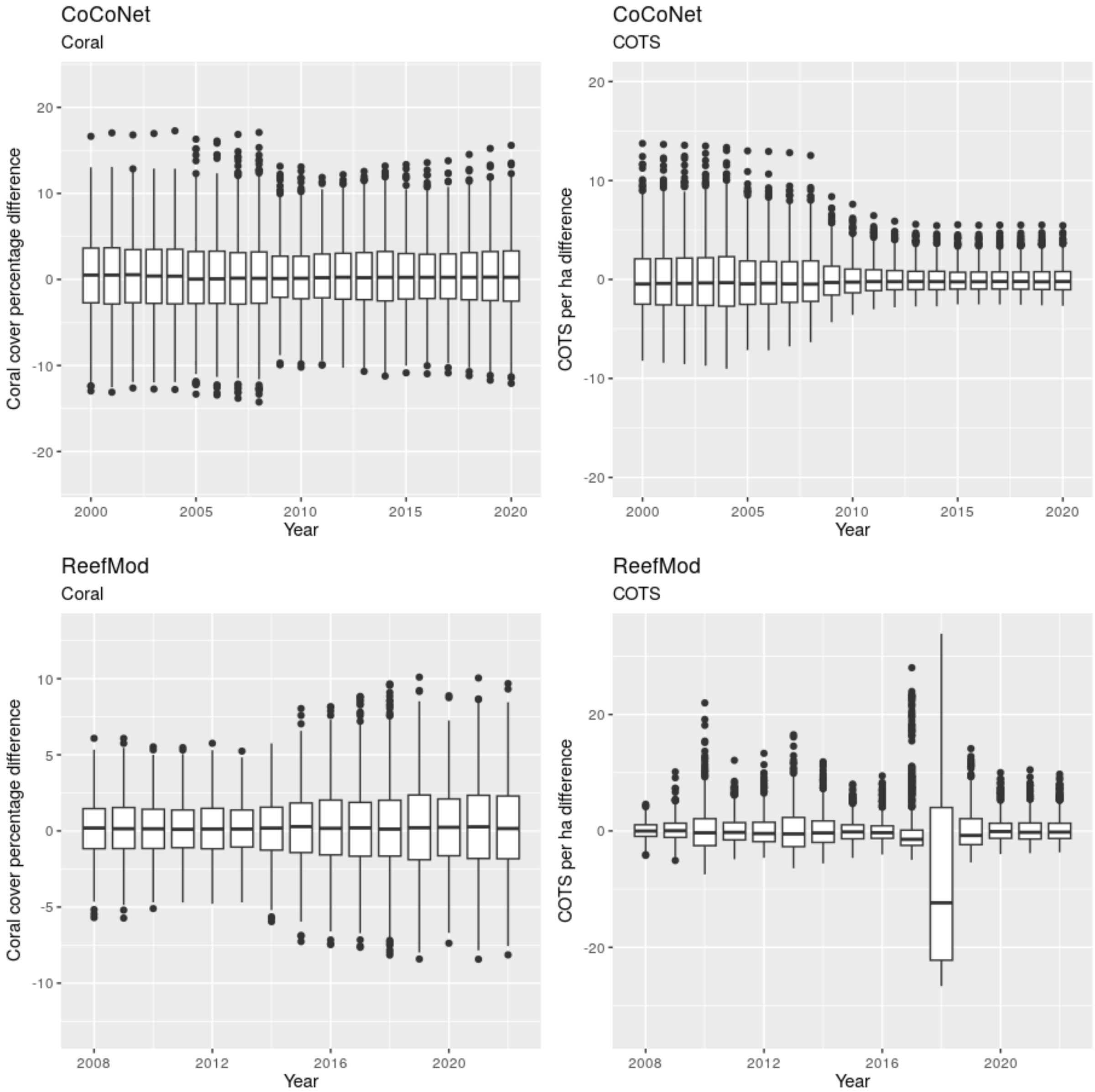

Figure A 54 Results of **zone-based monitoring**. Boxplot showing the difference between estimated total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

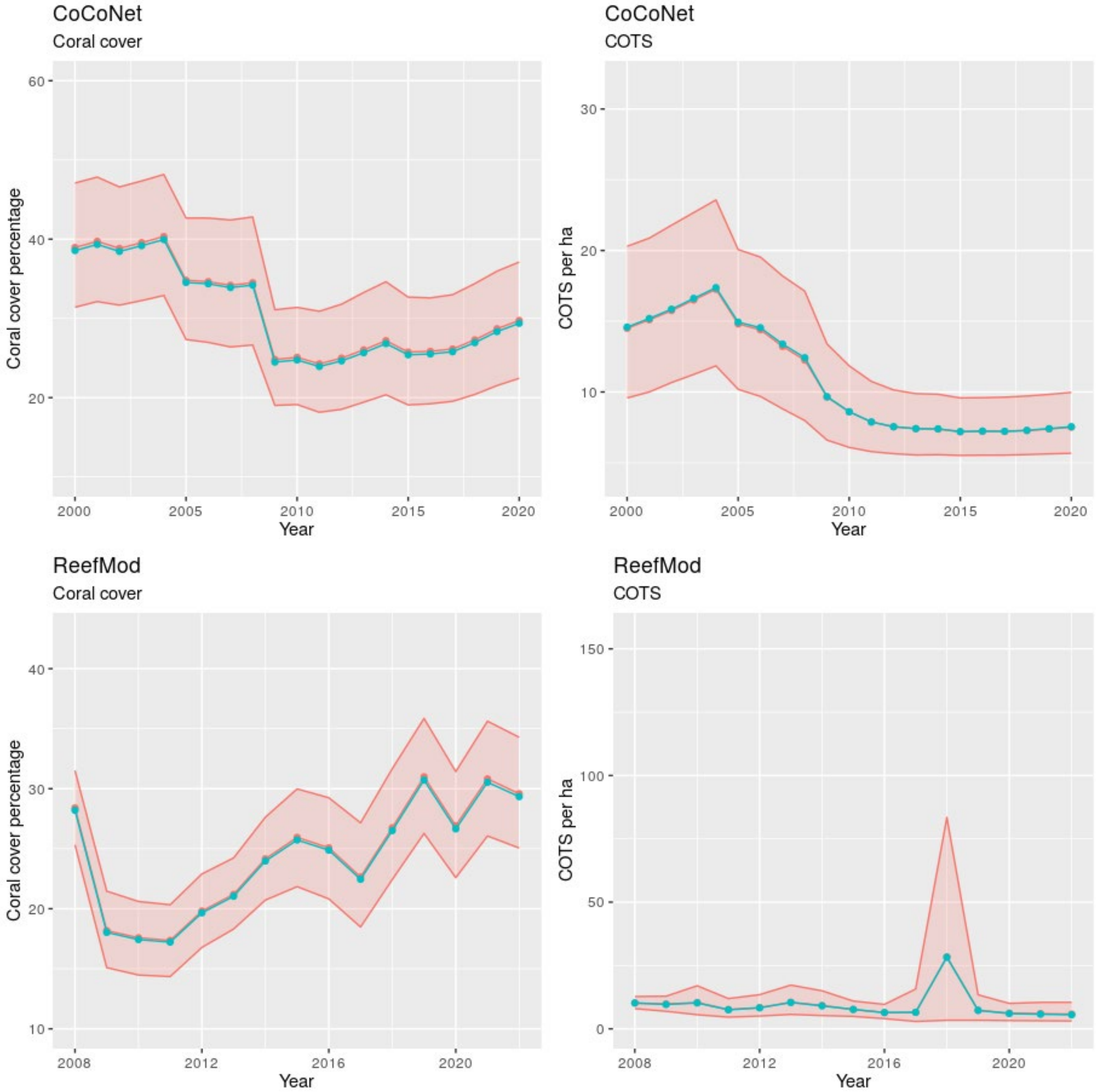

Figure A 55 Time series plots showing estimates (red) and true value (blue) from **zone-based monitoring** design over years with 95% intervals. Plot shows total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

Region Sampling

Figure A 56 shows boxplots of the difference in the estimated average coral cover and COTS density against the true value for CoCoNet and ReefMod-GBR, and **Figure A 57** show the related time series. Again, the estimator is unbiased, resulting in an accurate measure for the average coral cover and COTS density over the entire GBR, but with a noticeable increase in variability when compared to random sampling. This is likely due to the high variation between regions in our simulation. For instance, there is more coral cover in the Far North and South regions than North and Central in CoCoNet simulations, noted below in **Figure A 72**, and likewise similar for that of COTS densities, noted below in **Figure A 73**.

Further, stratifying by region means a lower proportion of reefs are sampled in the Far North and South regions than the North and Central regions. Considering only reefs with at least 4 sites, there are 649 in the Far North, 185 in the North, 107 in the Central, and 1,233 in the South. Under this sampling design, we would expect 6.8% of North region reefs and 11.7% of Central region reefs to be monitored while only 1.9% of Far North and 1.0% of South region reefs would be.

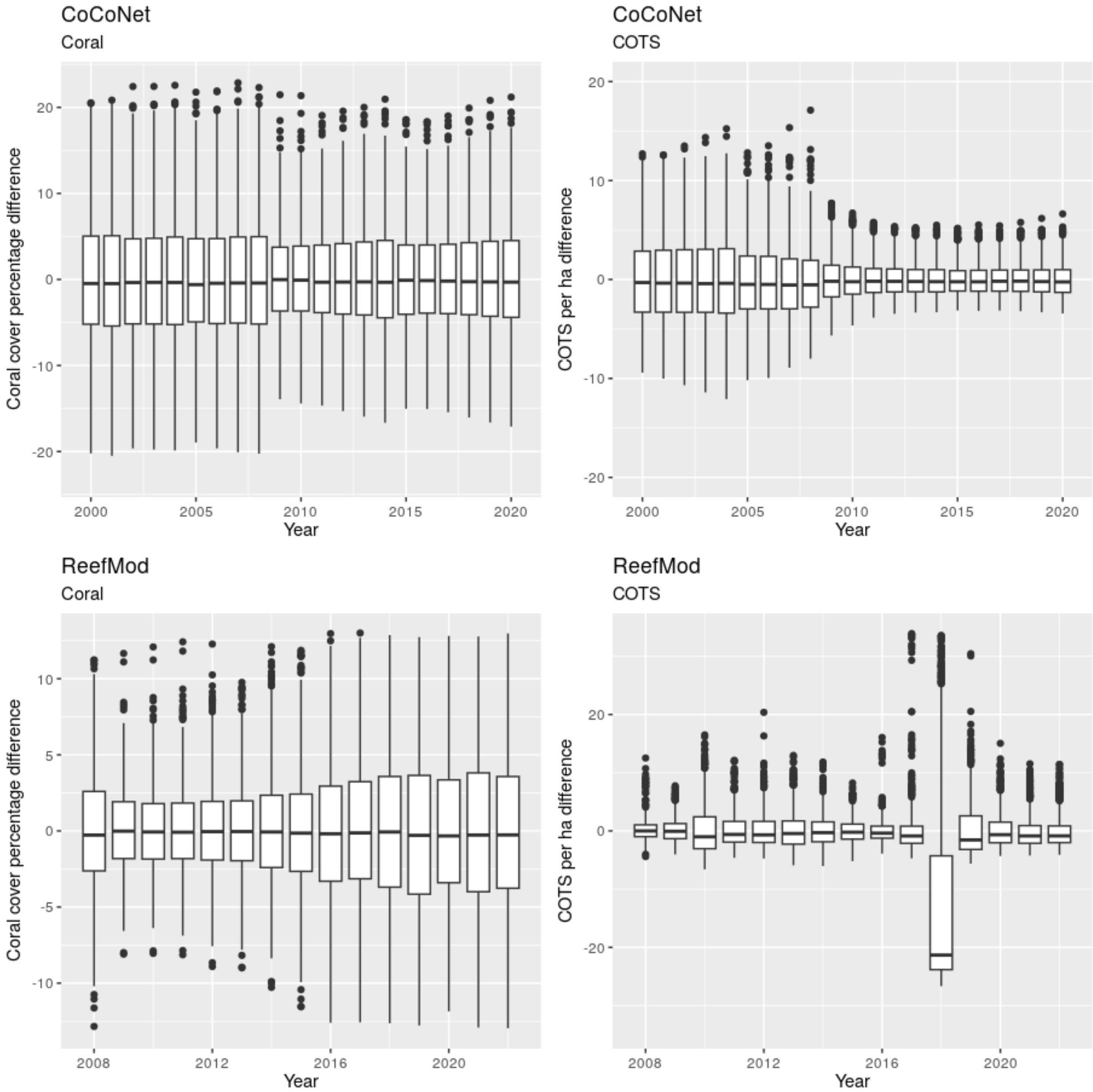

Figure A 56 Results of **Region based monitoring**. Boxplot showing the difference between estimated total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

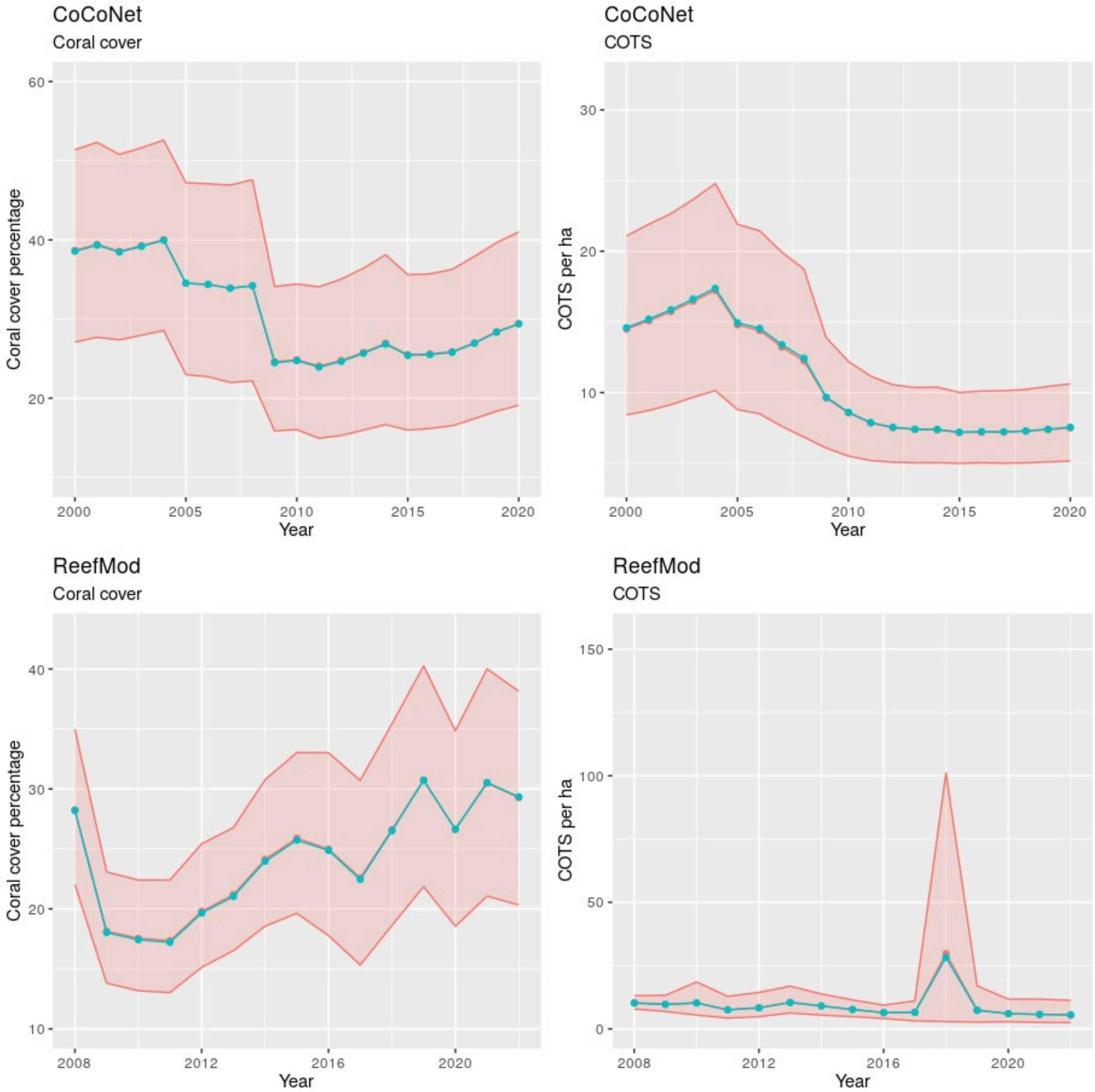

Figure A 57 Time series plots showing estimates (red) and true value (blue) from **Region based monitoring** design over years with 95% intervals. Plot shows total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

Priority Reef Sampling

Figure A 58 shows the boxplots of the difference between estimated coral cover and COTS densities and true values over the GBR, while **Figure A 59** shows the resulting time series plot. There is a noticeable difference between the estimated average coral cover and COTS density from monitoring *only* priority reefs compared to the average over the entire GBR. Estimates based on CoCoNet consistently overestimate average coral cover while underestimating COTS density. This is because COTS have higher densities at non-priority reefs in CoCoNet simulations. The same estimates using ReefMod-GBR generally are within uncertainty bounds, though the estimated means do not match with the true means (bias). There does appear to be a negligible increase in estimated variation compared to the 50 Random Sampling scenario, though this does not appear significant and not consistent through all years.

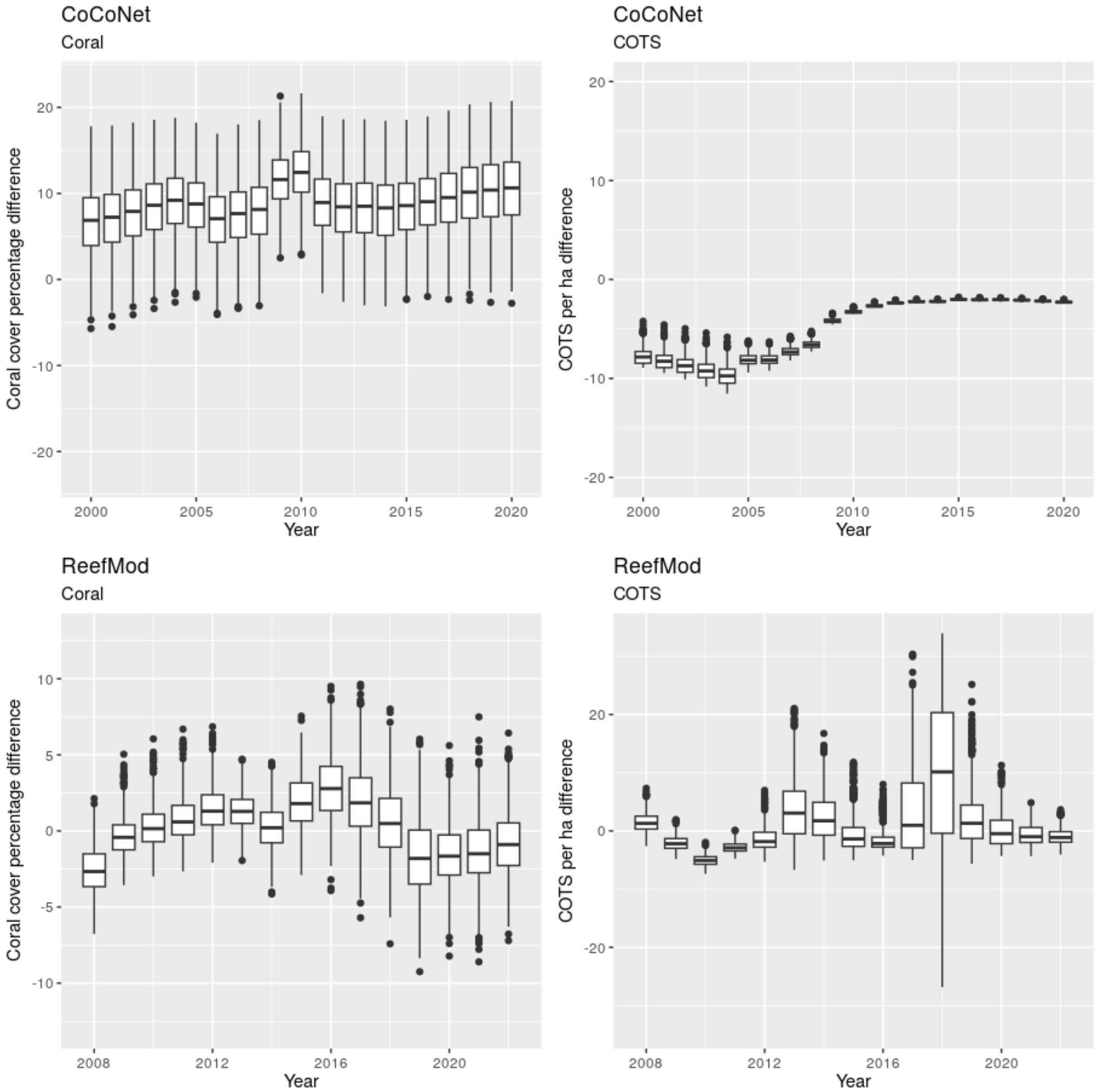

Figure A 58 Results of **Priority reef monitoring** design. Boxplot showing the difference between estimated total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

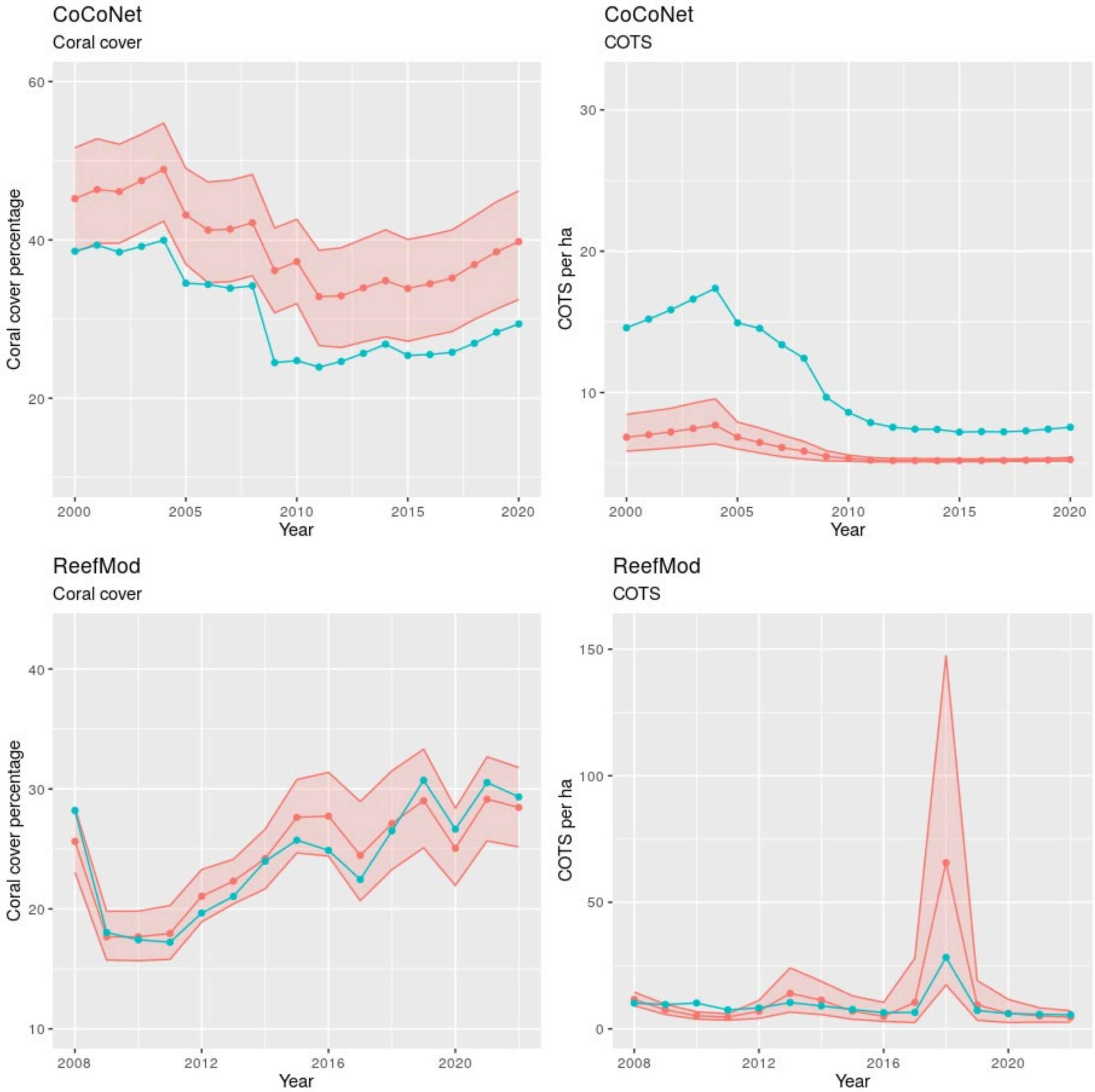

Figure A 59 Time series plots showing estimates (red) and true value (blue) from **Priority reef based monitoring** design over years with 95% intervals. Plot shows total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

Target Reef Sampling

Boxplots for the difference between estimated coral cover and COTS densities based on monitoring only target reefs are found in **Figure A 60**, with the respective time series plots found in **Figure A 61**. While the estimated averages from monitoring *only* target reefs are closer to the estimated true average for CoCoNet for coral cover, they still underestimate COTS densities for the entire GBR. However, estimates based on ReefMod-GBR are similar to the true average. Compared to monitoring designs based only on priority reefs, the estimates do not appear to have a noticeable difference in variation compared, though coral cover estimates do appear to have less variability.

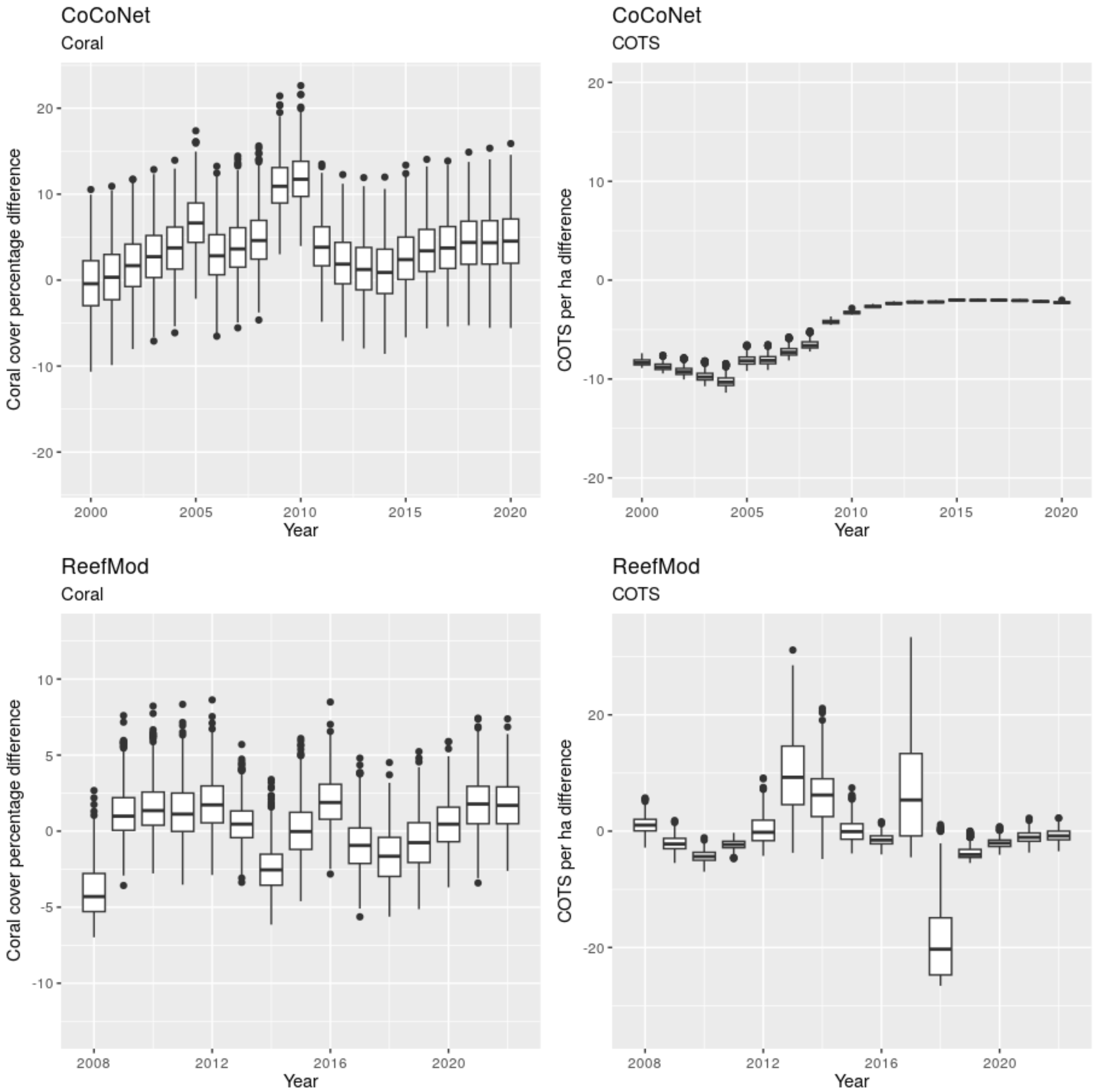

Figure A 60 Results of **Target reef monitoring** design. Boxplot showing the difference between estimated total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

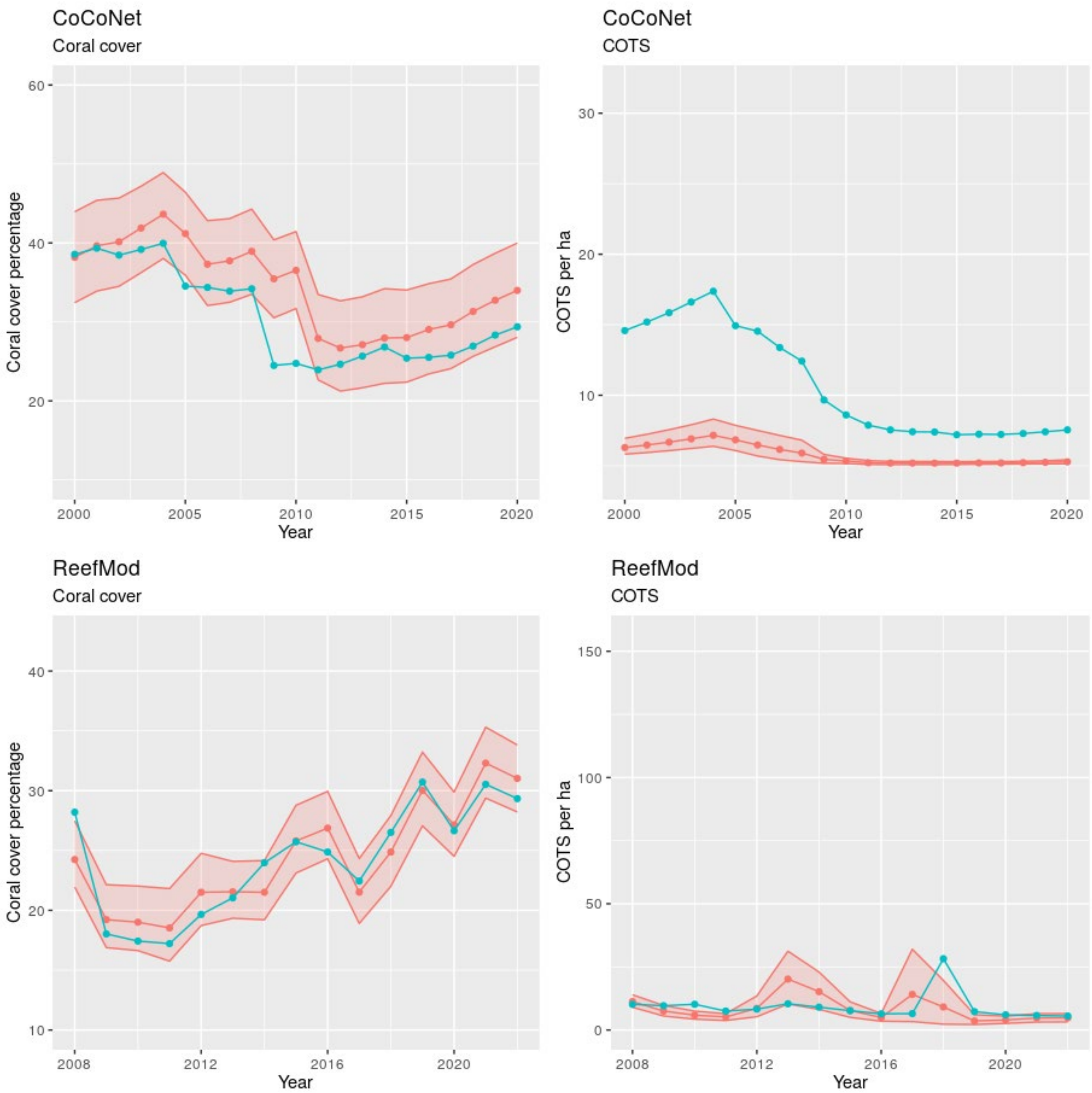

Figure A 61 Time series plots showing estimates (red) and true value (blue) from **Target reef based monitoring** design over years with 95% intervals. Plot shows total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

COTS Risk Sampling

The COTS Risk Sampling monitoring scenario shows good agreement in the estimates of coral cover and COTS density with the true averages over the entire GBR, as noted by the boxplots in **Figure A 62** and time series plots in **Figure A 63** The noted exception to this is estimated COTS densities for CoCoNet which is consistently underestimating the average. The reason for the underestimate is that there are individual reefs (205) that have been assigned zero COTS risk so they have no chance of selection in the sample, however they have a non-zero estimated COTS density in CoCoNet. If we removed the zero COTS risk reefs from the sample frame, then the COTS density estimates we would also expect the CoCoNet COTS density estimates to be unbiased. The estimated variability is increased for coral compared to Random Sampling with 50 reefs but similar or slightly less for COTS.

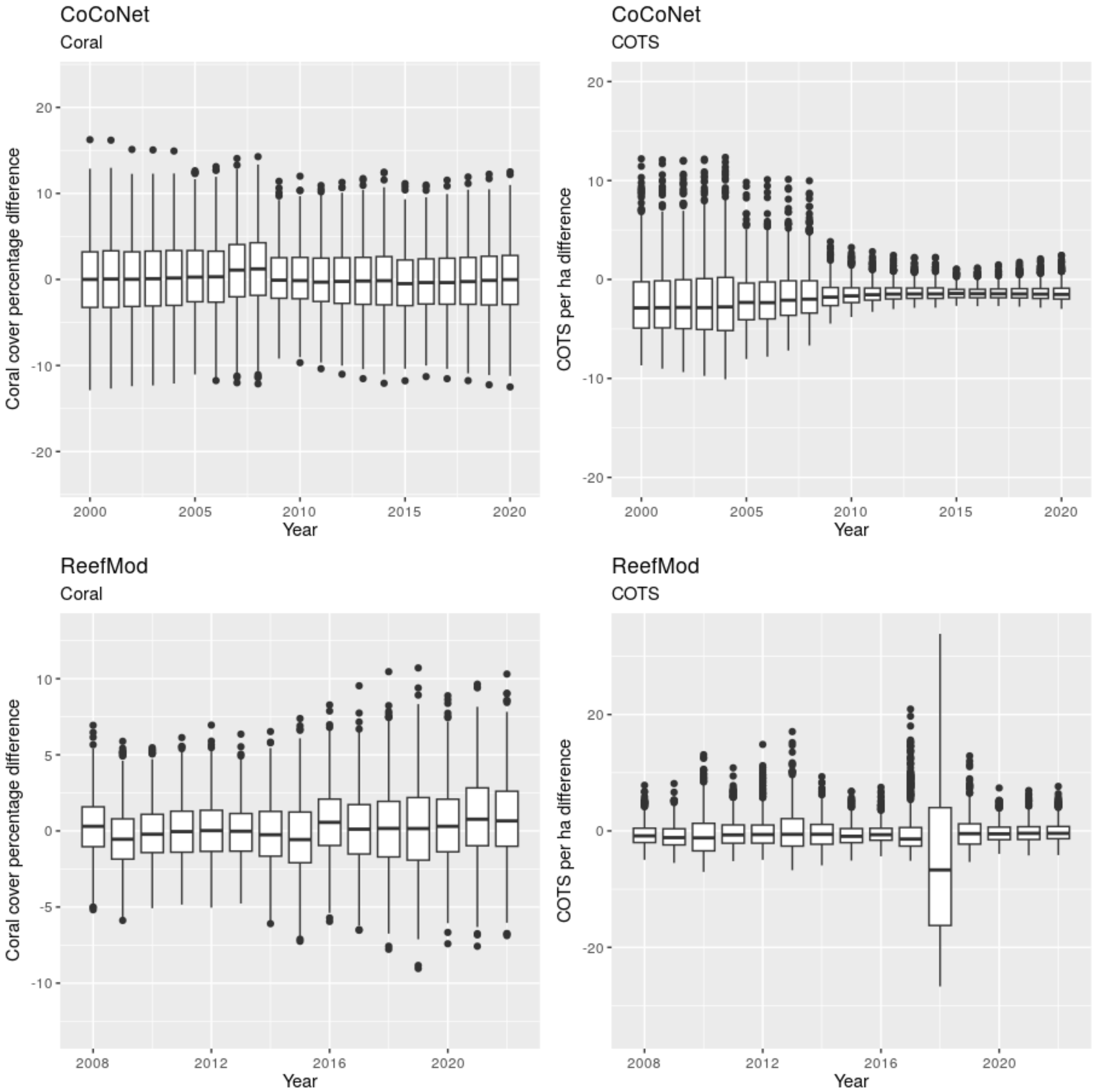

Figure A 62 Results of risk of **COTS probability design**. Boxplot showing the difference between estimated total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

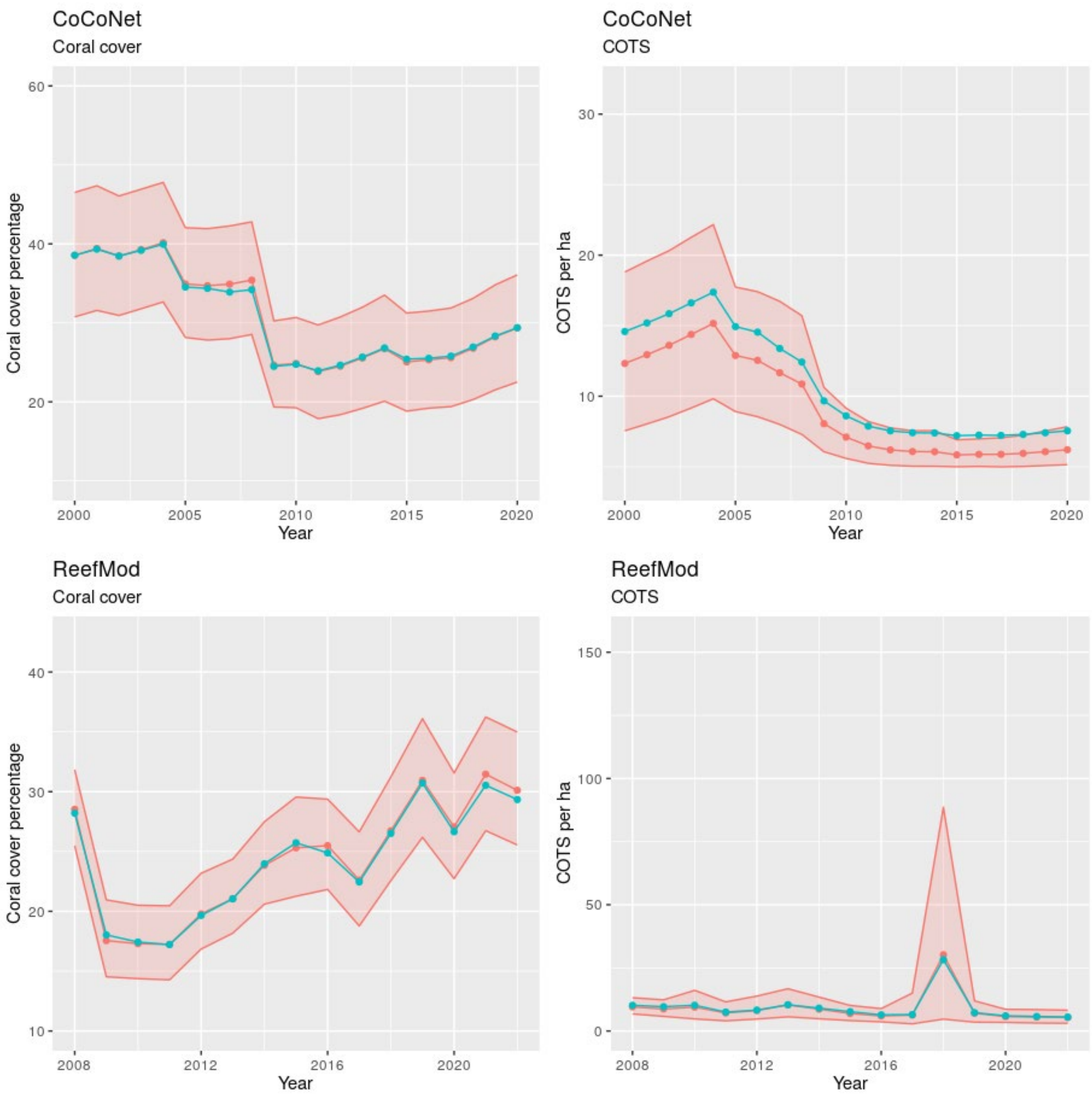

Figure A 63 Time series plots showing estimates (red) and true value (blue) from **COTS risk based monitoring** design over years with 95% intervals. Plot shows total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

Size Based Sampling

Figure A 64 shows boxplots for the difference in estimated and true average coral cover and COTS densities for the Size Based monitoring designs, and **Figure A 65** shows the resulting time series plots. The estimator is unbiased, noting that the boxplots in **Figure A 64** centre around zero and the estimated average coral cover and COTS densities in both CoCoNet and ReefMod-GBR line up with the true averages as seen in the time series plots. However, estimated variation does appear slightly more than the Random Sampling with 50 reefs scenario, particularly for coral cover based on ReefMod-GBR simulations and COTS density estimates based on CoCoNet. Importantly though, the sampling frame is different from that of Random Sampling, with the Size Based design considering all possible reefs and not just reefs with at least four sites.

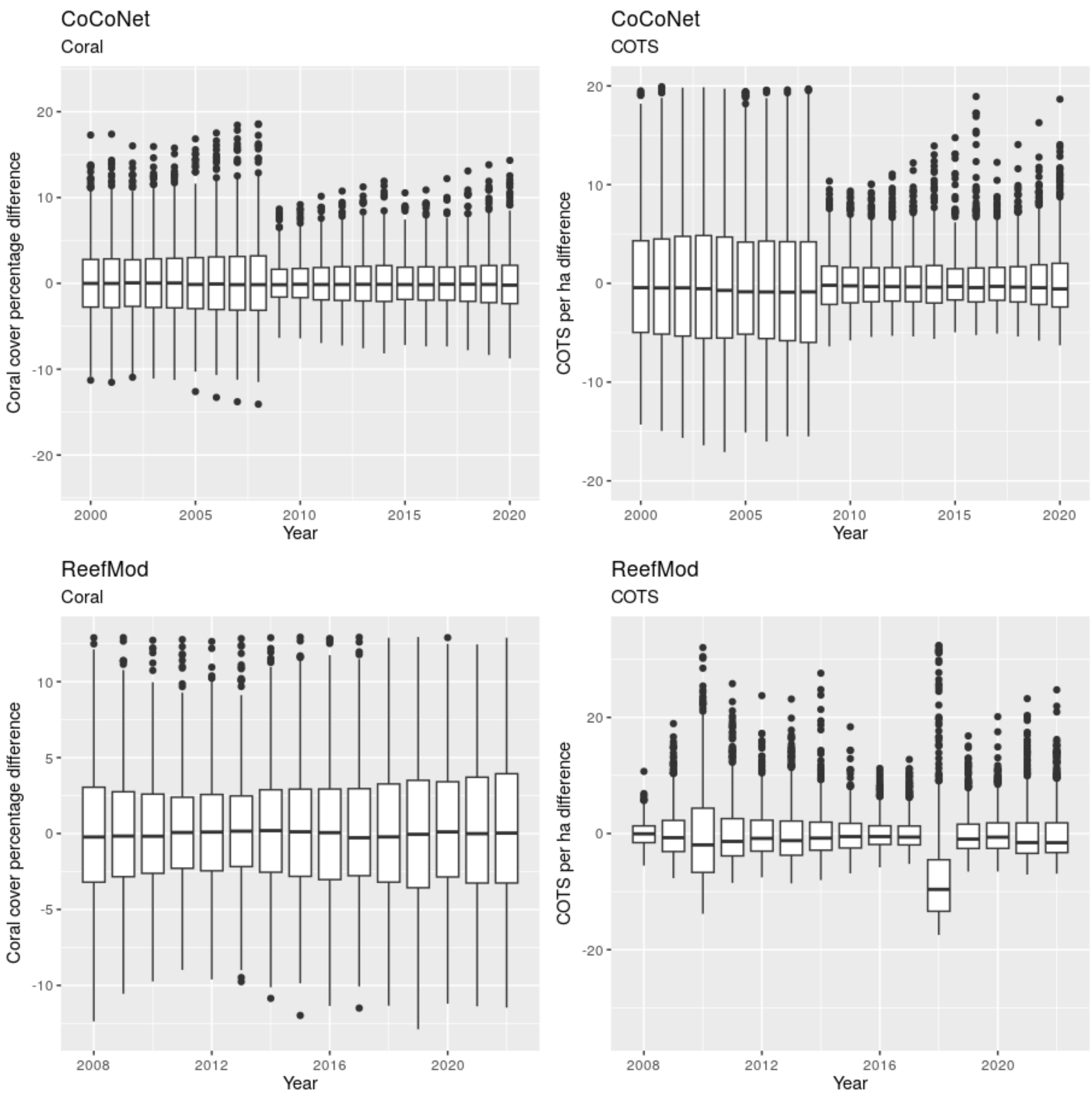

Figure A 64 Results of **Size based monitoring** design. Boxplot showing the difference between estimated total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

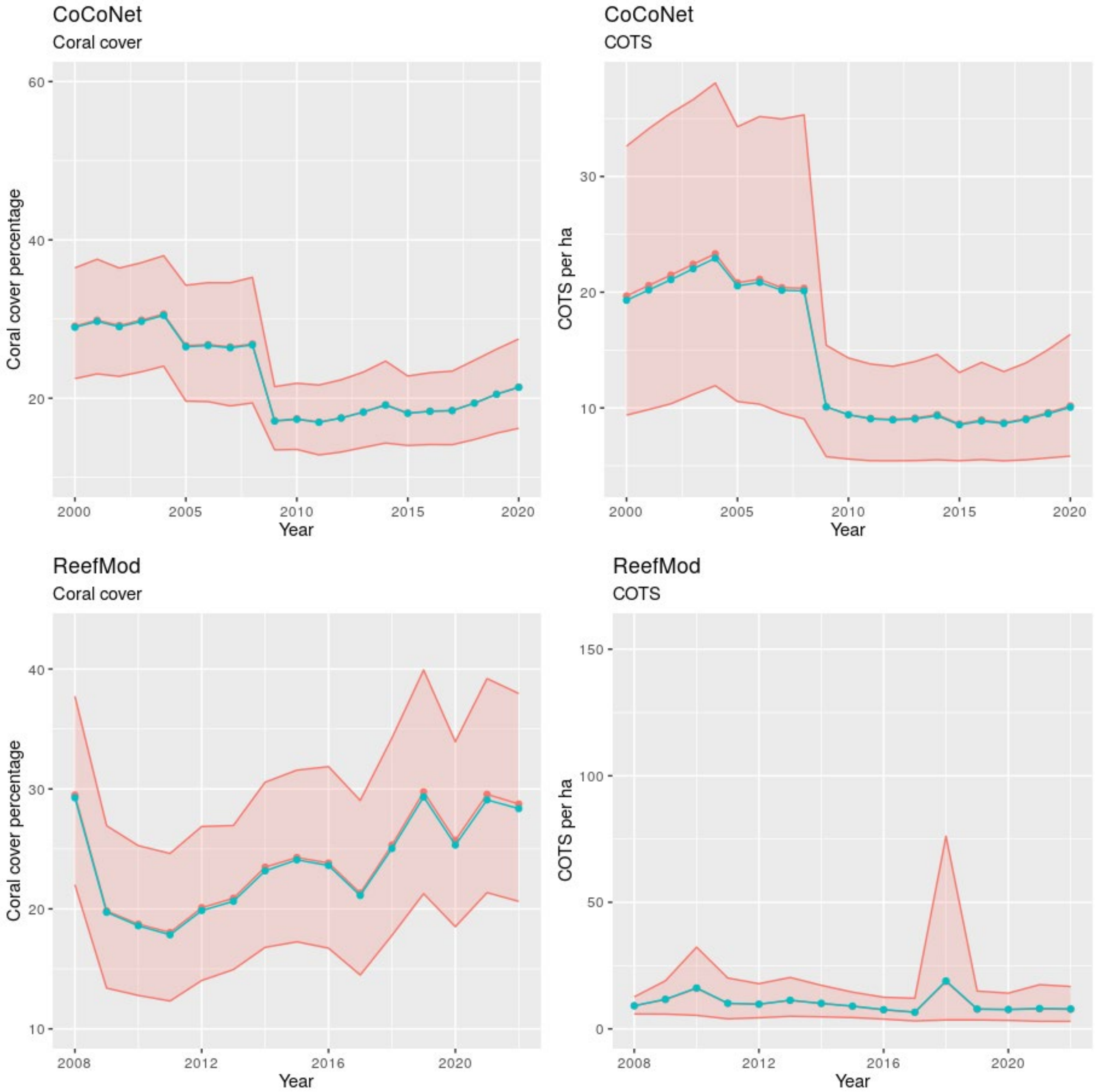

Figure A 65 Time series plots showing estimates (red) and true value (blue) from **Size based monitoring** design over years with 95% intervals. Plot shows total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

LTMP Based Sampling

Boxplots showing the difference between estimated coral cover and COTS densities for the LTMP Based monitoring design are found in **Figure A 66** while the time series plots are shown in **Figure A 67**. For CoCoNet, the monitoring design consistently overestimates the average coral cover over the entire GBR while consistently underestimating COTS densities. Similar to that of priority reefs, COTS densities are likely higher at reefs that are not classified as LTMP reefs in CoCoNet simulations. For ReefMod-GBR, the estimator is considerably better, though not within the uncertainty bounds for many years prior to 2016 for coral cover. Of most concern is that in both models, the trend over time has patterns that are not consistent with the ‘truth’. The variation is comparable to that of Random Sampling with 50 reefs.

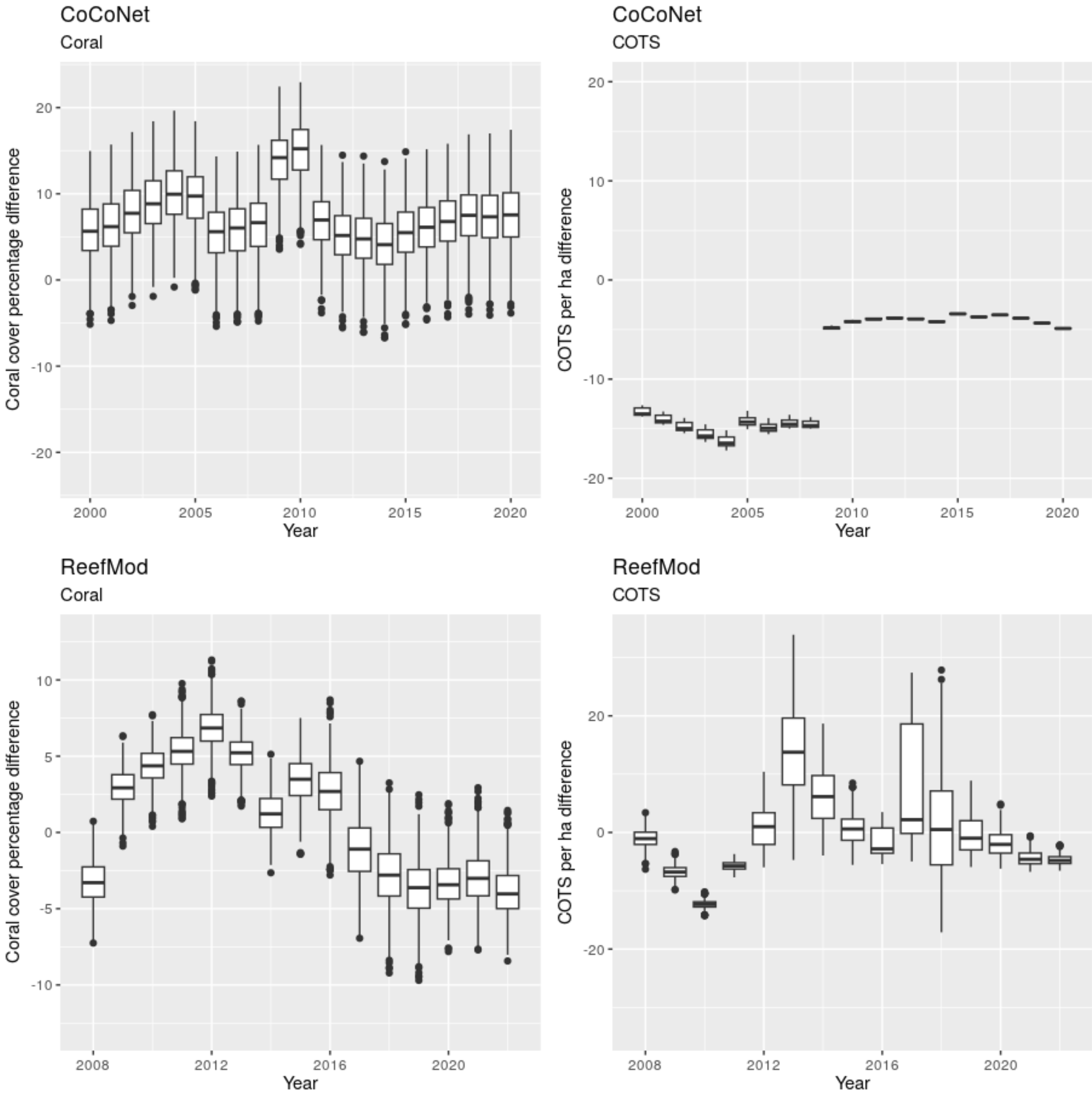

Figure A 66 Results of **LTMP monitoring** design. Boxplot showing the difference between estimated total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

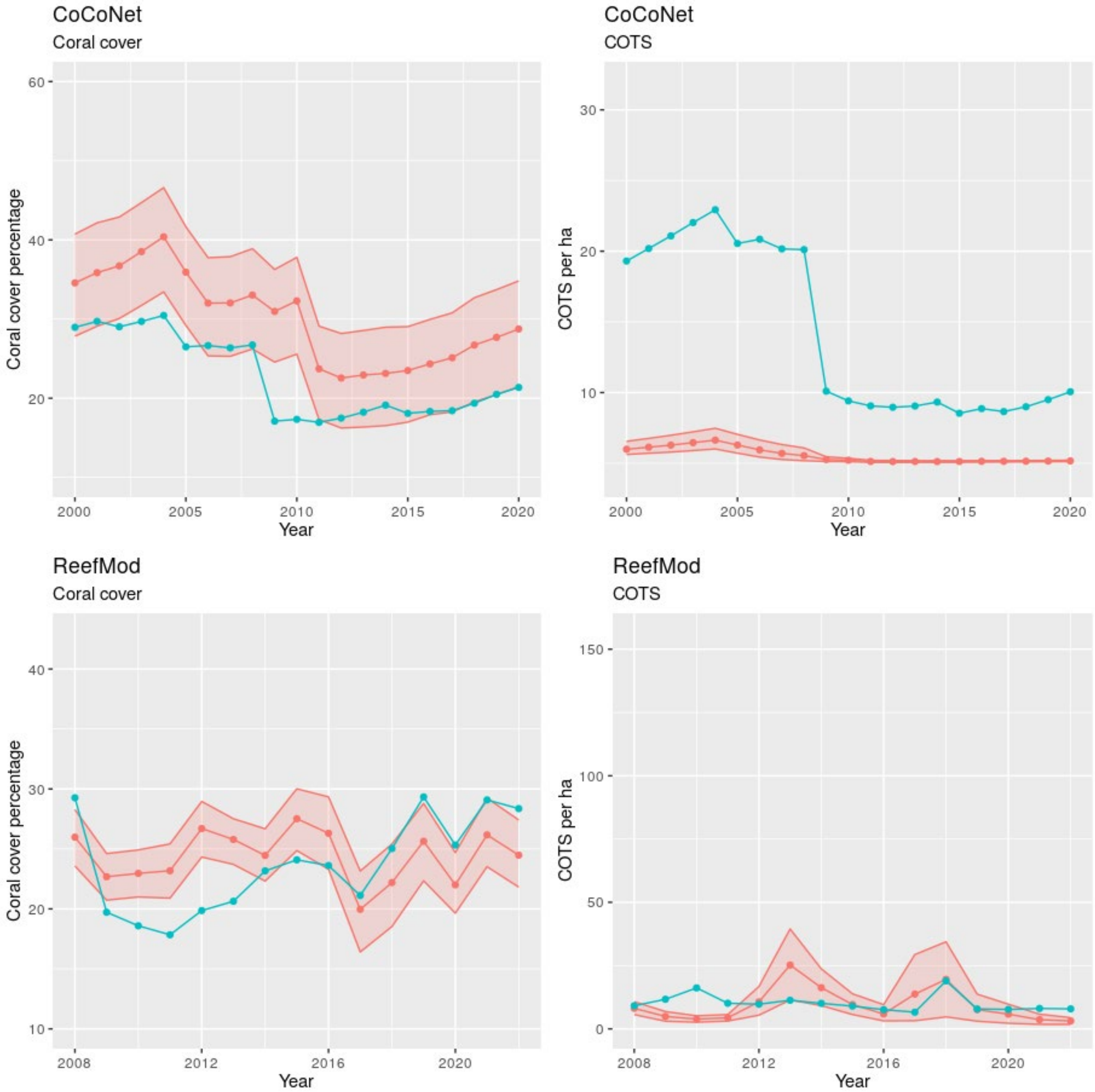

Figure A 67 Time series plots showing estimates (red) and true value (blue) from **LTMP reef based monitoring** design over years with 95% intervals. Plot shows total average coral cover (left column) and average COTS densities (right column) and the true values using CoCoNet (top row) and ReefMod (bottom row) models.

Results By Control Region

CoCoNet

Because CoCoNet is calibrated to LTMP data at the regional scale instead of the coarser GBR-wide or finer individual reef scale, we further investigate the resulting estimates of coral cover and COTS densities at the control region scale. **Figure A 68** shows the estimated average coral cover with the true average coral cover grouped by control region. While there is still disagreement between the estimated and true averages, with the estimates being higher, the uncertainty bounds contain the true estimate more often. **Figure A 69** shows the estimated average COTS densities per region compared to the true averages. Here is where the discrepancy seen with the averages at the GBR scale are apparent, with good agreement between the estimated and true average COTS density in the North and Central regions and strong disagreement in the Far North and South regions. This indicates that CoCoNet is indicating larger COTS densities in areas not typically surveyed by LTMP. This discrepancy would also show the disagreement in coral cover as well, given the interconnectedness in COTS and coral cover. The proportion of reefs that are LTMP in the North and Central are also higher than that in the Far North and South, indicating that LTMP based monitoring will be more accurate in the North and Central regions.

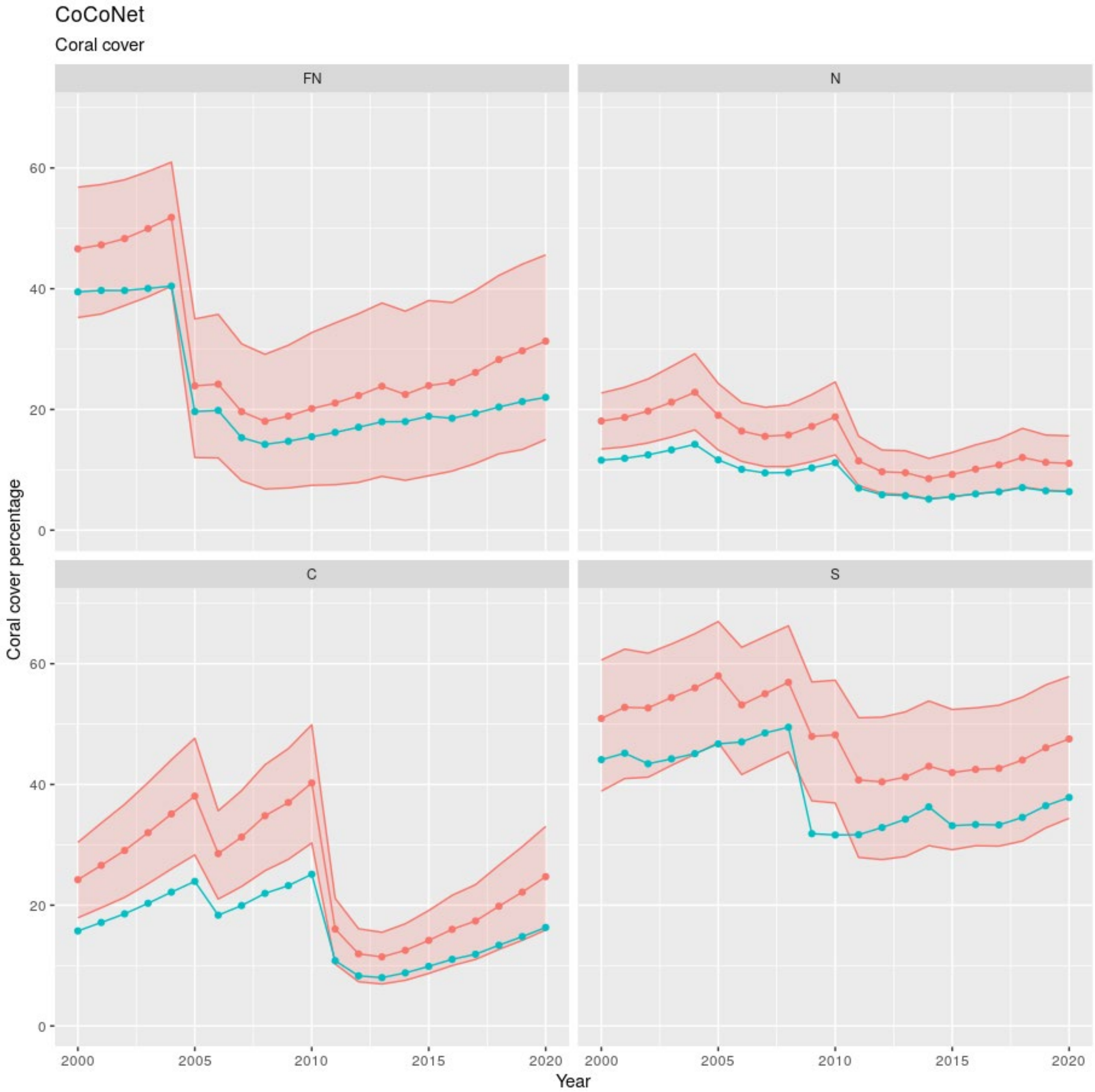

Figure A 68 Estimated coral cover grouped by region for **LTMP based monitoring** of 50 reefs based on CoCoNet. Regions are Far North (FN), North (N), Central (C), and South (S).

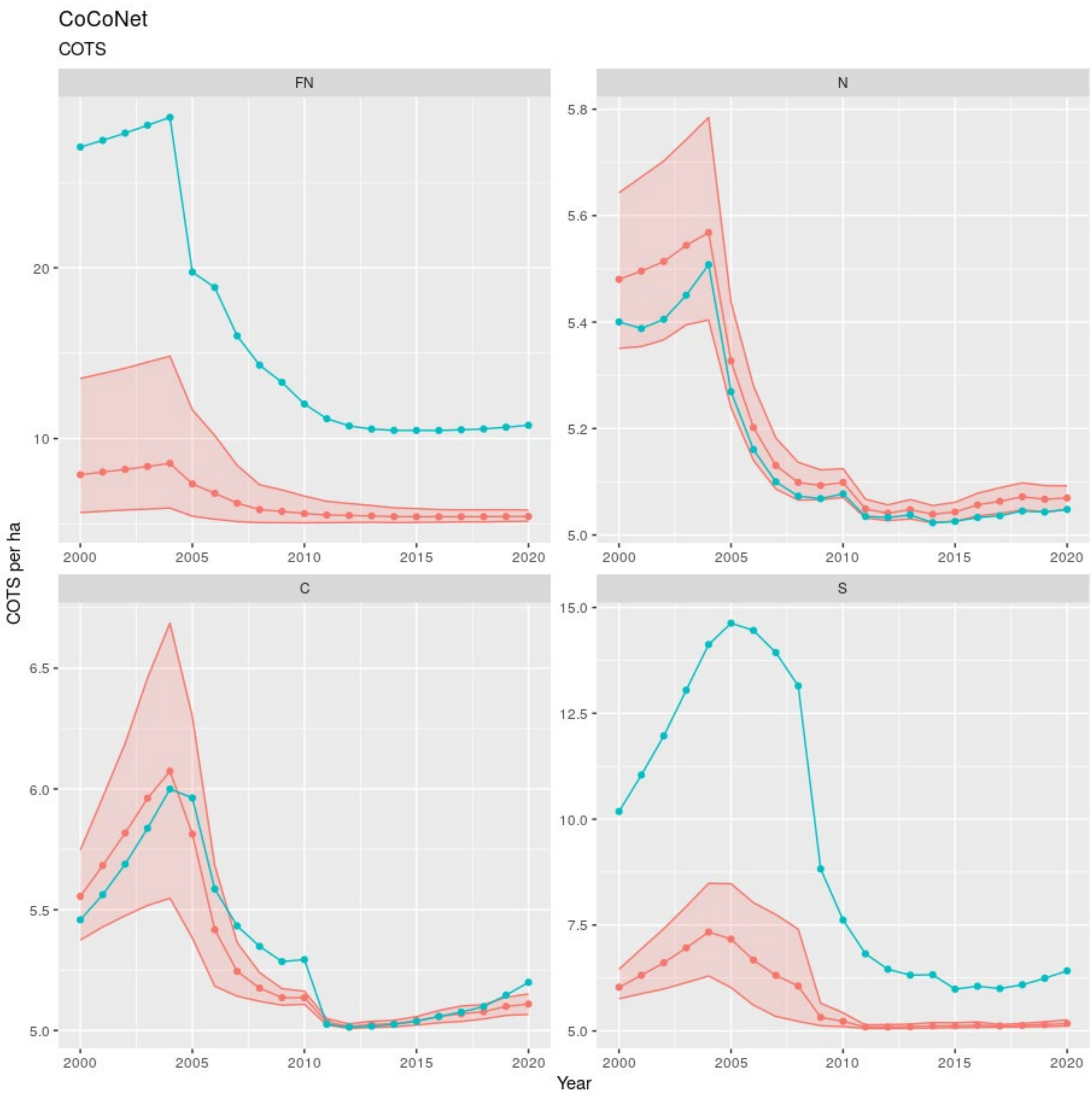

Figure A 69 Estimated COTS density grouped by region for **LTMP based monitoring** of 50 reefs based on CoCoNet. Regions are Far North (FN), North (N), Central (C), and South (S).

ReefMod-GBR

For comparison purposes we also investigate region-based results from ReefMod-GBR. **Figure A 70** shows the results by region for coral cover while **Figure A 71** shows the time series results by region for COTS density. The main region that is not well represented for coral cover is the South while the main region that is not well represented is the Far North for COTS density. Again, this shows the disproportionate representation of the LTMP in the different regions.

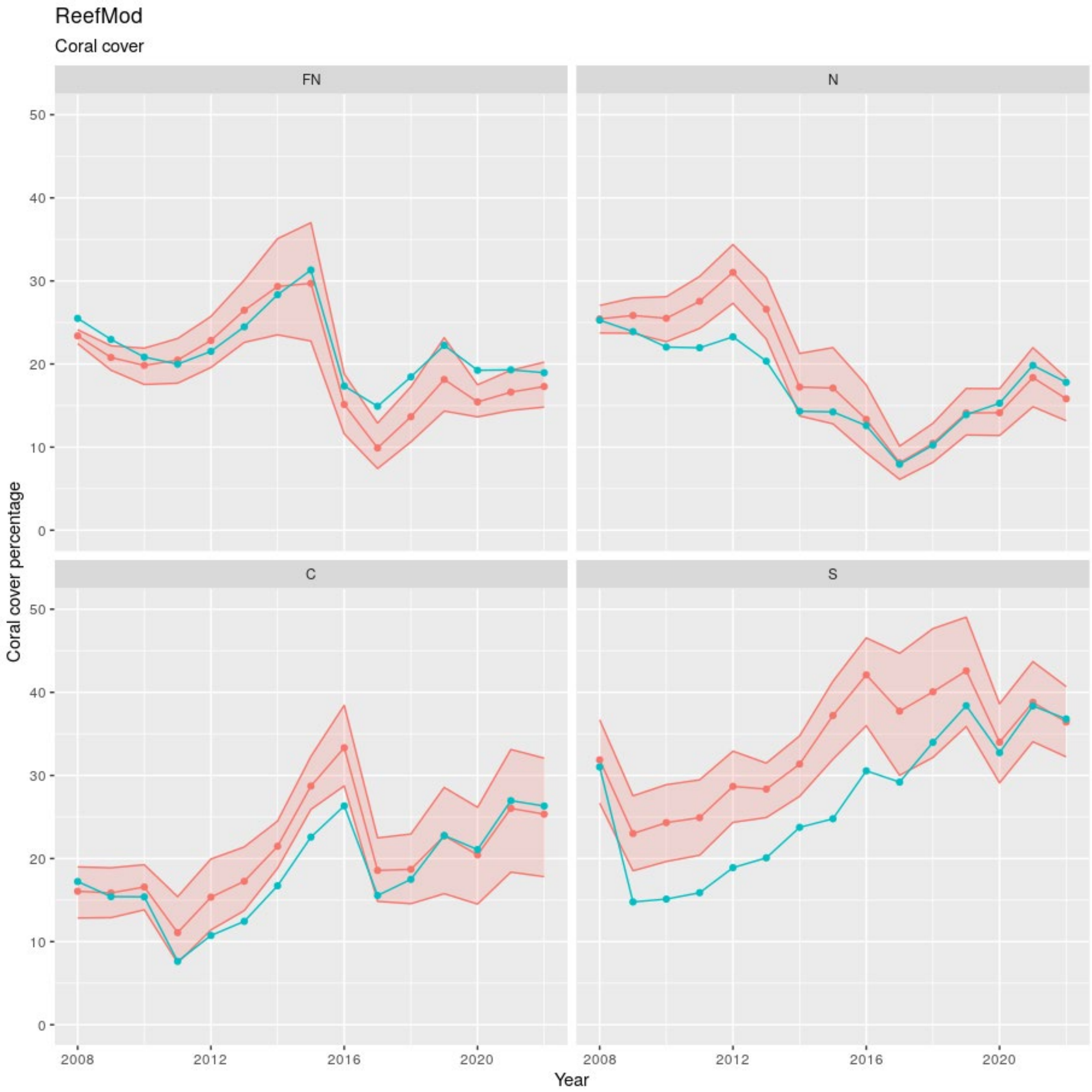

Figure A 70 Estimated coral cover grouped by region for **LTMP based monitoring** of 50 reefs based on ReefMod. Regions are Far North (FN), North (N), Central (C), and South (S).

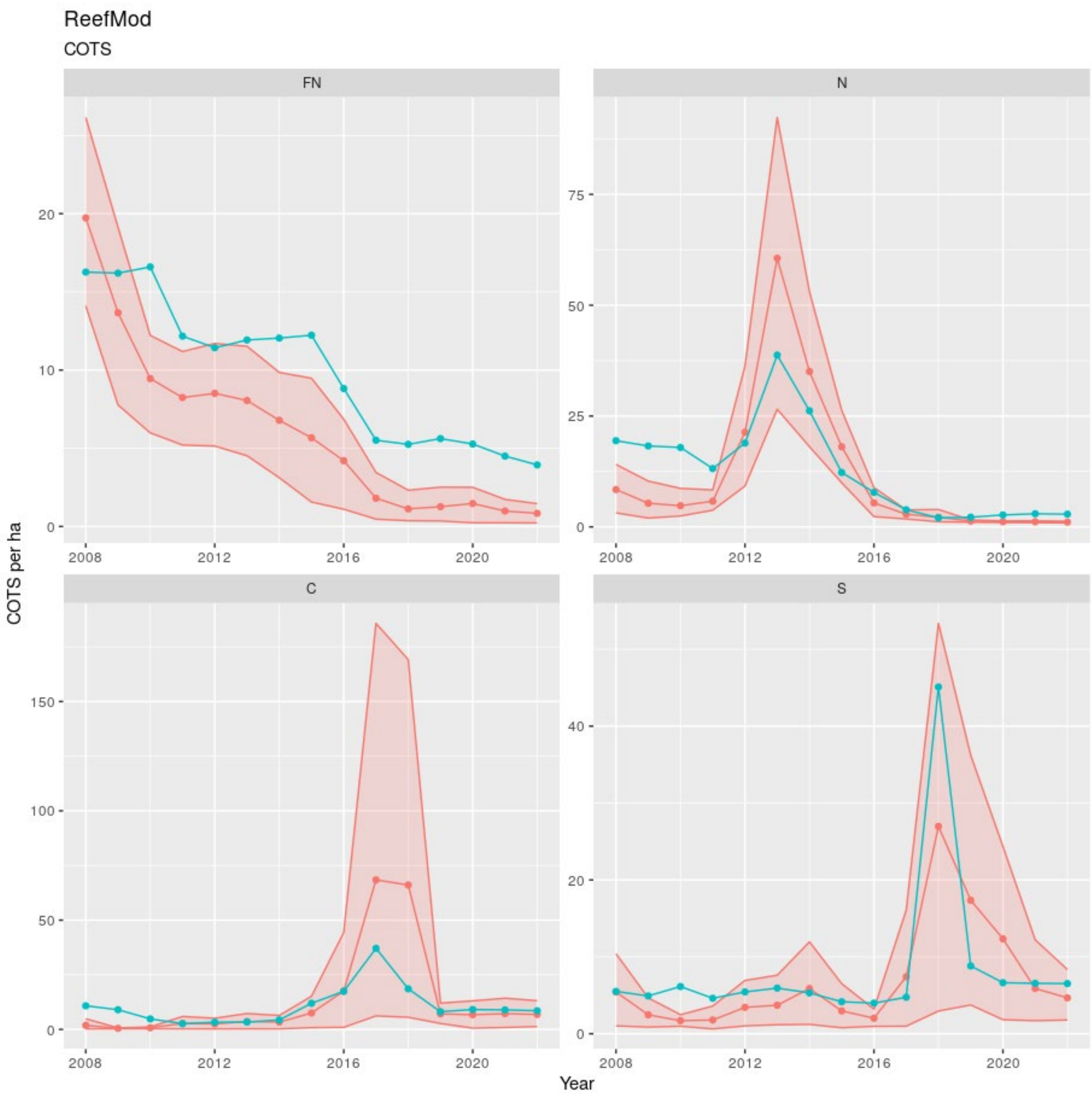

Figure A 71 Estimated COTS density grouped by region for **LTMP based monitoring** of 50 reefs based on ReefMod. Regions are Far North (FN), North (N), Central (C), and South (S).

Comparison with Random Sampling

Lastly, to show the above regional results to Random Sampling of 50 reefs, we show the Random Sampling results by region. **Figure A 72** and **Figure A 73** show the time series plots for estimated coral cover and COTS densities for CoCoNet while **Figure A 74** and **Figure A 75** show the coral cover and COTS density estimates for ReefMod-GBR. As expected, the estimators are unbiased at the region level as well in all cases, but we note that there is noticeable similarity in uncertainty between Random sampling and LTMP Based sampling.

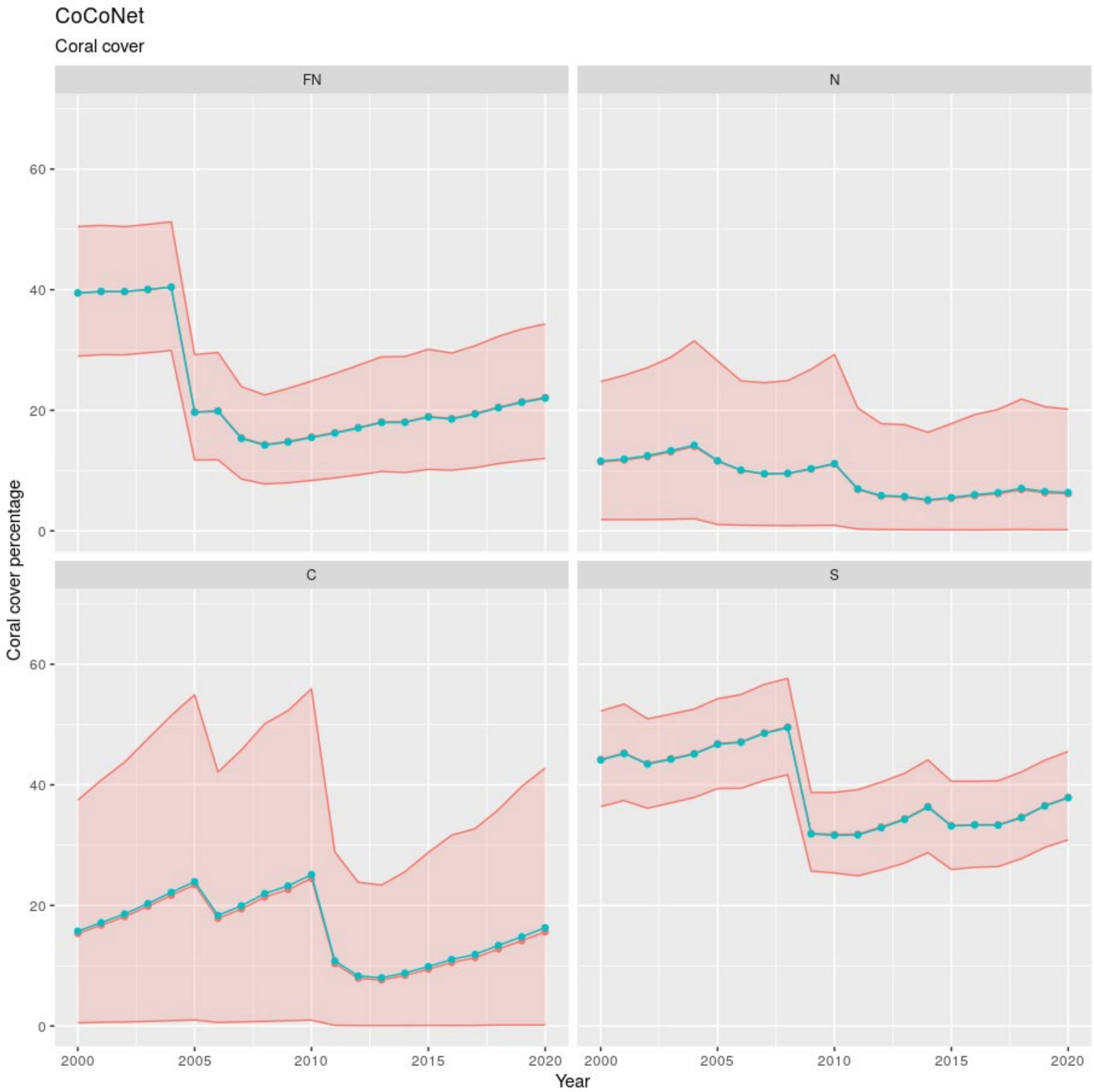

Figure A 72 Estimated coral cover grouped by region for **Random reef monitoring** of 50 reefs based on CoCoNet. Regions are Far North (FN), North (N), Central (C), and South (S).

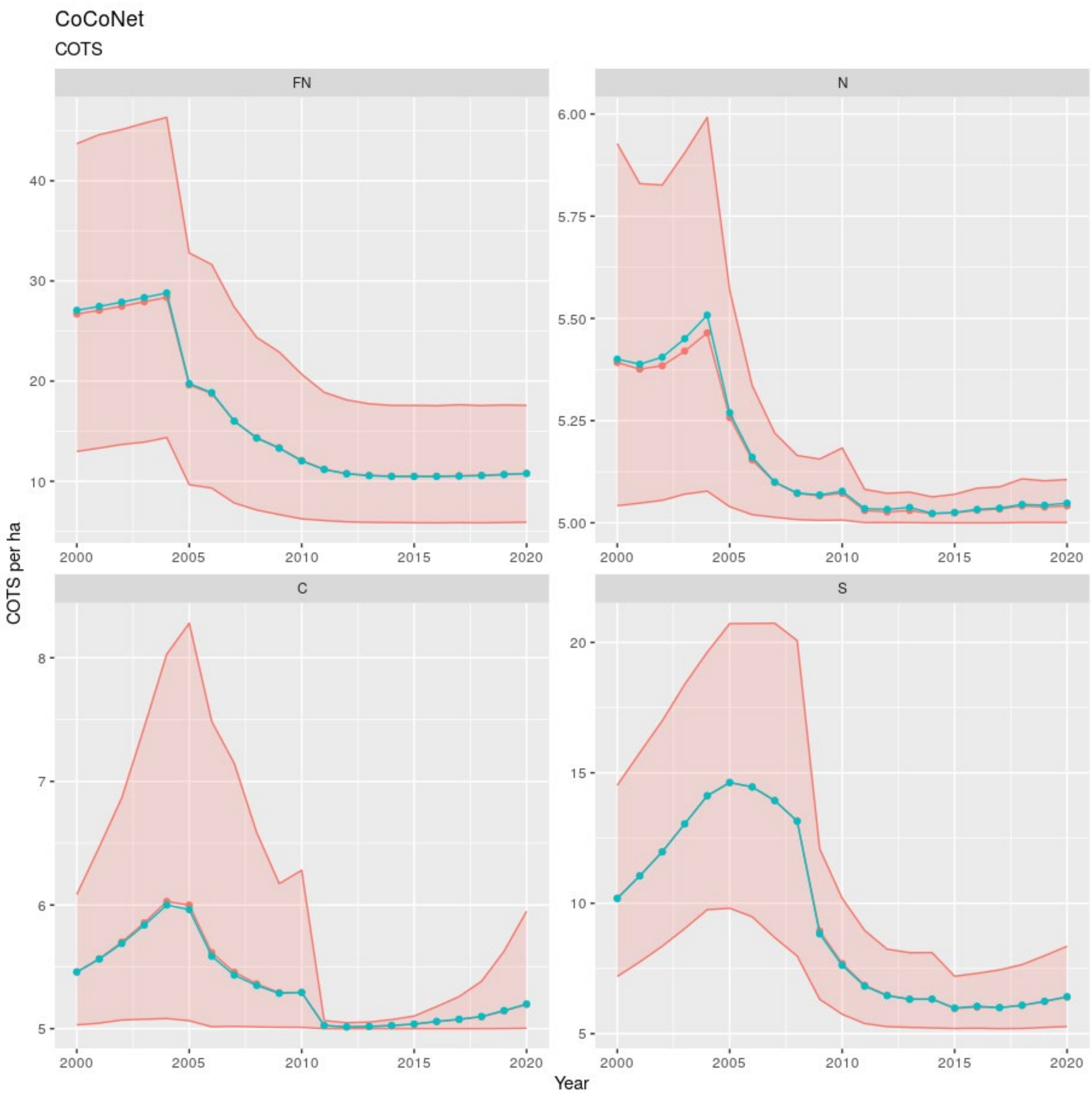

Figure A 73 Estimated COTS density grouped by region for **Random reef monitoring** of 50 reefs based on CoCoNet. Regions are Far North (FN), North (N), Central (C), and South (S).

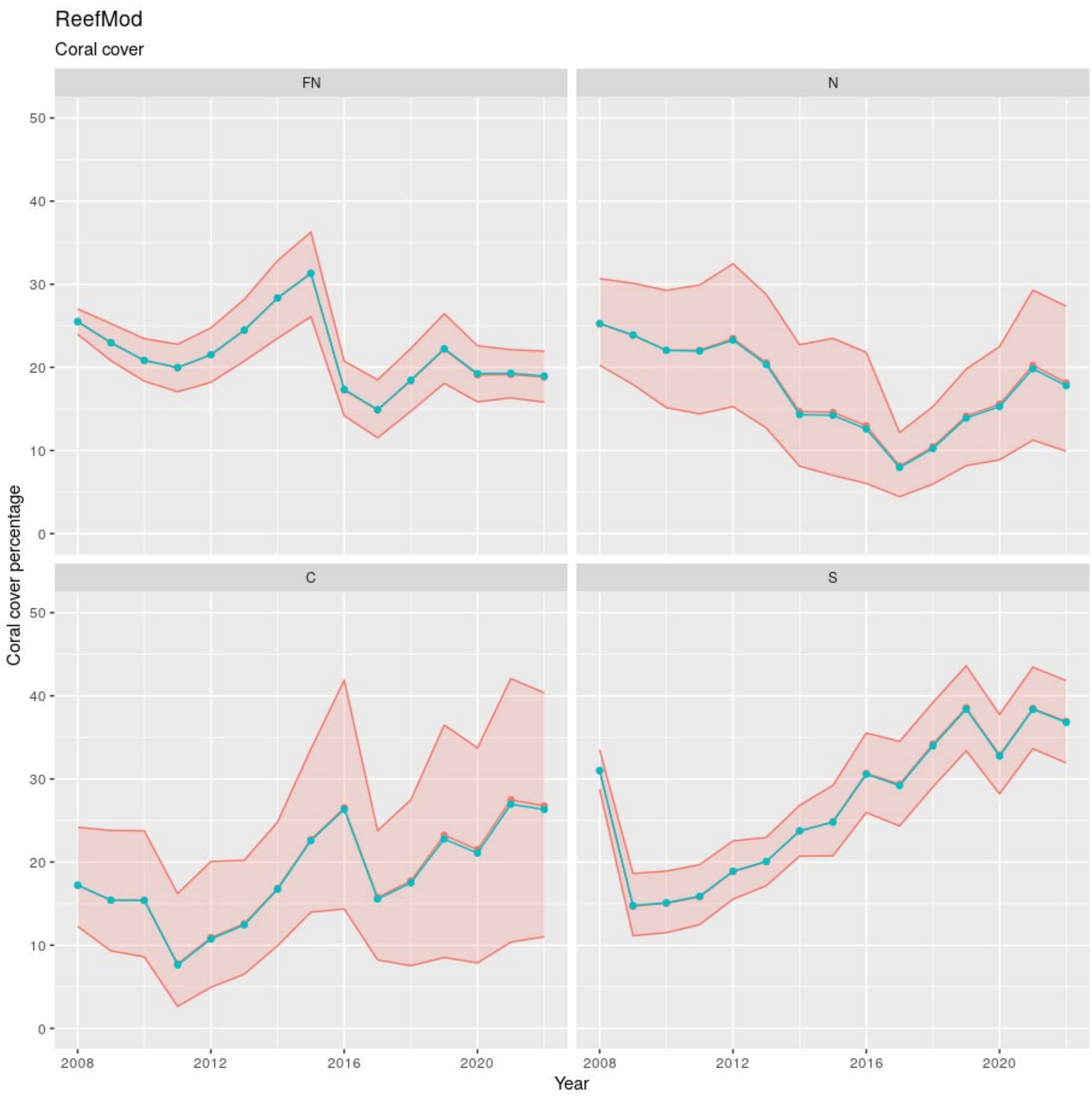

Figure A 74 Estimated coral cover grouped by region for **Random reef monitoring** of 50 reefs based on ReefMod. Regions are Far North (FN), North (N), Central (C), and South (S).

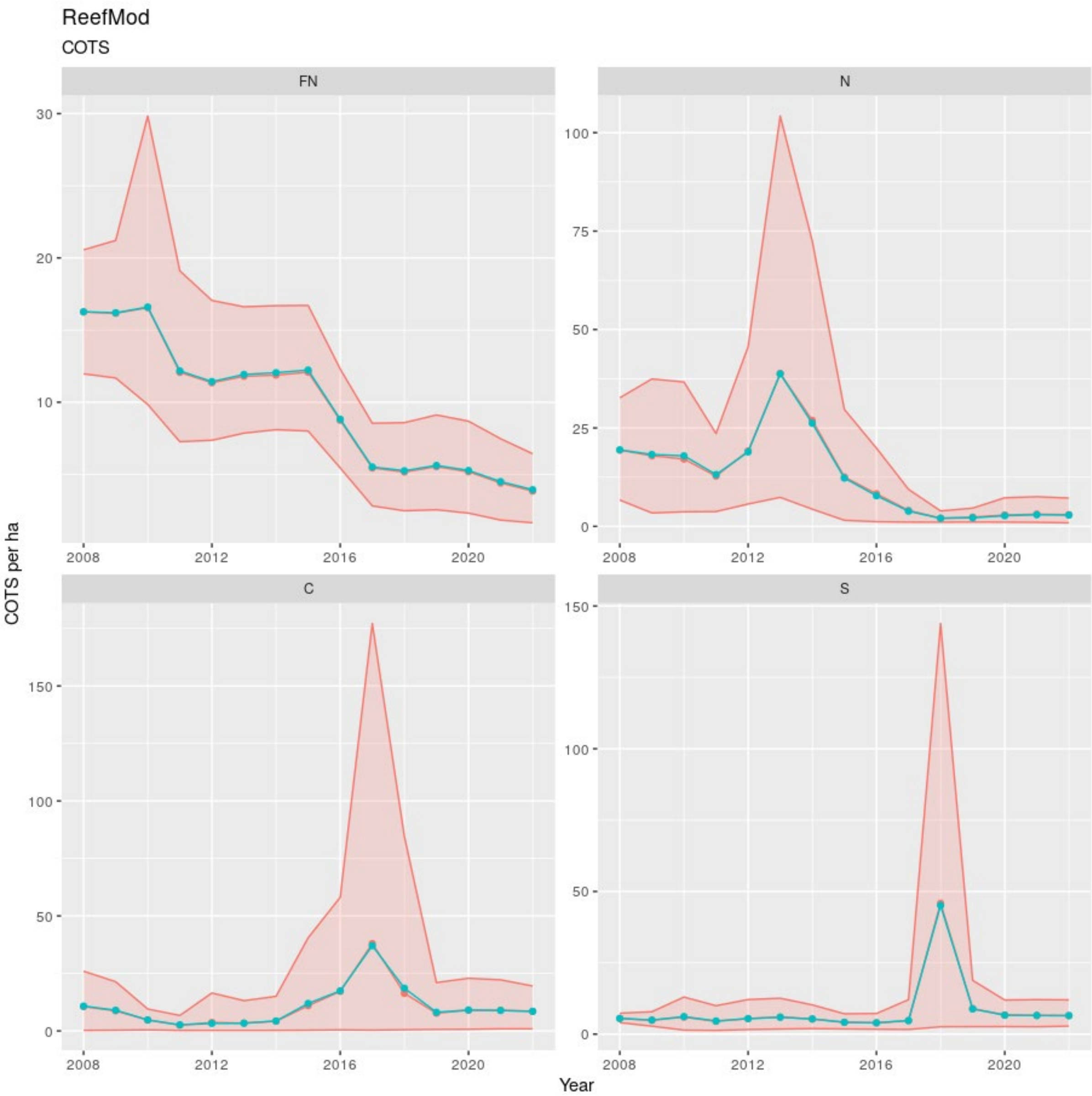

Figure A 75 Estimated COTS density grouped by region for **Random reef monitoring** of 50 reefs based on ReefMod. Regions are Far North (FN), North (N), Central (C), and South (S).

Selecting a sample

For illustrative purposes, we selected a cluster sample of 16 clusters (25 km radius) with 3 reefs in each cluster (**Figure A 76**). This was purely to demonstrate the use of the cluster algorithm. Implementing this design would require the consideration of a 'logistics layer' (to remove reefs that cannot be sampled for various reasons). While GBRMPA plan on developing such a layer, it does not yet exist. An alternative would be to hold a workshop with managers and those to undertake the monitoring (industry and science) to ensure that all of those reefs in the design are accessible and safe to monitor.

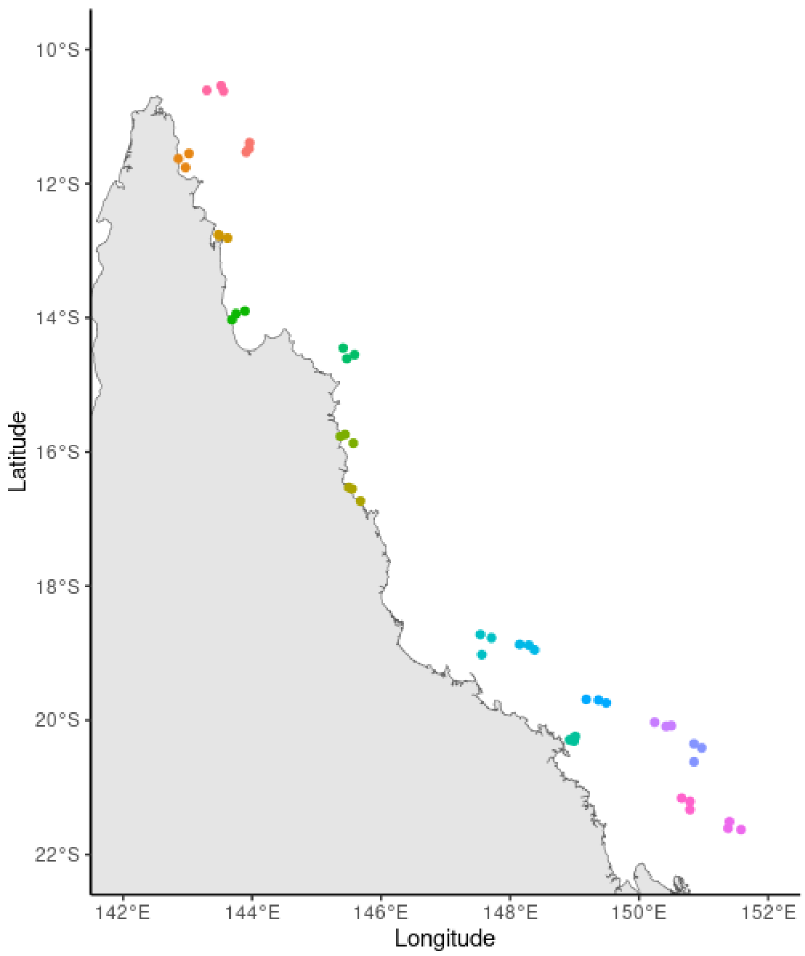

Figure A 76 Example of selection of 16 clusters of 3 reefs.

Table A 3 Example of reef IDs, names, locations, and clusters for monitoring 16 clusters of 3 reefs.

Reef ID	Reef Name	Longitude	Latitude	Cluster
11-205	U/N Reef	143.91	-11.53	1
11-109b	U/N Reef	143.95	-11.48	1
11-089b	U/N Reef	143.96	-11.39	1
11-156	Wizard Reef	143.02	-11.55	2
11-139	U/N Reef	142.97	-11.76	2
11-135	U/N Reef	142.86	-11.63	2
12-119	Wye Reef	143.62	-12.81	3
12-089	Exit Reef	143.49	-12.78	3
12-085	Hazelgrove Reefs	143.48	-12.76	3
16-080	Korea Reef	145.55	-16.55	4
16-047	Double Island Reef	145.68	-16.73	4
16-039a	Alexandra Reefs (No 1)	145.5	-16.53	4
15-093	Pickersgill Reef	145.57	-15.87	5
15-064	Hope Islands Reef (West)	145.44	-15.74	5
15-059b	U/N Reef	145.37	-15.77	5
14-001	U/N Reef	143.69	-14.03	6
13-111	Burkitt Reef	143.75	-13.94	6
13-104	Kestrel Reef	143.89	-13.9	6
14-137	Carter Reef	145.59	-14.55	7
14-112	Stewart Shoal	145.47	-14.61	7
14-085	Hilder Reef	145.41	-14.45	7
20-041w	Whitsunday Island Reef (No 21)	148.99	-20.31	8
20-041m	Whitsunday Island Reef (No 12)	148.92	-20.29	8
20-041d	Whitsunday Island Reef (No 4)	149.01	-20.24	8
19-312	U/N Reef	147.56	-19.02	9
18-091	Lynchs Reef	147.71	-18.77	9
18-088	Centipede Reef	147.54	-18.72	9
18-134	U/N Reef	148.29	-18.88	10
18-119	Lion Reef	148.38	-18.95	10
18-112	Viper Reef	148.15	-18.87	10
19-134	Circular Quay Reef	149.49	-19.74	11
19-128	Line Reef	149.18	-19.69	11
19-127	Block Reef	149.37	-19.7	11
20-524	U/N Reef	150.97	-20.41	12
20-327	U/N Reef	150.85	-20.62	12
20-190	U/N Reef	150.85	-20.35	12
20-149	U/N Reef	150.5	-20.08	13
20-119	U/N Reef	150.42	-20.09	13

Reef ID	Reef Name	Longitude	Latitude	Cluster
20-115	Little Bugatti (Wheatley) Reef	150.24	-20.03	13
21-449	U/N Reef	151.58	-21.63	14
21-434	Heralds Prong No 3	151.38	-21.61	14
21-432	Heralds Reef Prong	151.4	-21.51	14
21-086	Paul Reef	150.79	-21.33	15
21-079	U/N Reef	150.79	-21.21	15
21-072	U/N Reef	150.66	-21.16	15
99-498	U/N Reef	143.3	-10.61	16
99-464	U/N Reef	143.52	-10.54	16
99-379	U/N Reef	143.56	-10.62	16

APPENDIX E - SUMMARY OF OBJECTIVES VS MONITORING SCENARIOS

Decisions around monitoring design involve choosing statistical designs and monitoring tools that can best collect data to meet the monitoring and surveillance information needs in a cost-effective manner. There are many combinations of tools and survey designs to consider, each with its own strengths and weaknesses. To determine the optimal approach, we evaluated how the current COTS monitoring program addresses the desired information needs and assessed how incremental changes in tools and statistical design (and combinations of those) could enhance the program's ability to meet these needs. By systematically analysing these variations, we aim to refine the monitoring strategy to ensure it is both efficient and effective in achieving its goals.

Specifically, we considered the following scenarios:

1. *Routine (cull dives and manta tow)* - This is the bare minimum for the Control Program and is less than what is currently delivered through program operations. It involves manta tows around the entire perimeter of a reef before and at regular intervals during culling, as well as six months post-culling. Cull dives are undertaken at 10-hectare sites when manta tows have detected a COTS or a COTS feeding scar. Cull dives continue until an ecological threshold is reached, focusing on cull sites within reefs that have higher COTS numbers and coral cover as first priority.

2. *Control Program (cull dives, manta tow and some RHIS)* – This is the current standard approach and includes manta tows before culling, at regular intervals during culling, and six months post-culling. Cull dives are undertaken at any sites where manta tow detects a COTS or a COTS scar. RHIS surveys are conducted at the start of culling on sites within target reefs that have a high initial COTS CPUE (>0.08), repeated approximately every three months until culling is complete. A final RHIS survey is conducted once a cull site is "closed".

3. *Control Program + LTMP* - Building on the Control Program data, this adds the benefits of the LTMP – both the reef wide manta tow and the fixed transects - to the current COTS Control Program. The data collected through LTMP complements the routine data gathered by the COTS Control Program, enhancing the overall monitoring efforts.

4. *Control Program + LTMP + RJFMP* - Building on the previous strategy, this approach incorporates additional manta tow surveillance from the RJFMP. This added surveillance runs alongside the current COTS Control Program data, extending and enhancing the data available for monitoring and decision-making. **This is the extent of the data currently available to the COTS Control Program.**

5. *Routine + LTMP + extra baseline manta tow* - This approach continues routine reef and cull site monitoring and surveillance via manta tow and cull dives, and collects extra COTS and coral data by deploying manta tow at extra baseline reefs using a spatially balanced sample design. It could also reallocate some RJFMP effort to cover these extra baseline sites.

6. *Routine + eDNA surveillance* - This monitoring approach integrates eDNA surveillance at specific sites. For some objectives this may be at COTS Control Program target reefs and

for others it may be at proposed baseline monitoring reefs using a statistical design. While we would presume LTMP would continue, it has not been included in this scenario to demonstrate differentiation of adding eDNA to Routine monitoring alone.

7. *Routine + SALAD* surveys - Incorporate SALAD survey monitoring at some reefs. For some objectives this may be at COTS Control Program target reefs and for others it may be at proposed baseline monitoring reefs using a statistical design. While we would presume LTMP would continue, it has not been included in this scenario to demonstrate differentiation of adding SALAD surveys to Routine monitoring alone.

8. *Routine + ReefScan + extra baseline ReefScan* - Replace routine reef and cull site monitoring via manta tow with towed underwater video (following adequate or continued side by side calibration period). Collect COTS and coral data at extra baseline reefs selected using a spatially balanced sample design (method/s). While we would presume LTMP would continue, it has not been included in this scenario to demonstrate differentiation to Routine monitoring alone.

9. *Routine + baseline manta tow + environmental covariates* - Continue to use the routine reef and cull site monitoring via manta tow and cull dive surveys. Collect COTS and coral data at extra baseline reefs selected using a spatially balanced sample design (method/s). Collect environmental covariate data at least at baseline reefs (particularly water quality (WQ) parameters).

The tables below consider the ability of each monitoring scenario to collect the data to answer each monitoring objective. The cells are colour coded to indicate whether the scenario will fully answer the question (dark green), comes close to meeting the question but improvement is possible (light green), partially meets the question (amber) or doesn't meet the question (red).

Questions	GBRMPA Priority 1-4	Routine (Cull program dives + manta)	Control Program (Cull program dives + manta + some RHIS)	Control Program + LTMP	Control Program + LTMP + RJFMP
Where should the cull effort be deployed to get maximum benefit?	1	Manta tow monitoring provides data on both COTS densities and coral cover. Previous cull data CPUE provides more accurate estimates of relative COTS densities at sites previously culled than sites with manta tow alone. This data feeds into a much broader prioritisation process so is not used in isolation but the more surveillance data the more informed the decisions around the deployment of effort.	Coral estimates based on RHIS data are not as accurate as manta tow at the reef level scale which is required to inform decisions around effort deployment, although they are still considered in the broader decision process.	LTMP data provides additional manta tow surveillance at a given set of reefs (including reliable trends in coral cover through time) to feed into the prioritisation process.	Extra manta tow surveillance is currently used alongside Routine monitoring in the reef prioritisation process. RJFMP prioritises spatial coverage (current situation report) over repeating reef monitoring through time.
Where are the highest densities of the largest COTS?	2	Manta tow surveillance is used to identify priority reefs with high COTS densities. Manta tow is not a good method for distinguishing between differences in COTS densities at the higher end but is demonstrated to be reliable in determining when COTS are above a threshold requiring culling. Cull site dive data is the best current method for measuring high density COTS and also records COTS sizes, however these are only known post culling so not useful in a targeting sense.	RHIS data doesn't provide any additional information on high density COTS areas.	LTMP data provides annual COTS density estimates at a set of reefs using manta tow. Similar to Routine monitoring, LTMP manta tow is not the best method for distinguishing between high and higher COTS densities and does not measure COTS sizes.	Similar to other manta tow monitoring, RJFMP manta tow is not a good method for measuring high COTS densities or sizes. However, the addition of this surveillance to Routine operations provides some additional density information at broad spatial scales (across the GBR).
Where is the most coral to be 'saved' (individual reefs and/or regions)?	1	Manta tow provides some indication of hard vs soft coral cover at target/priority sites. However, differences in observers means that there is a large amount of uncertainty around coral estimates so relative cover estimates.	RHIS data does not provide a good indication of the amount of coral at the reef level.	LTMP observers are very highly trained and so the LTMP manta tow coral estimates are likely to be more reliable (particularly the trends) than the COTS Control coral cover estimates. The two datasets should be compared with care. While higher quality coral estimates, these are restricted to a limited set of reefs that don't cover off on the full set of environmental gradients across the GBR.	RJFMP observers are highly trained and so the RJFMP manta tow coral estimates are likely to be more reliable than the COTS Control coral cover estimates. This data provides additional spatial coverage for reef level coral cover estimates.

Questions	Routine + LTMP + extra baseline manta Note: does not include RHIS or RJFMP	eDNA + Routine	SALAD + Routine	ReefScan + Routine + extra baseline manta	Routine + baseline + environmental covariates
Where should the cull effort be deployed to get	Not directly needed in addition to Routine monitoring to answer this question, however the more	This objective is more about deciding between reefs at the upper end of COTS densities so	This objective is more about deciding between reefs at the upper end of COTS densities so	ReefScan is likely to improve the reliability of coral estimation by reducing observer bias and	Adding environmental covariates to baseline data collection may lead to improved modelling

Questions	Routine + LTMP + extra baseline manta Note: does not include RHIS or RJFMP	eDNA + Routine	SALAD + Routine	ReefScan + Routine + extra baseline manta	Routine + baseline + environmental covariates
maximum benefit?	monitoring data to feed into the decision making process the better. Baseline data would also provide a benchmark to compare against to determine how the reefs being culled compare to other reefs on the GBR.	eDNA is not the most appropriate method here.	SALAD is not the most appropriate method here.	improve accuracy of coral estimates at the site scale via GPS. Coral estimates will also be continuous rather than categorical allowing finer differentiation between measurements.	around which reefs respond best to culling and are worth putting more effort into e.g. Effort sinks.
Where are the highest densities of the largest COTS?	Introduction of baseline monitoring would increase the COTS density data to a broader set of reefs, likely including some outside the target reefs. Size data would only be available if SALAD was used for baseline monitoring.	Introduction of eDNA will not change our ability to answer this objective compared to Routine monitoring.	It is unfeasible to use SALAD to monitor COTS at the higher densities. However, SALAD brings the potential to have more accurate estimates of COTS sizes prior to culling. It is not feasible to complete SALAD at the same number of sites that are currently manta towed as part of Routine monitoring though.	Introducing ReefScan is likely to increase the number of reefs being monitored in a given amount of time and is also likely to be more accurate at estimating higher COTS densities. Improvements to the technology would be required to allow the estimation of COTS size.	No change from routine + baseline
Where is the most coral to be 'saved' (individual reefs and/or regions)?	Introduction of baseline monitoring would increase the coral data to a broader set of reefs, likely including some outside the target reefs.	Introduction of eDNA will not change from Routine monitoring.	SALAD can be used for estimation of coral, however the transects are small and are not the same transects as the COTS transects so care needs to be taken in pairing the two.	Introducing ReefScan is likely to increase the number of reefs being monitored in a given amount of time and will also allow the concurrent estimation of COTS and coral on a given transect. The method can be directly compared between reefs and so is likely to provide the best indication of the reefs with the greatest amount of coral once the technology is fully developed.	No change from routine + baseline

Questions		Routine (Cull program dives + manta)	Control Program (Cull program dives + manta + some RHIS)	Control Program + LTMP	Control Program + LTMP + RJFMP
Where are we most likely to find COTS (which reefs, or which part of a given reef) and why (prediction)?	1 reef level, 2 site level	Various COTS risk layers are calculated using Routinely collected manta and cull data. Other data such as environmental covariates are required for predictive models. In isolation the Routine monitoring data is not sufficient for answering this question, particularly as only those reefs that are pre-determined to be likely to have COTS on them are visited by the Control Program.	RHIS doesn't contribute to answering this question.	LTMP data provides a set of reefs with historical long-term monitoring data for COTS, adding to the temporal data feeding into predictive models. Some reefs are included in the monitoring program that do not have a high risk of COTS providing robust data on which to build predictive models. However, this is a relatively small percentage of reefs.	RJFMP surveillance adds to the spatial coverage of data across the GBR and may be directed to areas where the COTS risk is uncertain. This also provides good additional data to feed into COTS risk models.
What is the dominant coral type and cover at reefs where COTS are present?	2	Manta tow and cull divers do not collect coral type data. Manta tow divers collect coarse coral cover. This is available for all reefs that have been culled but is not as accurate as LTMP due to less experienced observers.	RHIS is undertaken at some reefs but the spatial scale of each RHIS site is very small so cannot be used to reliably measure dominant coral type and cover at the reef level.	The LTMP fish and benthic surveys record coral type but only on one section of the reef though.	RJFMP do not collect coral type data but they collect coral cover using manta tow.
When should we stop culling individual reefs?	1	Revisiting cull sites on consecutive trips provides good data to improve the answer to this question through time.	RHIS doesn't contribute to answering this question.	LTMP doesn't contribute to answering this question.	RJFMP doesn't contribute to answering this question.

Questions	Routine + LTMP + extra baseline manta Note: does not include RHIS or RJFMP	eDNA + Routine	SALAD + Routine	ReefScan + Routine + extra baseline manta	Routine + baseline + environmental covariates
Where are we most likely to find COTS (which reefs, or which part of a given reef) and why (prediction)?	Extra baseline monitoring would add to the spatial coverage of data across the GBR. This would also provide good additional data to feed into COTS risk models.	eDNA is likely to detect COTS at most reefs at some level but not currently established for differentiating signals between sites so not the best method for this objective.	Of the visual methods, SALAD currently gives the best location information about where COTS are situated within a reef. The main restriction here is the time and expertise required to conduct these surveys.	The GPS co-ordinates of COTS on ReefScan would allow future analyses on which parts of reefs are more likely to have COTS on them.	Adding environmental covariates to baseline data collection may lead to improved modelling around which reefs are more likely to have COTS on them. This data is unlikely to be able to be collected at a scale that will answer any within reef questions about COTS preferences.
What is the dominant coral type and cover at reefs where COTS are present?	Coral type data would not be collected with extra baseline manta.	Introduction of eDNA will not change from Routine monitoring.	SALAD records the coral type adjacent to COTS so is the data best suited for this purpose.	Coral cover data would improve with ReefScan but it currently does not identify coral type.	Coral type data would not be collected with extra baseline manta.
When should we stop culling individual reefs?	Extra baseline manta tow monitoring won't add to this question.	Currently eDNA cannot be used to answer this question but in the future it may be possible to determine an eDNA threshold below which culling should stop.	It's not practical to use SALAD to answer this question.	Replacing manta tow with ReefScan may improve the speed and accuracy of decisions around ecological thresholds in the future.	Adding environmental covariates to data collection may lead to improved modelling around ecological thresholds.

Questions		Routine (Cull program dives + manta)	Control Program (Cull program dives + manta + some RHIS)	Control Program + LTMP	Control Program + LTMP + RJFMP
How much effort should be put towards monitoring vs suppression of known COTS outbreaks?	NA	Manta tow monitoring collected as part of Routine operations provides a good dataset to revisit this question over time. We don't know what is happening outside out of the target reefs using this data though so the question relates to how much risk/uncertainty we are prepared to accept.	RHIS doesn't contribute to answering this question.	LTMP adds baseline data for COTS and coral at both target/non-target reefs.	RJFMP adds baseline data for COTS and coral at both target/non-target reefs.
Where are the highest priority areas for COTS management?	1	Manta tow monitoring provides data on both COTS densities and coral cover. This data feeds into a much broader prioritisation process so is not used in isolation but the more surveillance data the more informed the decisions.	Coral estimates based on RHIS data are not as accurate as manta at the reef level scale which is required to inform decisions around effort deployment, although they are still considered in the broader decisions process.	LTMP data provides additional manta tow surveillance at a given set of reefs (including reliable trends in coral cover through time) to feed into the prioritisation process.	Extra manta tow surveillance currently used alongside Routine in the reef prioritisation process. RJFMP prioritises spatial coverage (current situation report) over repeating reef monitoring through time.
How do COTS persist outside of outbreaks?	3	Manta tow provides data on how COTS persist outside outbreaks. However, the Routine monitoring only includes those reefs on the Target/priority reef list so if a reef has previously been an outbreak reef and is no longer on the target list, it is unlikely to undergo any further monitoring as part of this program. Manta tow is also not appropriate for monitoring low density COTS so not ideal for monitoring outside outbreak times if the intention is to track density's rather than need to cull.	RHIS doesn't contribute to answering this question.	LTMP provides annual manta tow data for a consistent set of reefs so does provide some indication of how COTS persist outside outbreaks at a fraction of the reefs in the GBR. However, manta tow is not appropriate for monitoring low density COTS so not ideal for monitoring outside outbreak periods if the intention is to track changes in density.	Extra manta tow surveillance by RJFMP primarily provides additional spatial coverage rather than trend information so isn't ideal for answering this objective.

Questions	Routine + LTMP + extra baseline manta Note: does not include RHIS or RJFMP	eDNA + Routine	SALAD + Routine	ReefScan + Routine + extra baseline manta	Routine + baseline + environmental covariates
How much effort should be put towards monitoring vs suppression of known COTS outbreaks?	Extra baseline data outside priority reefs would provide a contrast to monitoring priority reefs and build up a picture around how often we might be missing outbreaking reefs.	Collecting eDNA data doesn't directly answer this question.	Collecting SALAD data doesn't directly answer this question.	Collecting ReefScan data doesn't directly answer this question.	Collecting environmental covariates doesn't add extra value to answering this question.
Where are the highest priority areas for COTS management?	Additional baseline manta would provide extra spatial coverage for prioritisation process but it would not significantly improve the ability to answer this objective given it would be a relatively small number of sites.	eDNA may provide early warning allowing management intervention to occur earlier.	SALAD may provide early warning allowing management intervention to occur earlier.	ReefScan is likely to improve the volumes of surveillance data collection across the GBR, providing significant improvements in the information available for the prioritisation process.	The addition of environmental covariates does not change ability to answer this question.
How do COTS persist outside of outbreaks?	Having baseline monitoring is an excellent way to capture trends in COTS both during and outside outbreaks. However, manta tow is not appropriate for monitoring low density COTS.	eDNA is a good way to detect changes in COTS at low densities outside outbreaks. However, it doesn't have the same resolution as a method like SALAD that can capture trends in COTS densities more accurately.	SALAD can measure trends in COTS densities outside outbreaks, however it is resource intensive so this could not be undertaken at a large number of sites.	ReefScan is likely to provide the resolution and volume of data to be able to track COTS densities outside outbreaks, provided it is used in conjunction with a method like eDNA to help track lower COTS densities.	The addition of environmental covariates does not change ability to answer this question.

Questions		Routine (Cull program dives + manta)	Control Program (Cull program dives + manta + some RHIS)	Control Program + LTMP	Control Program + LTMP + RJFMP
What is the status of coral cover and composition within regions and across the GBR?	2	Manta tow and cull divers do not collect coral composition data. Manta tow divers collect coarse coral cover. It is available for a different set of reefs (with particular attributes) each year (depending on target reefs) and so isn't suited for accurately tracking changes across regions or the GBR.	RHIS is undertaken at some reefs but the spatial scale of each RHIS site is very small so cannot be used to reliably measure trends in dominant coral composition and cover at the region or GBR level.	LTMP has highly trained divers that have been shown to accurately measure the status of coral cover across reefs. However, existing GBR monitoring (including LTMP) only represents ~40% only of the environmental regimes of the GBR (Mellin et al. 2020) and this should be considered in any inference.	RJFMP do not collect coral type data but they measure coral cover. However, the set of reefs changes every year so isn't suited for accurately tracking changes across regions or the GBR.
What are the COTS densities and demographics across the GBR?	1	Manta tow and cull data provide good broad-level coverage of COTS densities across the target reefs. However, this is a limited set of reefs chosen due to their attributes so unlikely to represent COTS densities across the wider GBR (especially reefs with different attributes). Demographic information is only available for COTS that are culled and generally only adult COTS are available for culling.	RHIS data doesn't provide any additional information on this.	LTMP data provides annual COTS density estimates at a set of reefs using manta tow. Similar to Routine monitoring, LTMP manta tow is not the best method for distinguishing between absolute COTS densities and does not measure COTS sizes.	Similar to other manta tow monitoring, manta tow is not a good method for measuring absolute COTS densities. However, the addition of this surveillance to Routine operations provides some additional density information at broad spatial scales (across the GBR).
What is the area of reefs that have been culled for the first time/multiple times over the reporting period?	1	Routine monitoring answers this question.	Not needed in addition to Routine monitoring.	Not needed in addition to Routine monitoring.	Not needed in addition to Routine monitoring.

Questions	**Routine + LTMP + extra baseline manta** **Note: does not include RHIS or RJFMP**	**eDNA + Routine**	**SALAD + Routine**	**ReefScan + Routine + extra baseline manta**	**Routine + baseline + environmental covariates**
What is the status of coral cover and composition within regions and across the GBR?	Having baseline monitoring is an excellent way to capture the status and trends in coral cover within regions and across the GBR. However, manta tow divers do not collect coral composition data. If the coral cover estimates are to be accurate then highly trained divers should be used (not those new to the COTS Control program).	eDNA does not help answer this question.	SALAD isn't a good method for monitoring coral at the region or GBR level as the coral transects are relatively small (50 m).	Introducing ReefScan is likely to increase the number of reefs being monitored in a given amount of time and the consistency in the estimates. At this stage it does not provide estimates of coral composition.	No change from routine + baseline
What are the COTS densities and demographics across the GBR?	Similar to other manta tow monitoring, RJFMP manta tow is not a good method for measuring absolute COTS densities. However, the addition of this surveillance to Routine operations provides some additional density information at broad spatial scales (across the GBR).	eDNA monitoring is better suited to measuring lower COTS densities and provides no demographic data. It does allow coarse density estimation with no in-water effort required so good for accumulating monitoring information across the reef (perhaps) opportunistically.	SALAD is effective for monitoring COTS densities at the low to mid range and also the COTS demographics. It is resource intensive so not good for monitoring large numbers of reefs.	Introducing ReefScan is likely to increase the number of reefs being monitored in a given amount of time and the consistency in the estimates. At this stage it does not provide estimates of COTS size.	The addition of environmental covariates does not change our ability to answer this question.
What is the area of reefs that have been culled for the first time/multiple times over the reporting period?	Not needed in addition to Routine monitoring.	Not needed in addition to Routine monitoring.	Not needed in addition to Routine monitoring.	Not needed in addition to Routine monitoring.	Not needed in addition to Routine monitoring.

Questions		Routine (Cull program dives + manta)	Control Program (Cull program dives + manta + some RHIS)	Control Program + LTMP	Control Program + LTMP + RJFMP
How do COTS densities change during spawning season?	2	Routine monitoring data collection over time will contribute towards answering this questions in terms of adult COTS at Target sites (not more broadly across the GBR).	RHIS doesn't contribute to answering this question.	LTMP doesn't contribute to answering this question.	RJFMP doesn't contribute to answering this question.
Where do outbreaks originate in the northern or far northern GBR?	3	Past Routine data collection has been limited in the Far North, however there is now some effort in the Region. Manta tow monitoring is not appropriate for monitoring low COTS densities and it is changes in the low densities that will give the best chance of detecting an initial outbreak signal. There are also croc risks in this region to be mindful of.	RHIS doesn't contribute to answering this question.	While LTMP provides COTS trend data at a set of reefs, manta tow is not capable of detecting changes in the lower range of COTS densities.	Some manta tow surveillance has been completed in the Far North as part of RJFMP. However, manta tow is not capable of detecting changes in the lower range of COTS densities.
Do outbreaks in the southern GBR originate independently of outbreaks in the far north, north and central GBR?	3	Routine monitoring occurs at sites in every Region of the reef and will over time help to answer this question. Manta tow monitoring is not appropriate for monitoring low COTS densities and it is changes in the low densities that will give the best chance of detecting an initial outbreak signal.	RHIS doesn't contribute to answering this question.	While LTMP provides COTS trend data at a set of reefs in each region, manta tow is not capable of detecting changes in the lower range of COTS densities.	Manta tow surveillance across the reef by RJFMP helps expand on the spatial coverage of monitoring across the reef but doesn't specifically address this question.

Questions	Routine + LTMP + extra baseline manta Note: does not include RHIS or RJFMP	eDNA + Routine	SALAD + Routine	ReefScan + Routine + extra baseline manta	Routine + baseline + environmental covariates
How do COTS densities change during spawning season.	If baseline information were collected at a given set of sites both during and outside spawning season it would contribute to answering this question but only in terms of adult COTS.	eDNA is the ideal method for answering this question as it can measure both juvenile and adult COTS.	If SALAD were deployed at consistent sites both inside and outside spawning season it would contribute to answering this question.	If ReefScan information were collected at a given set of sites both during and outside spawning season it would contribute to answering this question but at this stage it has limited ability to detect juvenile COTS.	Doesn't help to answer this objective.
Where do outbreaks originate in the northern or far northern GBR?	Adding baseline data at a consistent set of reefs in the Far North and North may help to answer this question if the data is also collected outside outbreak periods. Manta tow is unlikely to be the best method for this objective though.	eDNA monitoring is capable of detecting changes in low COTS densities and is ideally suited to this objective.	SALAD monitoring is capable of detecting changes in low COTS densities and is ideally suited to this objective, particularly paired with eDNA.	Introducing ReefScan would likely improve the coverage of monitoring in the North and Far North. Especially with health and safety concerns. However, it is unlikely to be capable of detecting the low densities that eDNA and SALAD can.	Doesn't help to answer this objective.
Do outbreaks in the southern GBR originate independently of outbreaks in the far north, north and central GBR?	Adding baseline data at a consistent set of reefs in each region may help to answer this question if the data is also collected outside outbreak periods. Manta tow is unlikely to be the best method for this objective though.	eDNA monitoring is capable of detecting changes in low COTS densities and is ideally suited to this objective.	SALAD monitoring is capable of detecting changes in low COTS densities and is ideally suited to this objective, particularly paired with eDNA.	Introducing ReefScan would likely improve the coverage of monitoring. However, it is unlikely to be capable of detecting the low densities that eDNA and SALAD can.	Doesn't help to answer this objective.

Questions		Routine (Cull program dives + manta)	Control Program (Cull program dives + manta + some RHIS)	Control Program + LTMP	Control Program + LTMP + RJFMP
How does reef condition across the GBR (as measured by RIMReP indicators e.g. coral cover, COTS density) change due to COTS management actions?	1	To attribute actions to COTS management, you need to monitor (over the medium term at least) COTS and coral at reefs both being managed and not being managed. This is not currently part of the Routine Monitoring program.	RHIS provides reef condition metrics at the site level but analysis of RHIS data demonstrated there is not enough power to detect changes in these metrics that could be attributed to management effort.	AIMS LTMP data is long-term monitoring data and could be used to attribute changes to COTS management actions (in the absence of other disturbances) at this limited set of reefs.	This data primarily adds spatial surveillance and so is not ideally suited to monitoring change due to management action.
What is the trend in coral cover at COTS management sites?	1	Manta tow divers collect coarse coral cover. It is available for a different set of reefs/sites each year (depending on target reefs) and so can be used for tracking coral changes at COTS management sites in the short term but not in the medium to long-term. The accuracy of manta tow coral estimates between divers also needs to be considered.	Cull site RHIS is conducted before and after culling at some sites. Analysis of the data suggests it is not suited to calculating trends in coral cover though.	AIMS LTMP data is long-term monitoring data and could be used to calculate the trend in coral cover at the reefs that are managed by the COTS control program. But this is a limited set of reefs.	Manta tow surveillance across the reef by RJFMP helps expand on the spatial coverage of monitoring across the reef but doesn't typically help with trend estimation.
What happens on reefs we aren't actioning?	2	Manta tow surveillance is collected at sites to make a decision whether to control or not. Some that are not actioned continue to undergo surveillance, however if they drop off the priority list they will stop undergoing monitoring.	RHIS doesn't help answer this question.	AIMS LTMP may provide some indication of what's happening at reefs that aren't being actioned but it is likely that this would only ever be a very small number of reefs.	The RJFMP would provide snapshots in time of what is happening at reefs that aren't being actioned.

Questions	Routine + LTMP + extra baseline manta Note: does not include RHIS or RJFMP	eDNA + Routine	SALAD + Routine	ReefScan + Routine + extra baseline manta	Routine + baseline + environmental covariates
How does reef condition across the GBR (as measured by RIMREP indicators e.g., coral cover, COTS density) change due to COTS management actions?	Baseline data would provide an excellent means of contrasting COTS Control managed sites to those not being managed (if sites not culled were revisited) as it would span a range of environmental gradients, regions, COTS and coral densities.	eDNA monitoring is not suited to answering this question.	SALAD monitoring records some aspects of reef condition, however the coral transects are relatively small and so not ideally suited to this activity.	Introducing ReefScan is likely to increase the number of reefs being monitored in a given amount of time and the consistency in the estimates. However, it would need to be deployed outside of the Routine monitoring sites to accurately answer this question.	Environmental covariates not needed on top of baseline.
What is the trend in coral cover at COTS management sites?	Baseline monitoring data would not help with calculating trends in coral cover at the cull site level.	eDNA does not help answer this question.	SALAD is not suited to this objective as the spatial scale of the tool does not match a COTS management site.	Replacing manta tow with ReefScan may improve the speed and accuracy of the coral data at the management site scale. However, to answer this question fully there would be a need to re-manta tow sites (period to be determined) once they have been 'managed' even if they are no longer on the Target list.	Environmental covariates not needed on top of baseline.
What happens on reefs we aren't actioning?	Baseline data would provide an excellent means of contrasting COTS Control managed sites to those not being managed as it would span a range of environmental gradients, regions, COTS and coral densities.	eDNA may provide some early warning data for COTS sites that are not being actioned.	SALAD data would be too resource intensive to answer this question.	The ability to monitor more sites than we can control would provide the ability to monitor and contrast what is happening at sites that are being actioned vs not.	Environmental covariates not needed on top of baseline.

Questions		Routine (Cull program dives + manta)	Control Program (Cull program dives + manta + some RHIS)	Control Program + LTMP	Control Program + LTMP + RJFMP
Are we suppressing COTS numbers across the GBR through the COTS Control Program (trend through time)?	1	Manta tow and cull provide data on COTS densities at target/priority sites. To answer questions about COTS numbers at the GBR scale then extra reefs (selected with known probabilities) would need to be monitored.	RHIS doesn't contribute to answering this question	LTMP doesn't contribute to answering this question.	Extra manta tow surveillance by RJFMP primarily provides additional spatial coverage rather than trend information so isn't ideal for answering this objective.
Is the COTS Control Program enhancing reef resilience?	1	In addition to data on COTS and coral densities (see other answers), this would include the data to answer questions on community diversity and species richness. The Routine monitoring program is not capable of answering these questions.	RHIS provides some information on community diversity at a very fine scale at some sites.	LTMP provides some comparison long-term monitoring sites which is important for evaluating reef resilience. It is limited in parts of the reef though.	RJFMP doesn't directly contribute to answering this question.
How much control effort is required to reduce COTS outbreaks to sustainable densities?	1	Revisiting cull sites on consecutive trips provides good data to improve the answer to this question through time (assuming priority sites would respond similar to culling as non-priority sites).	RHIS doesn't contribute to answering this question.	LTMP doesn't contribute to answering this question.	RJFMP doesn't contribute to answering this question.

Questions	Routine + LTMP + extra baseline manta Note: does not include RHIS or RJFMP	eDNA + Routine	SALAD + Routine	ReefScan + Routine + extra baseline manta	Routine + baseline + environmental covariates
Are we suppressing COTS numbers across the GBR through the COTS Control Program (trend through time)?	Having baseline monitoring is the best way to estimate COTS densities at the GBR and region level and allow comparison between managed/non-managed reefs. However, manta tow is not appropriate for monitoring low density COTS so the choice of tool for monitoring would need to be carefully considered.	eDNA is not the ideal tool for calculating the trend in COTS numbers at the GBR level.	SALAD can measure trends in COTS densities, however it is resource intensive so this could not be undertaken at a large number of sites.	ReefScan is likely to provide the resolution and volume of data to be able to track COTS numbers at a large number of sites, provided it is used in conjunction with a method like eDNA to help track lower COTS densities.	The addition of environmental covariates does not change ability to answer this question.
Is the COTS Control Program enhancing reef resilience?	Extra baseline data would provide a set of reefs to compare the managed reefs to. However, using manta tow as a tool to collect this data would not provide the desired community diversity or species richness information.	eDNA does not directly answer this question.	SALAD provides quantitative estimates of coral composition data alongside the COTS density data (albeit at shorter transects).	At this stage ReefScan is not able to answer questions regarding coral composition.	The addition of environmental covariates does not change our ability to answer this question.
How much control effort is required to reduce COTS outbreaks to sustainable densities?	Extra baseline manta tow monitoring won't add to this question.	Currently eDNA cannot be used to answer this question but in the future it may be possible to determine an eDNA threshold below which culling should stop. eDNA integrates beyond a single cull zone - this could be beneficial if making decisions around outbreaks at a reef level.	It's not practical to use SALAD to answer this question.	Replacing manta tow with ReefScan may improve the speed and accuracy of decisions around ecological thresholds in the future.	Adding environmental covariates to data collection may lead to improved modelling around ecological thresholds and what sustainable densities are.

Questions		Routine (Cull program dives + manta)	Control Program (Cull program dives + manta + some RHIS)	Control Program + LTMP	Control Program + LTMP + RJFMP
How is coral cover influenced by COTS management? e.g., do the control activities cause damage/disease?	4	Cull and manta tow are not able to measure damage/disease.	The deployment of RHIS is the only monitoring technique capable of measuring damage/disease however, it would not be possible to attribute damage/disease to COTS management using current monitoring methodologies.	LTMP doesn't contribute to answering this question.	RJFMP doesn't contribute to answering this question.
What is the coral loss due to COTS?	1	Manta tow divers collect coarse coral cover. It is available for a different set of reefs/sites each year (depending on target reefs) and so can be used for tracking coral changes at COTS management sites in the short term but not in the medium to long-term. The attribution of coral loss due to COTS vs another pressure is not possible using manta tow though.	Cull site RHIS is conducted before and after culling at some sites. Analysis of the data suggests it is not suited to calculating trends in coral cover though.	AIMS LTMP data is long-term monitoring data and could be used to calculate the trend in coral cover at the reefs that have COTS on them. But this is a limited set of reefs and the temporal frequency means that assumptions need to be made around when the loss started occurring.	RJFMP would only help answer this question if the monitoring effort was used to revisit sites (to estimate coral cover) that had COTS on them.
What are the key drivers of primary COTS outbreaks?	1	Cull and manta tow data collected as part of Routine monitoring alone cannot answer this question. They can be combined with environmental data across the reef to investigate via modelling however, investigating drivers of outbreaks would require monitoring changes in COTS densities at the lower end, which manta is not suitable for (and cull is only undertaken above ecological thresholds).	RHIS does not contribute to answering this question.	LTMP doesn’t contribute to answering this question.	RJFMP doesn't contribute to answering this question.

Questions	Routine + LTMP + extra baseline manta Note: does not include RHIS or RJFMP	eDNA + Routine	SALAD + Routine	ReefScan + Routine + extra baseline manta	Routine + baseline + environmental covariates
How is coral cover influenced by COTS management? e.g., do the control activities cause damage/disease?	Extra baseline manta tow monitoring won't contribute to answering this question.	eDNA does not contribute to answering this question.	SALAD do not contribute to answering this question.	It is possible that in the future AI methods may be able to detect damage/disease. If data were collected frequently enough at managed sites it may be possible to attribute cause.	Adding environment covariates won't contribute to answering this question.
What is the coral loss due to COTS?	Additional baseline monitoring manta tow data would not assist in answering this question as no attribution could be made to whether the loss was due to COTS or some other cause.	eDNA does not help answer this question.	Does SALAD attribute cause? Still only 50 m transects though but probably best chance of answering this question at this point.	At this stage ReefScan is a long way from being able to answer this question.	Adding environmental covariates would not help answer this question.
What are the key drivers of primary COTS outbreaks?	Extra baseline manta tow monitoring won't directly contribute to answering this question. However, it would provide a contrasting set of data (not reefs necessarily expected to outbreak) that would be beneficial to include in a model for outbreak drivers.	eDNA may provide some lower density COTS density trends through time that could be later linked to environmental data to investigate potential outbreak causes.	SALAD may provide some lower density COTS density trends through time that could be later linked to environmental data to investigate potential outbreak causes.	ReefScan would likely provide a larger volume of data at a range of COTS densities that could be incorporated in models to address the outbreak driver question.	Environmental covariates at baseline monitoring sites would be the most substantial step forward in answering this question. However the temporal frequency of sampling required to contribute significantly would lead to huge resources required.

Questions		Routine (Cull program dives + manta)	Control Program (Cull program dives + manta + some RHIS)	Control Program + LTMP	Control Program + LTMP + RJFMP
Where is the COTS initiation box?	1	To determine the extent of the initiation box, the program would need to be able to pick up outbreaks very early on. Through time manta tow and cull across the reef will contribute to determining this but more definitive answers would be obtained with increased ability to pick up when and where COTS densities change from low to high.	RHIS does not contribute to answering this question.	LTMP data provides some long-term historical manta tow data where some reefs have experienced outbreaks however, the spatial and temporal coverage and manta tow method are not ideally suited to answering this question.	The RJFMP is not deployed on time and spatial scales to allow determination of the initiation box extent.
What is the progression of COTS outbreaks along the coast?	2	To determine the progression of outbreaks, the program would need to be able to pick up outbreaks very early on. Through time, manta tow and cull data across the reef will contribute to answering this but more definitive answers would be obtained with increased ability to	RHIS does not contribute to answering this question.	LTMP data provides some long-term historical manta tow data where some reefs have experienced outbreaks however, the spatial and temporal coverage and manta tow	The RJFMP is not deployed on time and spatial scales to allow determination of the initiation box extent.

Questions		Routine (Cull program dives + manta)	Control Program (Cull program dives + manta + some RHIS)	Control Program + LTMP	Control Program + LTMP + RJFMP
		pick up when and where COTS densities change from low to high.		method are not ideally suited to answering this question.	
When/where are COTS likely to be aggregated.	1	Routine monitoring currently doesn't provide the capacity to indicate when/where COTS are aggregated.	RHIS does not contribute to answering this question.	LTMP doesn't record any aggregation metrics.	RJFMP doesn't record any aggregation metrics.
When and where are COTS outbreaks most likely to occur?	1	As the Routine monitoring data builds up through time the manta and cull data will both be valuable in analysing this question. However, currently the monitoring effort is completely dedicated to places we expect the outbreaks occur and so there is a risk that we miss some locations if we don't understand all of the outbreak processes.	RHIS doesn't contribute to answering this question.	LTMP provides monitoring for a consistent set of reefs through, so analysis of this data combined with Control Program data helps provide insight into this question. However, sampling is only annual and at a limited set of reefs that don't span the full range of environmental gradients in the GBR. In particular, monitoring is limited in the Far North where there is increasing evidence of outbreaks occurring.	Extra manta tow surveillance by RJFMP adds spatial coverage, improving the monitoring data available to answer this question.

Questions	Routine + LTMP + extra baseline manta Note: does not include RHIS or RJFMP	eDNA + Routine	SALAD + Routine	ReefScan + Routine + extra baseline manta	Routine + baseline + environmental covariates
Where is the COTS initiation box?	Extra baseline data would not help to answer this question although it may pick up outbreaks at reefs that perhaps were not expected.	eDNA is suited to monitoring COTS at low densities and so could be used to monitor reefs to provide early warning of an outbreak.	SALAD is suited to monitoring COTS at low densities and so could be used to monitor reefs to provide early warning of an outbreak. The monitoring effort required would prevent it being deployed across large numbers of reefs over a short period though.	ReefScan will be able to provide monitoring data across greater areas of the reef more quickly, however eDNA and SALAD are more suitable for determining any changes at the lower densities.	Adding environmental covariates would not help answer this question.
What is the progression of COTS outbreaks along the coast?	Extra baseline data would not help to answer this question.	eDNA is suited to monitoring COTS at low densities and so could be used to monitor reefs to provide early warning of an outbreak. With vessels in different regions at any given time, eDNA can provide contrast in the COTS densities along the GBR at a point in time.	SALAD is suited to monitoring COTS at low densities and so could be used to monitor reefs to provide early warning of an outbreak. The monitoring effort required would prevent it being deployed across large numbers of reefs over a short period though.	ReefScan will be able to provide monitoring data across greater areas of the reef more quickly, however eDNA and SALAD are more suitable for determining any changes at the lower densities.	Adding environmental covariates would not help answer this question.
When/where are COTS likely to be aggregated.	Baseline manta does not record any aggregation metrics.	It's not possible to measure whether COTS are aggregated using eDNA.	SALAD records the location of COTS within a reef and so could be used to study this question providing there were temporal contrast in the data collected.	ReefScan will be able to provide the GPS coordinates of the COTS detected and so could be used to study this question providing there were temporal contrast in the data collected.	Adding environmental covariates may help research in the future to analyse why COTS aggregate.
When and where are COTS outbreaks most likely to occur?	Extra manta tow surveillance adds spatial coverage, improving the monitoring data available to answer this question.	eDNA is a good way to detect changes in COTS at low densities improving monitoring data available to answer this question.	SALAD can measure trends in COTS densities during and outside outbreaks, however it is resource intensive so this could not be undertaken at a large number of sites.	ReefScan is likely to be very valuable in building up data with a bigger spatial/temporal coverage across the reef to answer this question.	The addition of environmental covariates does not change ability to answer this question.

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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