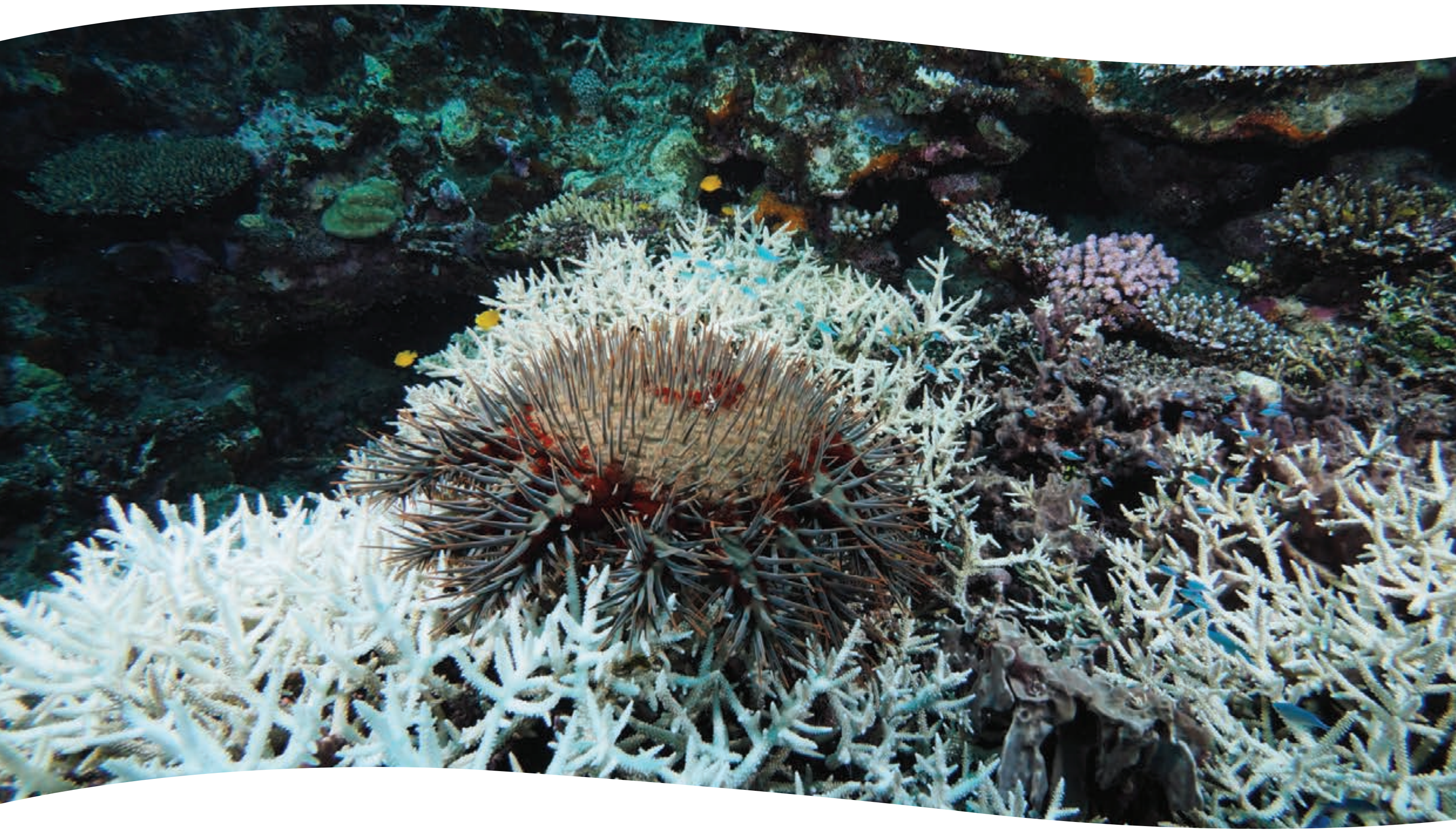
Tropical Water Quality Hub

National Environmental Science Programme

Technical Report

Monitoring and Surveillance for the Expanded Crown-of-Thorns Starfish Management Program

David A. Westcott, Cameron S. Fletcher, Daniel W. Gladish and Russ Babcock



CSIRO

Monitoring and Surveillance for the Expanded Crown-of-Thorns Starfish Management Program

David A. Westcott[1], Cameron S. Fletcher[1], Daniel W. Gladish[2], Russ Babcock[3]

[1] CSIRO Land and Water, Atherton, Qld 4883
[2] CSIRO Data61, Ecosciences Precinct 41 Boggo Rd, Dutton Park, QLD 4072
[3] CSIRO Oceans and Atmosphere, Qld Biosciences Precinct 306 Carmody Rd, St Lucia, QLD 4072

Supported by the Australian Government's
National Environmental Science Program
Project 4.1 Crown-of-thorns starfish: surveillance and life history

National Library of Australia Cataloguing-in-Publication entry:
978-1-925514-78-0

This report should be cited as:
Westcott, D.A., Fletcher, C.S., Gladish, D., and Babcock, R. (2021) *Monitoring and Surveillance for the Expanded Crown-of-Thorns Starfish Management Program.* Report to the National Environmental Science Program. Reef and Rainforest Research Centre Limited, Cairns (49pp.).

Published by the Reef and Rainforest Research Centre on behalf of the Australian Government's National Environmental Science Program (NESP) Tropical Water Quality (TWQ) Hub.

The Tropical Water Quality Hub is part of the Australian Government's National Environmental Science Program and is administered by the Reef and Rainforest Research Centre Limited (RRRC). The NESP TWQ Hub addresses water quality and coastal management in the World Heritage listed Great Barrier Reef, its catchments and other tropical waters, through the generation and transfer of world-class research and shared knowledge.

Cover photographs: (front) A crown-of-thorns starfish feeding on branching corals. (back) A coral bommie at Milln Reef. Images: David Westcott.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS

AI	Artificial Intelligence
AIMS	Australian Institute of Marine Science
BOM	Bureau of Meteorology
COTS	Crown-of-Thorns Starfish
eDNA	Environmental DNA
GBR	Great Barrier Reef
GBRMPA	Great Barrier Reef Marine Park Authority
IMOS	Integrated Marine Observing System
IPM	Integrated Pest Management
LTMP	Long Term Monitoring Program
MMP	Marine Monitoring Program
NOAA	National Oceanic and Atmospheric Administration
NESP	National Environmental Science Program
R&**D**	Research and Development
RIMRep	Reef Integrated and Reporting Monitoring Program
TUV	Towed Underwater Vehicles
TWQ	Tropical Water Quality

ACKNOWLEDGEMENTS

Some of the early discussions on monitoring tools and design occurred in a workshop held at James Cook University in 2018. We thank the participants in that workshop, Barbara Robson, Jason Doyle, Pascal Craw, Morgan Pratchett, Mary Bonin, and Sven Uthicke, for their contributions on the day and in discussions since. Morgan Pratchett, Sven Uthicke, Emma Lawrence and Scott Foster provided valuable critiques which have improved the final product.

We thank the Australian Government's National Environmental Science Program (NESP) Tropical Water Quality (TWQ) Hub for funding this project.

EXECUTIVE SUMMARY

Crown-of-Thorns Starfish (COTS; *Acanthaster* spp.) are efficient predators of coral and COTS population irruptions (often termed 'outbreaks') are a major contributor to coral loss throughout the Indo-Pacific region. On Australia's Great Barrier Reef (GBR), COTS have been identified as a key cause of coral mortality contributing to the significant degradation experienced by the GBR in recent decades. As a consequence, significant resources have been invested in the development and implementation of the Integrated Pest Management (IPM) COTS Control Program. The IPM COTS Control Program has been demonstrated to be effective at achieving Control Program objectives at scales of the site, the reef and hundreds of reefs and to have the potential to moderate outbreaks at the scale of the GBR. Critical to achieving regional and GBR-scale outcomes, however, is high quality monitoring data on COTS and the coral assets being protected to guide decision making.

In this report we review the monitoring and surveillance needs of the IPM COTS Control Program in the context of managing existing and new outbreaks into the future. We consider the need for a dedicated monitoring and surveillance program and identify appropriate objectives for such a program in each phase of the outbreak cycle. We then review the specific monitoring tasks this implies and the monitoring tools that are, or will soon be, available. Based on these considerations, we then assess four potential options for the design of a Monitoring and Surveillance program for the COTS IPM Control Program.

An efficient and effective COTS control program must have a dedicated monitoring program. Decisions about control, from developing appropriate strategies through to the day-to-day management activities of control vessels and divers all require reliable data on COTS and coral collected at relevant scales, i.e. at the right times and the right places. These data needs are not met by any existing external monitoring programs and little prospect that they will be met by other proposed monitoring programs (e.g. Reef 2050 Integrated Monitoring and Reporting Program, RIMRep) due to the very different questions they are designed to address. While opportunities for COTS monitoring to leverage from, and contribute to, other monitoring programs must be taken advantage of, there is no alternative to implementing a COTS specific monitoring program if we wish to maximise the value for money and the impact of COTS control investments. Because many of these activities are already integrated into the control fleet's activities implementing a COTS monitoring program requires a relatively modest additional investment beyond the current activities.

Review of the tools available for monitoring identified three basic tools that will underpin the operations of a monitoring program – culling, Towed Underwater Vehicles (TUVs) to replace Manta Tows and eDNA, the latter primarily deployed in sentinel and validation roles. These tools provide the range of data and confidence required across the range of spatial and temporal scales relevant to a control program. Critically they are also either already used within the Control Program (culling and tows) or they require little modification of the Control Program's activities (eDNA). These are attributes that ensure minimal additional overhead.

Monitoring tasks to inform the Control Program in each phase of the outbreak cycle (Inter-Outbreak, Initiation and Establishment, Outbreak, Post-Outbreak) were reviewed and this identified a suite of standard data needs in each phase of the outbreak:

1) Distribution, density and trends of adult COTS across all sites on individual reefs to provide data on baselines, detect outbreaks, trigger starting and stopping of management at sites and reefs,
2) Hard coral cover and assemblage structure and trends across all sites on individual reefs to provide assessment of asset condition in decision making
3) Other measures of reef health and their trends across sites on individual reefs to provide assessment of asset condition in decision making

These data needs could be addressed through each phase and at scales from the site to the GBR through the deployment of a combination of culling, TUVs and eDNA tools.

We then outline four strategies that address a range of contexts for monitoring, from addressing key research questions to informing control, and do so at a range of costs. Of these we recommend that two strategies be considered for development and implementation in the IPM COTS Control Program. The first of these is a strategy that is based on culling and TUV surveys and represents the minimum recommended monitoring investment. This strategy builds on the existing Control Program's operations and capability, greatly simplifying its implementation in that program. By focusing on the very first stages in the initiation of an outbreak and deploying technologies that maximize the resolution and scope of the data collected during monitoring, it provides: i) early warning of an outbreak, ii) enables a management response at the point at which COTS are susceptible to control, iii) directs where management should be invested, iv) provides a broad range of high quality data on coral and reef assemblages that are key to decision making, and v) has the potential to provide this information the scales required and on appropriate timeframes. In doing so it vi) maintains a standing control fleet for future outbreak response, and vii) feeds into other monitoring programs. The second strategy enhances this capacity by incorporating eDNA monitoring, particularly to detect key events in the outbreak cycle, to provide rapid large-scale assessments and a confidence building through its deployment in monitoring and in sentinel and validation roles. It does this at limited additional cost. The additional scope of data and improved confidence provided makes this combination of Culling, TUVs and eDNA the strategy we recommend.

The report makes the following recommendations:

1) The Expanded COTS Control Program must have a dedicated monitoring program to ensure that it delivers effective and high value for money protection of coral on the GBR. This program, along with control, must be maintained throughout the outbreak cycle.
2) The minimum recommended monitoring program would be based on current culling and next-generation TUV technologies (Strategy 3). New TUV technologies will revolutionize COTS monitoring data collection, vastly improving decision making and enabling a timely, precise and informed management response. Furthermore, this program would contribute currently unrivalled data to a range of other monitoring and reef management activities.
3) Incorporation of eDNA technologies, particularly those focused on adult COTS, into Strategy 3 (Strategy 4) would allow for tow and cull validation thereby providing enhanced confidence in decision making in the control program while larval eDNA tools offer the potential of an early-warning (c. 2 years in advance) capability. This combination of culls, TUVs and eDNA is the recommended strategy.

4) Investment in on-water monitoring of COTS should be guided by a rigorous statistical design to maximize the value and the utility of the data. The development of this sampling design must, along with the refinement and operationalization of new monitoring tools (TUVs and eDNA), be an R&D priority.

1.0 INTRODUCTION

Crown-of-Thorns Starfish (COTS; *Acanthaster* spp.) are efficient predators of coral, and COTS population irruptions (often termed 'outbreaks') are a major contributor to coral loss throughout the Indo-Pacific region. On Australia's Great Barrier Reef (GBR), COTS have been identified as a key cause of coral mortality (De'ath et al. 2012, Mellin et al. 2019) contributing to the significant degradation experienced by the GBR in recent decades (De'ath et al. 2012, Stuart-Smith et al. 2018). The feeding activities of high densities of adult COTS across large areas of the GBR directly undermines reef resilience by adding to coral mortality, suppressing coral recruitment and recovery (Haywood et al. 2019), and ultimately may reduce the capacity of corals to acclimate and adapt to changing environmental conditions (Ortiz et al. 2018). COTS outbreaks differ from other broad-scale threats to the reef, i.e. cyclone damage (Gardner 2003) and bleaching (Hoegh-Guldberg 1999, Hughes 2003, Claar et al. 2018, Hughes et al. 2018a, Hughes et al. 2018b), in that they are amenable to management at the scale of the GBR itself (Westcott and Fletcher 2018a). Consequently, since the 1960's there has been an intermittent but significant investment in attempts to locally reduce COTS populations during outbreaks on the GBR (Zann and Weaver 1988, Lassig 1991, Gladstone 1993, Rivera-Posada and Prattchet 2012, Westcott et al. 2016a, Price 2018).

While a variety of interventions for managing COTS outbreaks have been considered by researchers and practitioners (Westcott and Fletcher 2018b), COTS management still relies primarily on manual control. Manual control has been employed at local scales, i.e. at key reefs or dive sites, since the 1960s, with varying levels of success (Zann and Weaver 1988, Gladstone 1993, Rivera-Posada and Prattchet 2012, Pratchett et al. 2014, Westcott and Fletcher 2018a, Westcott et al. 2020). The lack of any operationally mature alternative approaches means that it is likely to remain the mainstay of COTS control into the foreseeable future (Hoj et al. 2020). However, the basis on which manual control is conducted has evolved dramatically during the current outbreak, which began on the GBR in 2010. Prior to 2013, COTS control on the GBR was implemented primarily by individual tourism operators at small, commercially important sites as it became clear that those sites were under threat (Zann and Weaver 1988). Those operations were conducted in isolation and without a larger scale objective or vision (Gladstone 1993) and were largely, though not entirely, considered to have failed (Zann and Weaver 1988). Today, control is conducted as a coordinated program that is focused on strategic objectives, driven by structured decision making based on integrated pest and adaptive management principles, and operates at site, reef, regional and GBR scales with a fleet of five dedicated vessels and professional COTS cull divers (Westcott et al. 2016b, Fletcher et al. 2020). This radical expansion and evolution of the COTS control program has resulted in a program that has the potential for achieving ecologically significant impact on the initiation and spread of COTS outbreaks and may well provide a necessary foundation for the success of other reef interventions (Condie et al. 2018, Fletcher et al. 2021, Westcott et al. 2021, Condie et al. submitted).

Advances in direct COTS management are welcome developments in terms of our ability to support the resilience of the reef into the future. However, the magnitude of the challenge posed by COTS remains daunting and it is by no means clear that management is yet equal to that challenge (Pratchett and Cumming 2019). The GBR covers an enormous area and its reefs are geographically complex, with many aspects still poorly described, while the dynamics of COTS across this seascape are known only in general terms. If a COTS Control Program is to be successful in achieving ecologically relevant objectives, and is to do so in an efficient manner, then management interventions must be conducted at the times and places that will produce the greatest gain in terms of the program's objectives (Westcott et al. 2016a, Westcott et al. 2021). This can only be done if management decisions, at all stages of the outbreak cycle and at all scales of operation, are based on reliable and current information on the distribution of COTS abundance and density across both individual reefs, regions, and the GBR, and on reliable information on the distribution and condition of the coral assets that we seek to protect. Up-to-date information, collected at the scales relevant to COTS control objectives, requires effective monitoring and surveillance designed to address the specific information needs of the COTS control program. Given that manual COTS control is currently one of the most effective means of protecting coral (Westcott et al. 2020), and will form a key component of future investments in management intervention on GBR (Condie et al. 2018, Condie et al. submitted), an appropriately designed and coordinated monitoring and surveillance strategy will also be a key component of any strategy aiming to conserve coral cover on the GBR over short, medium and long timescales (Westcott et al. 2016a, Fletcher et al. 2020, Westcott et al. 2021).

In this report we review the monitoring and surveillance needs of the Integrated Pest Management COTS Control Program in the context of managing new and existing outbreaks into the future. We consider the need for a dedicated monitoring and surveillance program and identify appropriate objectives for such a program in each phase of the outbreak cycle. We then consider what specific monitoring tasks this implies, and the contribution new and existing technologies can make to the design and operation of such a program. Finally, we suggest a number of options for the design of a Monitoring and Surveillance program for the COTS IPM Control Program.

2.0 RATIONALE FOR, AND REQUIREMENTS OF, AN EFFECTIVE MONITORING PROGRAM

Monitoring is a critical component of any strategic ecological control program as it provides the foundational data on the distribution of the abundance of the focal entity across the region of interest and over time. This information becomes central to all decisions made in the design and implementation of a species management program and without it such programs cannot be assessed for their effectiveness in meeting objectives or outcomes. An ideal monitoring program can be characterised as enabling (Lindenmayer and Likens 2018):

i) description of long-term trends in distribution and abundance;
ii) evaluation of the influence of drivers of population dynamics;
iii) management decision making in response to pre-established trigger points;
iv) assessment of the effectiveness of management interventions and investments;
v) on-going evaluation of a species' status or management need;
vi) prioritisation of management investment relative to other needs; and
vii) contribution to broader environmental reporting (e.g. Consensus Statements).

To be effective in fulfilling the roles identified above in any specific instance, the information produced by a monitoring program must be: i) tailored to the attributes of the species and the control program, ii) specific to the questions being asked, and the tasks being addressed, by the program, iii) conducted on temporal and spatial scales appropriate to the program, and, iv) have a sufficient level of accuracy and confidence for the needs of the program. At the same time, the program should be (i) cost-effective, (ii) capable of being consistently applied, and must (iii) produce information that is readily interrogated, such that results and inferences can be produced in a timely fashion after sampling and by the staff available. Monitoring methods that achieve these design goals while collecting useful information on other matters of interest (e.g. covariates for COTS analyses and decisions such as coral cover, other threats, other species of interest) are especially desirable.

Not surprisingly given these considerations, the ideal monitoring method inevitably remains just that, an ideal, while implemented monitoring programs are characterized by carefully made trade-offs and compromises. These compromises seek to achieve the most effective balance of feasibility and practicality, experimental rigour and confidence in the resulting estimate, and the monitoring objectives being addressed. In doing so they must consider factors such as the focal species' traits, dynamics of the key ecological processes relevant to the issue, the errors and error structures of candidate methods, analytical assumptions, resourcing constraints and, a suite of social and logistic constraints influencing what is possible in the field (Lindenmayer and Likens 2018). Consequently, tailoring methods to a particular context is a key, and often iterative, step in monitoring design.

3.0 WHY A COTS MONITORING PROGRAM?

Anyone coming to COTS and the GBR from other pest management contexts, which are essentially all terrestrial, can only be struck by the degree of uncertainty associated with the information used in decision making on the GBR. Not only is basic information on the distribution of COTS patchy and incomplete, but so too is the corresponding information on the distribution of habitat as well as coral communities and their condition. Just as concerning is the lack of consensus among experts about the processes driving COTS population and reef dynamics (Babcock et al. 2016a, Pratchett and Cumming 2019, Babcock et al. 2020, Westcott et al. 2020). For example, we currently have no coordinated means of reliably detecting new (i.e., primary) outbreaks, or of efficiently monitoring their subsequent spread (i.e., secondary outbreaks), beyond *ad hoc* observations, the limited surveying conducted under GBRMPA's Field Management Program and AIMS's Long-Term Monitoring Program (LTMP), and the culling activities of the COTS Control Program itself.

This lack of focused surveillance effort means that a timely response to incipient or early-stage primary outbreaks depends on COTS being detected during infrequent large-scale monitoring activities or through chance reports during unrelated activities, greatly reducing the probability of successful and early control being achieved. Without dedicated surveillance we are destined to repeat the mistakes of the past, where outbreaks are already well established and widespread before we acknowledge and respond to their presence. This is a major concern as a rapid response to pest species incursions or population irruptions ensures management is implemented when the population is small and localised and is one of the single most important determinants of successful management response in terrestrial, aquatic, marine, agricultural and epidemiological settings (Hulme 2006). Failure is inevitable when the threat is clear and established (Zann and Weaver 1988, Birkeland and Lucas 1990, Gladstone 1993, Fisk and Power 1999, Hulme 2006, Fletcher et al. 2015). Similarly, our ability to delimit incipient outbreaks, in particular, and thereby to most effectively target our management effort to the parts of the COTS population where we can have the greatest impact, depends crucially on an efficient large-scale monitoring program that describes both the spatial distribution of baselines and deviations from them. Ultimately, the capability to i) predict and detect incipient outbreaks, ii) detect breaches of key ecological thresholds, and, iii) monitor the spread of existing outbreaks, will be an essential component of any efficient and successful COTS control program. The question is how best to do this?

Detecting and monitoring outbreaks is a critical component of successful COTS management, and one that can be applied immediately, it is, however, a response to processes already in train. Ultimately, the most effective management response may well lie in anticipating and preventing outbreaks rather than responding to their presence. Achieving this would be greatly facilitated by, the confirmation of the role of candidate drivers and information that would enable the prediction and management of those drivers. A range of drivers have been hypothesised to contribute to the initiation of primary outbreaks, including sea temperatures, the strength and dynamics of ocean currents, loss of top-down control of COTS populations, inorganic nutrients promoting phytoplankton, and factors that influence them, such as flood events in GBR catchments (Birkeland and Lucas 1990, Wooldridge 2009, Pratchett et al. 2014, Pratchett et al. 2017). Despite this diversity of potential drivers, no consistent monitoring of them currently informs tests of their relative roles nor COTS control.

Some candidate drivers of outbreaks are amenable to either remote or automated monitoring, while others will require dedicated field monitoring. In the absence of certainty about which drivers are responsible, a logical approach is to monitor as many of the candidate drivers as possible while simultaneously monitoring COTS demography, distribution and abundance (Babcock et al. 2016a), and to do so on a regular basis focussing on the Initiation and Dispersal Boxes (the section of the reef where primary outbreaks are hypothesised to begin and spread to, see below) but also including other regions (to account for the possibility that outbreaks can initiate elsewhere). This approach would allow: i) detection of hypothesized outbreak conditions, ii) timely detection of and response to primary outbreaks, and iii) testing and development of hypotheses for outbreaks and ultimately their control through addressing their root causes in the long term. One component of a cost-effective approach to monitoring environmental drivers of outbreaks, for example, might be based on a combination of remote sensed data and (semi-) automated water sampling conducted at established sampling stations and onboard continuous sampling during research, management and tourism activities on the reef to provide real-time, spatial sampling of outbreaks and outbreak pre-conditions. Appropriately targeting the sampling to the Initiation Box, the initiation phase of the outbreak and the hypothesised drivers of outbreaks would be critical to ensuring adequate power for resolving the drivers of COTS outbreaks in a cost-effective manner.

3.1 Monitoring for COTS across the outbreak cycle – what information is needed

Effective and efficient control of COTS requires monitoring that: i) provides up-to-date information on COTS densities and control options within reefs to structure day-to-day on-water decision making in the control program; ii) provides regional information on the distribution of COTS outbreaks and coral resources to determine priorities reefs for COTS management; iii) collates information on the status and trends of COTS on the GBR real time to both track the status of existing outbreaks and to provide early-warning of new outbreaks; iv) builds a better understanding of the underlying drivers and dynamics of COTS outbreaks to underpin long-term improvements to management; and v) monitors and assesses the performance of our efforts to moderate the impacts of COTS on the GBR. Considered in the context of all the phases of a COTS outbreak cycle (Figure 1) and in terms of control operations, a monitoring program specifically designed to service the needs of COTS management on the GBR would include the following tasks:

1) Monitoring of physical and ecological pre-conditions for outbreaks
2) Pre-outbreak or baseline monitoring of COTS abundance, density, coral, reef condition across the GBR
3) Early detection of events leading to outbreak initiation
4) Early detection and delimitation of incipient outbreaks
5) Monitoring and delimitation of existing outbreaks and their spread
6) Monitoring of control outcomes and performance
7) Post-outbreak monitoring

Tasks 1) and 2) represent the monitoring and surveillance required during any inter-outbreak period and essentially represent the Control Program maintaining ‘readiness’ (Figure 1). Monitoring during these phases allows for the testing of hypotheses for the drivers of outbreaks and provides key data on baseline conditions relative to COTS and assets on the GBR. Tasks 3) and 4) represent monitoring that provides an ‘early warning’ by identifying significant increases in pre-spawning adult densities, spawning/settlement events and subsequent appearance of high densities of adults, and, which triggers a management response. Tasks 5) and 6) represent the ‘control’ phase during which monitoring provides up-to-date intelligence on the distribution and intensity of the outbreak to inform decision making in control and provides feedback on the performance of the control efforts. Task 7) describes population processes leading to outbreak decline and represents ‘assessment’ and return to ‘readiness’ monitoring.

It is important to note that this sequence implies that outbreaks are temporally discrete processes that, with the possible exception of the Swains, progress in an orderly fashion along the GBR, e.g. from a north origin southward, with a short gap between the end of one outbreak and the initiation of the next. While this might be the expectation based on previous outbreaks and monitoring (e.g., figure 4 in Vanhatalo et al. 2017), it is by no means guaranteed. It is entirely possible that a new outbreak could initiate prior to the end of the previous outbreak, or that outbreak conditions might re-emerge in locations where an outbreak had recently been suppressed. While such events would complicate the monitoring and control task and require that different phases be addressed simultaneously in different regions, they do not negate the utility of the sequence that we have described. Rather they highlight the need to maintain monitoring across the GBR and throughout all outbreak phases - reefs and regions will progress through these phases and our experience to date suggests that this is likely to be the case for the GBR north of the Swains.

The most immediate needs for the Control Program running today are monitoring tasks 4 and 5, which provide the information necessary to make on-water control decisions that can target effective control actions to protect individual high value reefs. Better monitoring will lead to better decisions, and more reefs protected with the resources available. Within the next few years, however, our ability to leverage this manual control capability to dramatically minimize the impact of the next outbreak on the GBR will depend on task 3, and potentially task 2. These tasks require investment in monitoring while COTS densities in the initiation box are still low but may allow us to target manual control actions so effectively that we partially or completely avoid impacts from the next COTS outbreak (Babcock et al. 2020, Fletcher et al. 2021, Westcott et al. 2021). Our ability to prevent outbreaks entirely will depend on using monitoring tasks 1 and 2 to test hypotheses for the drivers of outbreaks relative to baseline conditions of COTS and coral on the GBR. This process will require consistent monitoring of a range of parameters over a large region and a long period of time, but if successful, would allow the impacts from future outbreaks to be completely avoided without requiring large-scale manual control. Throughout each of these processes, monitoring task 6 will provide the information necessary to identify the most effective management approaches in each situation. Task 7) describes population processes leading to outbreak decline and represents ‘assessment’ and return to ‘readiness’ monitoring.

This list of tasks makes it clear that the monitoring and surveillance requirements of a COTS control program are multifaceted and range from biophysical and oceanographic variables through to monitoring of COTS and coral populations, to the performance of the control program itself, and even potentially to the economic value of the assets being protected. This will require very different types of monitoring to be implemented at different spatial and temporal scales in different phases of the outbreak and in different parts of the GBR at any given point in time.

The breadth of the data needs, and the spatial scales at which this data would ideally be collected, mean that it is almost certain that the program will need to rely on other programs for some monitoring activities. There are a number of monitoring and surveillance programs currently active, e.g., AIMS' Long Term and Marine Monitoring Programs (LTMP and MMP respectively) and proposed for the GBR region, e.g. Reef Integrated and Reporting Monitoring Program (RIMRep). Such programs and the data that they might provide will be identified elsewhere in this report but, in their current configuration, they would not fulfil the role required in an effective COTS monitoring program. In the first instance, however, we consider each of the phases identified above, describe the monitoring questions, the data needs and the methods for collecting that data.

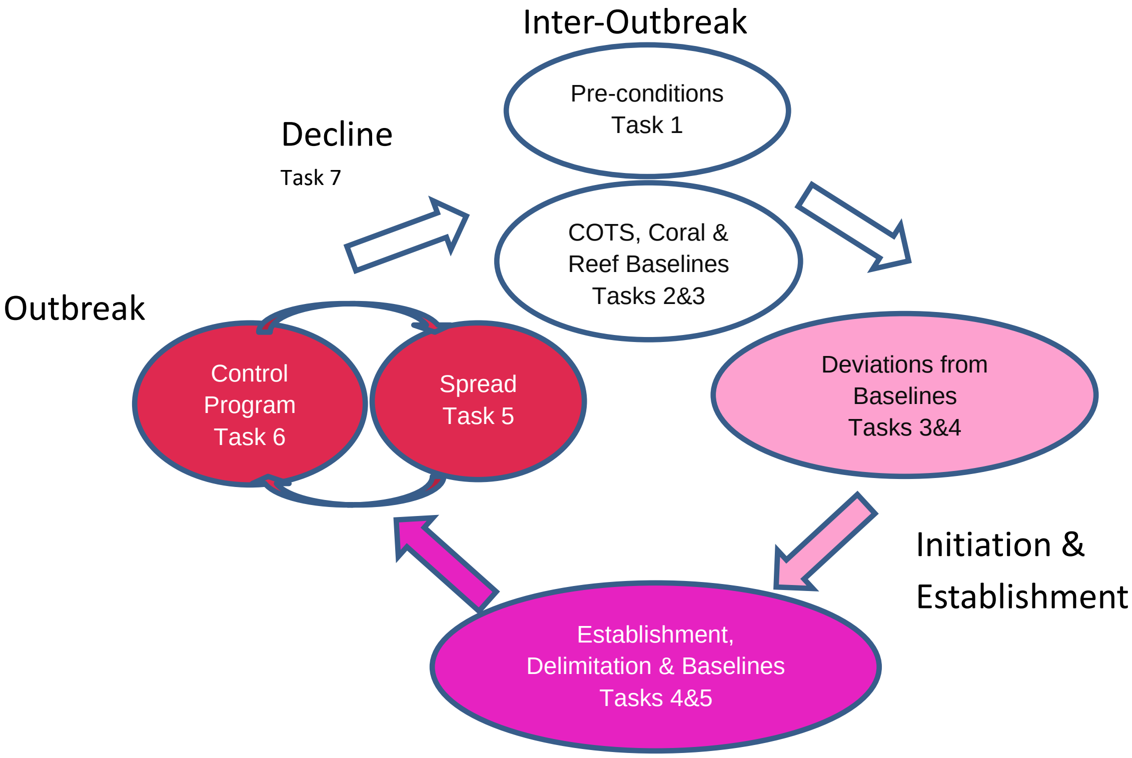


Figure 1: Monitoring for each phase of the outbreak cycle: Inter-outbreak, Initiation & Establishment Outbreak and Decline. While an ideal monitoring program would include monitoring in all phases of the outbreak (indeed all phases may occur across the reefs of the GBR at any one point in time) the colour coding indicates the urgency of monitoring for a management response with white indicating the least need through to red indicating a fundamental requirement.

3.2 Monitoring for COTS across the extent of the GBR

The design of a monitoring program must also consider how effort is distributed in space. The GBR is vast and this effectively precludes an approach that comprehensively surveys all reefs. Rather, we must choose how we distribute effort across its extent, and we must do this in a manner that is informed by existing data and emergent patterns, the current outbreak status, our understanding of how waves of outbreaks develop and progress, the distribution of relevant assets and threats (current or potential), and by the program's current information needs. These needs will vary across the outbreak phases, and their implications for how monitoring might be designed and structured during each phase are considered in the following sections. Here, we consider implications of how outbreaks are thought to develop and spread on how monitoring and surveillance effort might be distributed at the scale of the GBR, and the implications of the huge spatial extent for monitoring errors and sampling within regions.

Our understanding of the spatial structure of Outbreak Initiation and spread suggests that we define two geographic areas. The first of these is the Initiation Box (Pratchett et al. 2014), a concept commonly used in the context of COTS outbreaks on the GBR that refers to a region in which outbreaks are hypothesised to begin. The formulation of the Initiation Box concept stems from the observation that the first two outbreaks appeared to have begun in the region between Cairns (c. 16° 47' S) and Lizard Island (c. 14° 38 S) (Kenchington 1977, Reichelt 1990). The two subsequent outbreaks also appeared to follow this pattern (Pratchett et al. 2014), however, analyses of limited sampling data in AIMS' LTMP surveys (Vanhatalo et al. 2017) raise the possibility that primary outbreaks, or their early spread, may occur as far north as 12° S. Despite uncertainty over whether the Initiation Box actually defines the area of outbreak initiation or is instead an artefact of limited sampling, and uncertainty about its potential boundaries, the experience of four consecutive outbreaks appearing to begin in this region suggests that the region should be a focus of surveillance, particularly during the Inter-Outbreak and Initiation and Establishment Phases. Clearly, the persistent uncertainty around the Initiation Box and its boundaries suggests that reef-wide outbreaks could initiate outside the Initiation Box (Pratchett 2010, Babcock et al. 2020) as currently defined, demanding focus not be exclusive to that region.

If an outbreak does begin within the Initiation Box, we can expect that larvae produced by that outbreak will disperse downstream, predominantly southwards on prevailing currents, to other reefs beyond the Initiation Box's boundaries. Both theoretical modelling and past experience clearly indicate that successful control and containment of a pest species population is dependent on management of both the extant pest population (including adults and cryptic juveniles) and the area encompassed by COTS larval dispersal (Fletcher and Westcott 2013, Fletcher et al. 2015). As a consequence, Westcott et al. (2021) have suggested that to account for this a successful COTS control program requires both surveillance and culling to also be conducted in these downstream areas receiving larvae. They have called this area the Dispersal Box.

Given that COTS spawning occurs predominantly in or just before the monsoon season (Babcock and Mundy 1992, Babcock et al. 1994, Uthicke et al. 2019, Caballes et al. 2021), when the Gulf of Papua Current has weakened and the Southern Equatorial Current bifurcation tends to drive stronger southern flow across all but the northern section of the Initiation Box, we might expect most dispersal will be in a southerly direction. However, uncertainty about the location of outbreak initiation (Pratchett et al. 2017), variation in the bifurcation latitude (Zhai et al. 2014) and the potential for local currents and eddies to transport larvae north against the dominant flow (Hock et al. 2014), all argue for vigilance in a northern dispersal box. The exact location of these boundaries should be scaled to estimated larval dispersal distances (Fletcher and Westcott 2013). A first pass at these Dispersal Box boundaries, based on a single sampling period that occurred several years after the current primary outbreak

(Uthicke et al. 2015), might be estimated to be at 18° 27’ S and at 13° S for the Northern Dispersal Box. This might be extended to 12°S as a precautionary response to the results of Vanhatalo et al. (2017).

Defining the Initiation and Dispersal Boxes as a focus of monitoring and surveillance for the next outbreak does is not intended to suggest that other areas can be ignored. There is sufficient uncertainty about the drivers and early phases of COTS outbreak to mean that this would be a risky strategy. Rather the suggestion is that the evidence indicates that particular vigilance is required in these areas.

The magnitude of the spatial scale of any monitoring program on the GBR also has implications for the kinds of monitoring tools that are used and for the trade-offs made in terms of accuracy, precision and the balance of errors associated with any particular method. The need for data that is representative of individual sites, reefs, regions and of the GBR generally means that different methods will need to be employed at different scales, and that as scale moves beyond the site, that large areas will need to be covered. This will demand methods that are rapid, have adequate performance (i.e. accuracy, precision, etc), are relatively inexpensive simple to deploy within the context of Control Program operations and that they meet its specific data needs. It will also mean that consideration must be given to the type of data collected.

One consideration is the metrics that are used – are measures of absolute COTS density required at a particular scale or can we use a method that provides reliable indices of relative abundance and density? For example, in the current program, while density determines when culling stops at a site or reef, the decision to start is based on an index of density; recording a single COTS or COTS feeding scar during manta tows. This index has proven to be a reliable, if not perfect, indicator of densities above the culling density threshold (Westcott et al. 2021), i.e. while not an absolute measure of density, it has sufficient accuracy and precision to inform effective ecologically-informed decision making.

Another consideration is the balance that decisions based on monitoring data achieve between the probability of making a Type I error (a false positive) and a Type II error (a false negative). In the context of COTS monitoring, a Type I error would be to conclude that control was necessary when in fact it wasn’t, while a Type II error would be to conclude that control was not required when in fact it was. Both types of errors will inevitably be made, but in the context of COTS control there is an enormous asymmetry in the consequences of committing these two types of errors. The consequence of a Type I error is that investment is made in control when it is not needed, i.e., resources are expended unnecessarily. However, if control actions themselves can quickly identify when a Type I error has been made, for instance when culling efforts reveal fewer COTS than expected at a site, a Type I error may not incur significant costs. The consequence of a Type II error is that COTS control is not invested when it should be. Because follow up control actions do not occur, the chance that the error is quickly identified is low, and the ecological consequences are severe: coral at the uncontrolled site is lost and, even more importantly, the COTS population there produces larvae that spread further downstream, undermining the control program’s broader efforts. Often in monitoring there is a trade-off between the probability of making Type I versus Type II errors (Mapstone 1995). In COTS control, the asymmetry in consequences means that we should attempt to minimise the probability of making a Type II error, even at the cost of a greatly increased probability of making a Type I error.

This is the approach used in the current COTS Control Program (Fletcher et al. 2020). Manta tows are used to provide rapid, broadscale monitoring of the presence of COTS or COTS feeding scars, and this coarse information is used to classify a site or reef as in need of control or not. Cull dives then accurately assess whether absolute densities are above or below the relevant threshold. Assessment of data from the IPM COTS Control Program indicates that the probability of a Type II error was c. 3% while the probability of making a Type I error was 68% (Fletcher et al. 2020, Westcott et al. 2021). This represents an acceptable, if not perfect, trade-off given the low cost of a Type I error. This two-tiered approach effectively takes advantage of the ability of the manta tows to cover large areas by only using them as a coarse trigger and relying on the site scale reliability of cull dives to provide the more detailed site estimates. A similar two-tiered approach will be required in the development of the COTS Monitoring Program given the need for information at broad range of spatial scales, from the site to the GBR. Ultimately, decisions about each of the methods will be based on the performance and associated errors (or biases) of each method, how these interact with the information needs of the program, and pragmatic constraints such as cost and logistics.

3.3 Monitoring Tools for a COTS Monitoring Program

What monitoring activities can be conducted and how that monitoring should be structured given the Control Program's objectives is, to a large extent, dependent on the monitoring tools and technologies that are available, or will soon be available. A range of methods have been used in COTS monitoring for control and research purposes in the past, and a number of emerging technologies have progressed sufficiently in their development to clearly indicate their potential in future monitoring. These methods differ in their attributes and how they are or could be incorporated into COTS monitoring. Below we briefly summarise these tools for use in COTS and reef habitat monitoring for Control Program activities. Additional consideration of the most promising methods are provided in Table 2 and the utility of the methods in the light of the monitoring program design are considered in Section 4.5.

Culling: Cull divers swimming through a site systematically culling COTS and recording information on the size and numbers culled. This approach is slow but reliable (though this could be improved with automated data recording), allowing divers the freedom of movement to detect COTS underneath plate corals and potentially those hidden in the coral matrix. This is the current standard used in the control program for estimating COTS densities and size distributions. Culls provide good data at the site and reef scales, and even at regional scales and GBR scales over longer time periods however as the spatial scale increases the temporal resolution decreases. However, culls, by definition, measure the population density and size of COTS removed from the population, and the COTS remaining after management must be inferred by estimating age-size class detectability, thus confidence in the estimate increases with more dives at a site or reef. It is a high cost approach with depth limited sampling, however, as the fundamental management activity it comes at little cost to a monitoring program.

Diver-based Surveys: Standardized diver-based surveys that record adult COTS densities have also been conducted (Engelhardt 1999, Pratchett 2005, Beeden et al. 2014, MacNeil et al. 2016). In these surveys divers search plots or belt transects recording data on COTS and their habitat. Diver-based surveys are slow but estimates of similar reliability to those of a cull at relatively small scales (tens of metres to a hectare) making them most appropriate for addressing site level questions, though inference at larger scales is possible with appropriate sampling. Such methods have been used primarily in the context of research rather than control in the past. The accuracy of diver-based estimates is strongly influenced by the detectability of COTS at a site (MacNeil et al. 2016) and as is the case with culling (Westcott et al. 2021) its estimates would be improved with structured revisitation over periods of days or weeks as occurs with culls. This is not usually done.

Fine-scale Surveys: Modifications of diver-based surveys specifically designed to survey for cryptic juvenile starfish (Engelhardt 1999, Engelhardt et al. 2002, Wilmes et al. 2018, Wilmes et al. 2020) These require a higher skill level and greater time investment than do diver-based surveys for adults.

Scooter Surveys: Larger area surveys are possible if divers use underwater scooters. Scooters allow divers to move more rapidly while still retaining the capacity to stop and search specific locations more thoroughly. This allows them to cover non-COTS habitat and suitable areas with little sign of COTS at speed though in suitable habitat this comes with the cost of a greater chance of missing COTS than during cull dives. Because of this they are likely less accurate and precise than culling and standard diver surveys. They may have more reliable detection rates, though this needs to be examined, but will be slower than manta tows. Like culling, scooter surveys involve detailed searches of a site and consequently are best matched to the site and reef scales. With enough time scooter surveys could be scaled up to regional and GBR scales. It is a high cost approach with depth limited sampling and potentially additional OHS considerations.

Manta tows: The current standard procedure for rapid monitoring above the site scale. Manta tows involve towing a diver behind a small boat and while they record COTS and coral data. There is no scope for divers to check for COTS hidden in the coral matrix, so only COTS or COTS scars visible from above the coral can be detected. Manta tows enable rapid surveys of sites and of entire reef perimeters but provide highly unreliable estimates of COTS densities. They do however provide a reasonable estimate of the effort that will be required at a reef (Fletcher et al. 2021) and a reliable trigger of the need to cull a site (Westcott et al. 2020, Westcott et al. 2021). They are low-cost but depth limited.

Towed Underwater Vehicles (TUVs): TUV tows are similar to manta tows but humans are replaced with a remotely operated TUV that collects high-resolution images of the substrate from an angle and above across a swathe that varies with height from the substrate but is generally 10+ m. These images are then analysed using AI approaches to provide estimates of COTS sizes & number, coral cover and assemblages and reef condition. They have a vastly improved COTS detection capability compared with manta tows and early indications suggest that they will allow for reliable and precise estimation of COTS density and size (Kettle, B., pers. comm.). In particular, because the cameras capture vision at angles oblique to the direction of travel, as well as from directly above, and because machine learning-based algorithms can interrogate multiple frames, they are far better than humans at detecting partially obscured COTS and those that are visible for only a fraction of a second. They are faster (1.5 – 2 times), more comprehensive, and cheaper to implement than manta tows. They are low cost and capable of monitoring at all relevant depths. While work on development and operationalising of TUVs is ongoing (with programs at AIMS, Babel/CSIRO, and QUT), TUVs are a replacement for manta tows and will do so in the very near future.

eDNA: Based on detection of sloughed-off cells, gametes or larvae of COTS detected in water samples using eDNA methods (Uthicke et al. 2015, Doyle et al. 2017, Uthicke et al. 2018, Doyle and Uthicke 2020). This method is highly sensitive in detecting COTS DNA in water samples and appears to provide a reasonable index of COTS abundance (Doyle et al. 2017, Uthicke et al. 2018). These tools should be able to detect COTS regardless of their position in the coral matrix. Dipstick methods (Doyle and Uthicke 2020) provide a rapid sampling approach. Requires pumping and filtration of water on the vessel and laboratory processing and analysis (dipstick methods aside) once the samples are returned to shore. Currents and vertical mixing mean that the source location remains unknown, although eDNA detected at a reef appears to come from that reef (S. Uthicke, unpubl. data), hence locational accuracy is poor but could be improved with appropriate spatial sampling strategies. With adequate samples, the technique would perform well at larger scales and when sampling timeframes are longer. This means that it would also perform particularly well in a sentinel role or as a validation method for other sampling. eDNA larval detection based on plankton tows is the only feasible method for detecting larvae. This method is well established, and water samples are currently collected as part of some culling and other monitoring activities.

Settlement traps: Traps used to monitor larval settlement onto a reef and new recruits. These can be structures that provide shelter to larvae and from which they are washed for visual counting or eDNA analysis. Visual searches are very time consuming and eDNA methods are being investigated (S. Uthicke, pers. comm.).

3.3.1 Monitoring Coral

While the focus of this report is on the monitoring of COTS, information on coral cover and assemblages collected at the same range of spatial scales as is the COTS data is fundamental to COTS Control Program decision making. This information would ideally be collected contemporaneously as COTS data. Methods used or which might potentially be used are very briefly reviewed below.

Coral transects and plot surveys: These are the COTS diver-based survey equivalents for coral cover. Such surveys have been conducted in a variety of ways but are generally either plot, e.g. Reef Health Impact Surveys (e.g., Beeden et al. 2014) or transect based (e.g., Pratchett 2010, Hughes et al. 2017). Such surveys can be as comprehensive and as detailed as required, e.g. RHIS surveys record data ranging from benthos cover type through to coral diseases and physical damage (Beeden et al. 2014).

Image-based surveys: Plot and transect based coral surveys can also be conducted using high resolution imagery analysed either manually (e.g., Engelhardt et al. 2002) or using automated analysis approaches (e.g., Williams et al. 2019), . This approach reduces the field time required for measurement and uses images collected according to standardised protocols. Such approaches can allow citizen scientists to contribute, dramatically broadening the scope of data collection.

Manta Tows: Manta-tow surveys traditionally incorporate a categorical assessment of hard coral cover as well as recording COTS (Miller et al. 2009). These estimates are likely to be particularly susceptible to observer bias and environmental conditions experienced during the tow.

TUVS: TUV monitoring of coral can be done using analysis of the images collected during COTS monitoring. High resolution imagery and multiple images (e.g. Vertigo3 TUVs takes 15 5MP images every second, B. Kusy, pers. comm.) allow machine learning-based algorithms to quickly and reliably estimate attributes such as coral cover, coral type, fish abundance, and potentially also COTS feeding scars and to do this for entire reef perimeters.

Automated Surface Vehicles: Tools such as AIMS' ReefScan technology (M. Olsen, pers. comm.) are very similar to TUVs but instead of being towed these are automated and operate independently. They operate a much slower speeds, collect higher resolution imagery and have a broader range of sensors.

eDNA: Metabarcoding eDNA approaches allow for detection of presence and absence of species and consequently off the potential for characterising coral assemblages (Alexander et al. 2020) and reef community composition (Stat et al. 2017). Dipstick technologies (Doyle and Uthicke 2020) if further developed for community assessment could allow for citizen scientist engagement.

4.0 MONITORING PHASES AND NEEDS THROUGH THE OUTBREAK CYCLE

In section 3 we described the general attributes of monitoring through the different phases of the outbreak cycle, these being the Inter-Outbreak, Initiation and Establishment, Outbreak and Post-Outbreak phases. We then considered the tools that were available for monitoring. In this section we consider each of these phases in more detail and identify the specific data needs for a control program in each phase and the tools that might be used to achieve this. In Section 5 we then filter this down to a set of possible monitoring strategies.

4.1 Inter-Outbreak Monitoring

Past practice on the GBR has been to treat inter-outbreak periods as a time where no COTS related activity is required. As a consequence, only very limited monitoring (LTMP and MMP only) and no control has occurred during this phase. This has had disastrous consequences, with on-water control and surveillance abandoned and funding for the research required to develop and refine control ceasing (Lassig 1993, Pratchett et al. 2014, Babcock et al. 2020). In the context of the current outbreak, the practical outcome of this was that the pre-conditions for the outbreak were not detected, despite the use of an outbreak definition (10 COTS ha^{-1} versus 3-5 ha^{-1}) that was far too high (Babcock et al. 2014, Plagányi et al. 2020), and the initiation, establishment and initial spread had all occurred long before it was realised that an outbreak was occurring and that a management response was required. There was a delay of c. 3.5 years before any coordinate response was mounted and c. 8 years before a scaled-up and strategic response was implemented. This lack of timely response ensured that the outbreak had spread extensively along the GBR, that huge areas of coral habitat were lost, and that the response which was ultimately implemented was realistically only able to protect selected priority assets (see also Yamaguchi 1986 for a similar experience in Japan).

If repeating this unnecessary sequence of events is to be avoided in the next outbreak, we need to consider the key inter-outbreak information needs for ensuring that a timely management response is not only possible but implemented. The primary objective of monitoring during this period clearly must be to detect the pre-initiation and establishment phase of primary outbreaks. However, in the temporal sequence of events we might expect, or at least hope, that there will be an interregnum of some period during which there is no primary outbreak to detect. This is by no means guaranteed and for much of a single outbreak different parts of the GBR might be experiencing different outbreak phases. In this section we first consider monitoring of benign inter-outbreak conditions before moving on to consider detection of a new outbreak.

The inter-outbreak period effectively represents the baseline from which the GBR will deviate and, consequently, should, all other things being equal, represent the conditions under which COTS populations are apparently stable and causing little impact, when coral cover and communities are self-sustaining and potentially improving their cover and condition, and when reef health is high or improving. Monitoring to detect any potential or actual threat requires that these baselines are actively monitored during the inter-outbreak period and that this information is used to detect divergences from them.

The inter-outbreak period is also the period during which the range of drivers that result in a COTS outbreak may come together to initiate an outbrreak (e.g.,Wooldridge and Brodie 2015). Monitoring of hypothesized outbreak drivers during this period therefore represents an opportunity for their identification and determination of their relevant thresholds and, from this, the development of management interventions and a predictive capability. To date, there has been very limited effective sampling of pre-outbreak populations leading to potentially spurious assumptions about the distribution, density and dynamics of COTS in the lead up to each new wave of population irruptions.

The two contexts for monitoring during this period require very different approaches. The first requires in-water sampling of a broad range of COTS population, coral and reef community ecology parameters. Of greatest interest are measures of the density of COTS and their population size structure and how this is distributed across reefs, between reefs in a region and across the GBR. Because inter-outbreak densities will be low, candidate monitoring methods must be able to estimate low densities, or indices of these, e.g. feeding scars, with acceptable accuracy and precision, or, given that low densities are likely to be measured with relatively low accuracy, be able to detect trends over time at a site using highly repeatable methods. The second context for monitoring requires sampling of the biophysical attributes of GBR waters and their inflows, measured either through remote sensing or through manual or automated in-water sampling.

4.1.1 Pre-outbreak monitoring of COTS population dynamics, coral and reef condition, reef community drivers of initiation.

Over-arching Question: What are the baselines for COTS densities, distributions, and population structure and dynamics, for coral assets (e.g. coral and other substrate cover, community structure and health), for reef health (e.g. fish/invertebrate COTS predator communities)?

Objectives:

a. Describe the distribution and density of COTS, coral and reef condition across the GBR
b. Monitor trends, particularly, but not only, in the Initiation and Dispersal Boxes
c. Trigger control to allow a rapid and efficient management response to changes in risk
d. Enable prioritization of reefs for monitoring and control based on assessment of value and health

Data Types:

e. Detections of COTS – adults (located to at least the site), juveniles, juvenile settlement, larvae and settler supply, gametes, estimates of density, distribution and population size structure
f. Coral monitoring – status and trends in coral cover, size structure, assemblage composition and colony health.
g. Reef community structure and condition – e.g., damage, algal and soft coral cover, fish/predator communities

Potential Technologies:

h. eDNA through manual surface water sampling, potentially automated or passive samplers should they be developed
i. Fine-scale surveys – COTS recruitment

j. Diver-based surveys
k. Scooter surveys
l. Manta tows
m. TUV tows

4.1.2 Bio-Physical pre-conditions for outbreaks

Over-arching Question: What are the biophysical drivers underpinning the initiation of a primary outbreak?

Objectives:

a. Monitor hypothesized bio-physical drivers of outbreaks to predict outbreak initiation to serve as an early warning for management response
b. Assess hypotheses for outbreak initiation, including biophysical factors contributing to larval supply and settlement

Data Types:

c. Physical climatic and oceanographic variables including: i) sea temperature, ii) water quality, iii) flood plumes, iv) currents (strength, pooling, delta connectivity), v) nutrients, vi) salinity, vii) sediments, viii) ph, etc.
d. Resources - phytoplankton size, type, abundance, quality, stratification,
e. COTS densities – buildup of larvae/juveniles, description of larval dispersal kernels
f. Predators – fish (TUV tows and AI sampling), invertebrates (indexed by coral community health?)
g. Predators of all life stages

Potential methods:

h. Physical data - Existing buoys and sampling programs
i. Physical Remote (satellite) sensing
j. Phytoplankton sampling surveys
k. Diver surveys, other visual survey methods
l. eDNA surveys based on manual sampling, potentially automated or passive samplers should they be developed

Data Sources:

m. AIMS, NOAA, BOM, MMP, RimREP, eREEFS, IMOS, and others.

4.2 Initiation & Establishment

Early intervention is perhaps the most significant contributor to successful pest management programs (Hulme 2006). An efficient and effective management response to a COTS outbreak will only be possible if that outbreak is detected sufficiently early that an adequately scaled management response can be mounted (Yamaguchi 1986). Just how early this should be will be a function of the life-history stage that is vulnerable to control and the preparedness of management. If all aspects of the management response are in place and effective, then monitoring to inform management of a new outbreak needs only to detect COTS with sufficient lead time for management to be implemented when the COTS reach the life-history stage that can be managed. For example, if manual control can be employed against individuals of ≥ 10cm central disc diameter, then surveillance must at least be able to detect both changes in the density of individuals ≥ 10 cm diameter and the location of reefs where such changes are occurring. If, however, a standing control capacity is not maintained and funding must be sought, vessels and crew sourced and trained, and operational protocols established, then detection must occur much earlier, e.g. when spawning or elevated rates of settlement are detected two years earlier. A precautionary approach dictates that uncertainty about the time needed to field an operational capacity will increase the lead-in time required from the surveillance.

What, then, are the critical events that might act as early-warning triggers and which therefore should be subject to monitoring? While the exact drivers of outbreaks and the contributing population processes that presage COTS outbreaks have yet to be adequately described, we can identify three likely events that could be monitored in this context. The first event would be the build-up of adult densities to beyond relevant thresholds. The nature of these thresholds will be determined by a variety of factors, including the sensitivity of the monitoring methods. For example, current manta tow surveillance does not reliably indicate density and so in the current management program, a coarse but effective threshold of detection of ‘any COTS or feeding scar’ is used to trigger management (Fletcher et al. 2020, Westcott et al. 2021). New, more sensitive and reliable monitoring technologies might allow for more nuanced thresholds. If developed, such technologies might be focused on very minor changes initially, perhaps reliably detectable as trends across sites rather than as statistically distinct density changes at a site. The second event would be changes in the distribution and density of adults that result in improved spawning, and the third, high levels of larval settlement or recruitment.

Monitoring designed to trigger a management response to a primary outbreak must therefore be capable of detecting breaches of critical thresholds determined by the monitoring method employed and the lead-in time required to establish capability. Furthermore, it must be capable of describing the distribution of threshold breaches to inform where management should be invested. In the context of COTS control there are two density thresholds currently used. The first of these is the ‘Ecological’ threshold, defined as the density of COTS above which coral growth cannot keep up with COTS predation. This density varies with coral cover but lies between c. 4 and 5 COTS ha^{-1} (Babcock et al. 2014, Plagányi et al. 2020). This threshold targets the impact of COTS on coral. The ‘Reproductive’ threshold is defined as the density of COTS above which the rate of COTS fertilization success, and hence reproductive success, begins to increase non-linearly and is estimated to be c. 3 COTS ha^{-1} (Rogers et al. 2017). This threshold targets the reproductive processes that drive COTS dynamics. In the COTS control program the ecological threshold is nominally the trigger for starting and stopping control activities at a site or a reef. In practice, however, the triggers used for stopping and starting control mean that the more conservative reproductive threshold is almost always achieved (Westcott et al. 2021).

4.2.1 Detection of Potential and Incipient Outbreaks

Over-arching Question: Are adult densities increasing beyond key outbreak thresholds (e.g. Rogers et al. (2017)’s 3 COTS ha^{-1}) and how are such increases distributed on reefs, across reefs and across regions?

Objectives:

a. Early detection of successful COTS recruitment and spatial distribution
b. Early detection of increasing COTS adult density and spatial distribution to trigger control.

c. Confirm existence and location of the initiation box as the source of primary outbreaks

Data Type:

d. eDNA for presence or absence at reefs and connectivity nodes
e. TUV tows – for relative adult density and distribution
f. diver searchers for juvenile density and distribution
g. cull data for adult density and distribution

Potential methods:

h. eDNA through manual surface water sampling, potentially automated or passive samplers should they be developed
i. Manta tow
j. TUV tow
k. diver based surveys, e.g. transects and plot surveys
l. field reports from stakeholders

Geographic Scope:

m. GBR with focus on Initiation and Dispersal Boxes

4.2.2 Early detection of spawning or settlement events that indicate outbreak initiation

Over-arching Question: Is a super-normal spawning event about to occur or has a super-normal spawning event occurred?

Objectives:

a. Provide early warning of impending COTS outbreak to allow for management response
b. Detection of breaches of critical spawning or settlement thresholds
c. Description of the spatial distribution of threshold breaches
d. Testing of hypotheses for outbreak initiation
e. Validating models of larval dispersal kernels

Data Type:

f. Adult densities from tow data
g. eDNA detections of larvae and settlers in traps

Potential methods:

h. Diver based surveys, e.g. transects, scooters, culling
i. Manta tows
j. TUV tows, including deep tows.
k. Vessel and fixed location automated eDNA detectors
l. Plankton tows for larvae detection and settlement traps

Geographic Scope:

m. Initiation Box
n. Dispersal Box
o. Key connectivity nodes across the Initiation and Dispersal Boxes

4.2.3 Early detection of recruitment of settled juveniles

Over-arching Question: Are cryptic juvenile densities increasing and how is this increase distributed?

Objectives:

a. Early detection of successful recruitment to sub-adult population to provide an early warning for management response
b. Confirm existence and location of initiation and dispersal boxes

Data Type:

c. eDNA
d. field survey

Potential methods

e. eDNA through manual surface water sampling, potentially automated or passive samplers should they be developed
f. fine-scale surveys

Geographic scope:

g. Initiation Box reefs

4.3 Outbreak

Once an outbreak is established and spreading, the focus of monitoring shifts from preventing an outbreak and allowing an early control response to informing the strategic implementation of the on-going management response to either stop the outbreak or to minimize its impact. In this phase the key monitoring tasks are to, i) delimit the outbreak, i.e. determine the distribution, density and structure of COTS populations, on and across reefs in the outbreak and dispersal zones, ii) monitor the dynamics in these parameters over time, iii) confirm the distribution and condition of the assets (i.e. coral assemblages) we are protecting and their priority for management, and iv) monitor control performance and outcomes.

4.3.1 Monitoring an Established Outbreak

The first monitoring tasks are the delimitation of the outbreak (describing how COTS density and size structure is distributed on and across reefs) and the description of the distribution and condition of the asset we are seeking to protect (coral cover and community composition, reef health and other attributes relevant to the prioritization of reefs for control). This work essentially represents a continuation of the collection of baseline data on condition and status of COTS, hard coral and reef health, but becomes focused on the outbreak in order to guide control operations by identifying priority sites and appropriate timing of control operations in and downstream of the outbreak. As reefs are successfully controlled, maintenance monitoring is required to ensure that subsequent re-infestation or emergence of COTS do not erode or reverse the gains made.

Over-Arching Question: How are the outbreak and assets distributed across the reef, and, how is this changing over time?

Objectives:

a. in the outbreak zone - prioritization of reefs in terms of asset value and COTS threat to inform Control Operation decisions at the voyage and fleet scale.

b. downstream of the outbreak zone - assessment of COTS and coral baselines and early detection of emerging threat for immediate and longer-term planning and decision making
c. Up-stream of Control Operations – monitoring of reefs post-management, coral recovery

Data Type:

d. COTS density and population size structure
e. Coral cover, assemblage structure and condition
f. Other reef health attributes

Potential methods:

g. Culling operations
h. Manta tows
i. TUV, including deep water tows
j. transects and plot surveys

Data Sources:

k. Control Program and Control Program Monitoring
l. Eye-On-the-Reef
m. QPWS Field Management Program
n. AIMS LTMP and MMP

Geographic Scope:

o. GBRMPA identified Priority Reefs
p. All reefs within the Initiation and Dispersal Boxes
q. Strategically sampled reefs across the rest of the GBR

4.3.2 Monitoring of Control Program Performance

Monitoring also plays a critical role in the delivery of the Control Program. It provides continuous feedback on operations allowing for effective management of voyages and of vessels, it enables assessment and refinement of the COTS IPM Decision Support Tool and the Prioritization Tool in the light of data from the field, and, it provides up-to-date information of the progress of the outbreak and the status of the reefs being managed which again allows for more effective decision making and more efficient resource use.

Objectives:

a. Provide up-to-date information on condition at controlled reefs to guide decision making
b. Provide up-to-date information on program performance to allow for refinement and improvement of program
c. Monitoring of cull

Data Type:

d. COTS densities and population size structure
e. Numbers culled/unit effort
f. Coral condition, coverage, and assemblage structure

Potential methods:

g. Culling
h. Manta tows
i. TUV tows
j. RHIS data

k. eDNA verification of cull outcomes

Data Sources: Control Program Operators

Sampling Design:

l. Cull and Monitoring sites chosen as part of the Program's Operational Strategy
m. Spatial resolution for culling and coral status is the Site and summarized at Reef scale.
n. Temporal resolution of sampling defined by the Control Program's Operational Strategy

4.4 Post-Outbreak

4.4.1 Post-outbreak monitoring

Pre- and post-outbreak monitoring are in some respects the same phase, requiring very similar monitoring approaches. The difference, however, lies in their objectives, duration and location, as well as the consequences when monitoring fails. Whereas the pre-outbreak monitoring is focused on assessing the distribution of coral condition and the drivers of COTS outbreaks, post-outbreak monitoring is focused on assessing the distribution of asset condition and the drivers of COTS decline.

Objectives:

a. Describe baselines for coral, COTS and reef communities
b. Early detection of increasing density of adults

Data Type:

c. eDNA, larval and post-settlement
d. observational studies at focal sites and reefs
e. TUV tows

Potential methods:

f. eDNA – vessel or buoy mounted detectors of adult DNA
g. TUV tow
h. transects and plot surveys
i. Manta and TUV tow
j. Diver survey

4.5 Trade-offs in the choice of Monitoring and Surveillance Tools

In designing monitoring and surveillance we quickly run up against the need to make compromises that trade-off the shortcomings of particular tools with the realities of the system in which we are working, including relevant ecological, social, logistic and economic factors. These compromises have to be made, however, in a manner that still allows us to detect the key information we require with a sensitivity and confidence that is fit for our purpose. For example, a method with desirable accuracy and precision at small spatial scales may be too difficult or costly to conduct at larger spatial scales. This may necessitate the use of a less accurate but more easily implemented method that allows for more extensive sampling. The loss of accuracy might then be accommodated in various ways, e.g. by the use of less sensitive metrics, e.g. trends or proxies rather than accurate absolute threshold estimates (e.g., Fletcher et al. 2020, Westcott et al. 2021), by harnessing larger sample sizes to achieve discriminatory power, or through the use of modelling to estimate the impact of errors on estimates (e.g., MacNeil et al. 2016, Westcott et al. 2018) or the use of multiple tools (Westcott et al. 2021). To make these compromises we need to be clear about the type of decisions that must be made, the range of information that could be used to make those decisions, the constraints associated with the monitoring methods used, and the error rates that we are willing to accept in making our decisions.

In Table 1 we outline the key decisions about management that must be made at different spatial scales based on the monitoring and surveillance of COTS. Across all scales the basic data required is the density, size structure and distribution of COTS populations, however, the accuracy and precision required in the estimate varies with the spatial scale at which the decision is made. Site-scale decisions will have finer tolerances than decisions at larger scales. In Table 1 we also provide a recommendation of the monitoring technology that is most appropriate for each decision and each scale based on the considerations in Section 3.3 and below. These recommendations have filtered a list of eight past or potential methods to just three; culling, TUV tows and eDNA tools generally.

Table 1: Management decisions required at each management scale, the required attributes of resulting metrics and recommended candidate technologies.

Scale	Decision or Information Need	Tolerances	Metrics and their attributes	Recommended Technologies
Site	Baseline and trend in density and size structure	Medium	Rapid and repeated sampling of COTS density & size structure. Rapid and repeated sampling of coral cover and reef assemblages. Estimates with good precision and accuracy or reliable indices Modelled errors for improved estimate performance.	TUV Tows
	Start control	Medium-High	Rapid and repeated sampling of COTS density & size structure. Rapid and repeated sampling of coral cover and reef assemblages. Reliable COTS estimate or proxy; can accept higher Type 1 error with very low Type 2 error. high locational accuracy	TUV Tows
	Stop control	High	COTS density estimate, requires high accuracy & precision	Culls
Reef	Baseline and trend	Medium	Rapid and repeated sampling of COTS density & size structure. Rapid and repeated sampling of coral cover and reef assemblages. Good accuracy and precision. Modelling of errors to improve estimates	Culls, TUV Tows
	Start	Medium	Estimate of COTS density relative to threshold, high locational accuracy, high Type 1 error rate is acceptable if Type 2 error rate is very low	TUV Tows, adult eDNA

			Estimates of coral cover	
	Stop	High	COTS estimate, requires high accuracy and precision, repeated sampling, high locational accuracy	Culls
Region	Status of region	Medium	COTS density & size structure. Coral cover and reef assemblages. Trends in COTS density and outbreak status Reef level locational accuracy	TUV Tows, larval eDNA adult eDNA
	Where to invest control	Medium-High	COTS density & size structure. Coral cover and reef assemblages. Outbreak detection Estimates of distribution of density and size structure across reefs. Moderate locational accuracy Rapid enough to cover large areas	TUV Tows
GBR	Status	Medium	Trends in density and outbreak status Outbreak detection, Reef and Regional level locational accuracy	TUV Tows, larval eDNA adult eDNA
	Distribution	Medium-High	Estimates of density and outbreak status at reef and regional scales	TUV Tows, larval eDNA adult eDNA

Three of the methods reviewed in Section 3.3 are not considered further, for primarily logistical reasons. Diver-based surveys are excluded on the basis that they broadly replicate the kinds of data produced by culling without necessarily providing the benefit of culling to offset the difficulties and expense of scaling them up beyond the site. While this may not be a concern, and even desirable, in the context of research, it isn't appropriate in the context of a control program. Similarly, fine-scale surveys are excluded on the basis of the very large time investments involved, the very small areas that can be assessed with those investments and the long lag before control can begin. This renders them of little pragmatic utility in the context of control. Again, this does not mean that they are not of use for specific research and control questions, it just limits their utility in the context of the over-arching control program. Finally, settlement traps that require visual inspection are cost prohibitive while those based on eDNA detections are, for the moment, considered as a special case of the use of eDNA.

The attributes of the remaining five candidate methods are summarised in Table 2. Of these we suggest that two are unlikely to have a broad role in monitoring and surveillance for the COTS control program in the long term and consequently can be ruled out of further consideration. The first of these is the use of Scooter surveys. This approach offers the potential of a method for comprehensive searches, comparable in quality to cull dives, but which can cover larger areas more rapidly, particularly when suitable habitat is sparsely distributed. At larger scales, however, while more effective in locating hidden COTS and in accessing shallow areas than TUVs, they lack key benefits offered by TUVs to a large-scale (reef, region and GBR) monitoring program, including TUV's i) potential for scaling up, ii) high quality monitoring of a broad range of additional metrics, and, iii) rapid and low cost operation.

Furthermore, unlike TUVs which replicated the manta tows currently in use, Scooter surveys require an additional set of operating guidelines and considerations. While there will be circumstances in the combined COTS control and monitoring programs where the use of scooters could be advantageous, in the context of a COTS monitoring program that already combines manta tows and cull dives, they are perhaps best considered a modification of cull dives for use in specific circumstances.

The second of the methods unlikely to be used in the medium term are manta tows. Manta tows have been central to COTS monitoring since the beginning of the LTMP program (Endean and Stablum 1973, Moran and De'ath 1992, Miller et al. 2009), and are the current mainstay of broad-scale monitoring, however, they are inaccurate and imprecise when used to estimate COTS abundance and density, providing, at best, a coarse trigger threshold estimate (Fernandes et al. 1990, Fletcher et al. 2021, Westcott et al. 2021). They will inevitably be superseded by the more rapid, more versatile and more reliable TUVs, some of which currently work at least as well as manta tow divers and in many respects are already well advanced over their human equivalents (B. Kettle, unpubl. data, M. Olsen, pers. comm.). For example, in comparison with manta tows, they survey a broader swathe, operate at greater depths and at greater speeds, they have superior detection capabilities that are relatively constant across their full field of vision, operate in a broader range of light conditions, can detect COTS with exposures as short as 0.2 sec, and crucially, have negligible observer error. Furthermore, TUVs can simultaneously monitor a broad range of additional metrics (e.g. coral cover, assemblage, fish abundance and size) and the images can be stored for subsequent re-analysis.

The three remaining methods are in various stages of development for implementation. Culling is well established and has been used in the program since its inception. The single shot technique is now so efficient that by the bulk of diver time on most cull dives is spent searching for COTS rather than injecting. Technology improvements around injection delivery systems and replacements could therefore make only minor improvements to efficiency. In contrast, technology contributions to data recording, either manual data recording, e.g. underwater keyboard input or automated data recording of some sort would improve data quality, including locational accuracy, and enhance diver efficiency. This would improve in the accuracy and reliability of the data provided by the program and should be a priority.

As noted above, TUV tows update and improve manta tow approaches by drawing on recent technological developments. These TUVs (and similar tender and surface vehichles) have already been shown to work as well in many respects as humans as observers (e.g. Vertigo3 in COTS detection, B. Kettle, pers. comm., ReefScan, M. Olsen pers. comm.) and already have significant advantages over them, e.g. depth of operation (BlueROV, Vertigo3) and speed of operation (Vertigo3). Further research and technology development in machine learning would improve AI performance and the scope of the targets assessed, e.g. coral lifeform or genus identification and cover, fish species and size measurements, as well as improving COTS detection and assessment, e.g. size estimation, rates of injury and potentially measures such as reproductive status (Kettle, pers. com.). An important area for research investment would be in data management including enabling on-water analysis and interpretation, and remote integration with decision support tools and processes.

eDNA technology for detecting larval and adult COTS has been the subject of significant research in recent years and most of the ‘proof of concept’ steps in terms of its potential in a COTS monitoring program have been successfully completed (Doyle et al. 2017, Uthicke et al. 2018, Doyle and Uthicke 2020). While there is still work to be done on refining performance for monitoring purposes, e.g. monitoring of different life-history stages, the major area for future investment would be around the operationalization of the larval and adult technologies in the context of a long-term COTS monitoring program, potentially including: developing automated sampling; analysis and interpretation processes; and development of technologies that are appropriate to the operational envelopes of the control program and its partners.

Table 2: Attributes of candidate COTS monitoring tools.

	Method				
	Cull	**Scooter**	**Manta Tow**	**TUV Tow**	**eDNA**
Detection rate	High	Medium-High	Low	Medium	High
Detection of cryptic adult COTS	High	Moderate	Low	Moderate	High
Precision (Repeatability)	Moderate – high (observer bias relevant but detectability of large COTS high)	Moderate (observer bias relevant and influenced by sampling protocol, e.g. speed, stop frequency)	Low - Moderate- (observer bias relevant, speed, fundamental detectability limits)	Very High (negligible observer error, data is stored and can be reanalysed, estimates updated)	Low – Moderate (dependent on sample size and sampling strategy. Will increase with sample size and a scale-appropriate spatial sampling strategy)
Relative accuracy (ability to detect a trend reliably)	Moderate-high (detectability good, but limited by variability in proportion of COTS visible from above and below)	Moderate - high (detectability moderate, but limited by variability in proportion of hidden COTS and proportion COTS visible from below detected)	Moderate-low (detectability low, and limited by variability in proportion of hidden COTS)	Moderate-high (detectability for COTS that are fully or partially visible from above or an angle is high, but limited by variability in proportion of hidden COTS)	High (detects signal from all COTS, both hidden and unhidden, and visible from above and below)
Absolute accuracy (ability to detect true density of COTS at reef)	Moderate-High (detects all unhidden COTS, visible from above and below)	Moderate (detects a proportion of unhidden COTS visible from above, plus some visible from below)	Very Low (little relationship between manta estimates and cull estimates. Provides a workable index)	Moderate (detects all unhidden COTS visible from above and a proportion of COTS visible from an angle, but not COTS only	Moderate - high (quantitative estimates of density can be achieved. Provides an index of abundance)

				visible from below)	
Locational accuracy	Moderate - High (could be to a few metres with new technologies)	Moderate - High	Moderate-High (records location to the individual tow path but not position on the path)	High, (± 10m, better is possible)	Low (at sub-reef scale, improves to moderate at larger scales, currents and mixing challenge reliable discernment of source)
Sampling time – Site	Dives	Dives	Minutes	Minutes	Each sample, 45 minutes
Sampling time – Reef	Days to Months	Days	Hours - days	Hours	2 sites (samples) per reef
Sampling time – Region	Months	Months	Weeks	Weeks	Days-weeks
Sampling time – GBR	Years	Years	Months - Years	Months	Weeks-Months
Information Turn Around Time	Immediate	Immediate	Immediate	Immediate	Long, samples currently require transport, lab processing and analysis. There is potential to shorten this
Post processing	Manual, minutes	Manual, minutes	Manual, minutes	Automated, minutes to hours metric dependent	Sterile lab work and analysis currently required
Depth	<15m	<15m	<15m	<60m	All depths possible but mixing may make it a moot point
Cost	High	High	Moderate	Moderate	Moderate
Additional data collected	RHIS surveys, good quality, small sample area	Coral cover & other assessments possible, medium quality, moderate coverage	coral cover, poor quality, reef scale	Broad range of coral and reef community measures possible, image-based, AI analysis, high quality, reef scale	No other information currently collected. eDNA analysis of predators, or coral and reef assemblages possible.

Table 3: Summary of the scales at which the various monitoring approaches are most likely to be applied.

Scale	Method					
	Cull	**Scooter**	**Manta Tow**	**TUV Tow**	**eDNA larvae**	**eDNA adult**
Site	X	X		X		
Reef	X	X	X	X	X	X
Region			X	X	X	X
GBR			X	X	X	X

5.0 MONITORING AND SURVEILLANCE DESIGN RECOMMENDATIONS

In the preceding sections we have outlined the monitoring information needs, how those needs and the corresponding monitoring activities might be distributed across the different phases of the outbreak, how the data might be collected, and, how that monitoring might inform and refine management decisions and actions. However, what has been presented is essentially a list of monitoring needs and methods without consideration of how they might be brought together into a coherent program. In this section we consider four options for how an Integrated COTS Monitoring Program might be structured and operate.

In developing these monitoring strategies, we have been guided by the considerations outlined at the beginning of this report. Specifically, that a monitoring program should be; i) tailored to the attributes of COTS and COTS control, ii) specific to the needs of the COTS control program, iii) conducted on temporal and spatial scales relevant to COTS outbreaks and control, iv) sufficiently accurate and precise for the needs of the program, v) cost-effective, vi) capable of being consistently applied across different phases of the outbreak and by different operators, and, vii) produce information that is readily interrogated, such that results can be produced in a timely fashion after the sampling and by the staff available. The Monitoring Program options outlined vary in the extent to which they are likely to achieve these desired attributes.

The monitoring tasks can be broken down into four broad activities, i) monitoring of pre-conditions to develop a predictive understanding of the drivers of outbreak initiation and spread, ii) detection and delimitation of initiating and established outbreaks, iii) description of asset condition and value, and iv) monitoring of control program operations. The first of these uses methods and data that are sufficiently distinct as to require independent consideration, while the latter three are sufficiently similar in terms of methods and data requirements to be considered together.

In the following sections we present four strategies for COTS monitoring and surveillance. The first strategy is squarely focused on monitoring the pre-conditions for COTS outbreaks only, while the next three strategies are focused on monitoring COTS and coral, detecting outbreaks and informing their control. These latter three strategies are designed to anticipate likely management perceptions of how COTS control should be funded. The second strategy, eDNA Only, seeks to minimise the short-term cost of the Control Program by accepting a high-risk gamble (standing down the control fleet during the Inter-Outbreak period) which, if lost, will entail high ecological costs and a low probability of successfully meeting control program objectives in the long term. The second strategy, Culling and TUV tows, is a lean program that leverages the investment in an on-going control program without significant additional cost or task demands and provides detailed guidance for decision making. The fourth strategy, combining Culling, TUV tows and eDNA, provides a comprehensive and ultimately more reliable program for monitoring and decision making. This last strategy, while the most expensive, would have the highest probability of being successful, and this greater cost would be offset by the benefits provided by an early and effective response to a future outbreak. Finally, in this section, we consider some of the associated technology and research needs associated with monitoring and control.

5.1 Monitoring of Pre-Conditions for Outbreak Initiation and Establishment

Strategy 1: Remote and Automated Monitoring of Pre-Conditions

In this first strategy we are concerned with monitoring the bio-physical and ecological conditions hypothesized to be drivers of outbreak initiation to test those hypotheses and to predict outbreak initiation. As a research approach this can be recommended but as a monitoring tool to trigger a management response it is highly risky given that it assumes that the full suite of relevant drivers are monitored and that their relative roles are sufficiently understood to allow for reliable prediction. This cannot currently be justified.
This strategy in isolation is extremely high risk and not recommended.

Goal:
Monitor bio-physical drivers of outbreaks to i) provide early warning of potential outbreak initiation based on existing hypotheses, ii) test and refine hypotheses for outbreak initiation.

Steps:

- Identify and secure access to existing remote sensing monitoring programs – RIMRep, BOM, NOAA, AIMS, etc
- Identify and secure access to existing water quality and ecological monitoring programs, RIMRep, AIMS LTMP and Water Quality Monitoring, Qld Govt water quality monitoring, IMOS, eREEFS, RIMRep Reef Monitoring, GBRMPA Field Management Program, etc
- Harvest data at appropriate timeframes – data stored for subsequent analysis
- Develop automated analyses for detection of trigger points for management response
- Automate analysis for testing hypotheses for outbreak initiation

Innovation Needs/Opportunities

- Identification of hypothesized drivers of outbreak initiation
- Development of monitoring, trigger thresholds and detection algorithms
- Design of appropriate sampling strategy.
- Automated data sourcing, preparation and interrogation
- Assessment of existing monitoring programs, e.g. RIMRep, AIMS, BOM, NOAA, Qld Govt, assessment of potential for integration of data flows from these. Ensuring existing and/or proposed programs will actually provide data that is fit for purpose.

5.2 COTS and Reef Monitoring

Strategy 2: eDNA Only Strategy

This strategy is based on the assumption that management is seeking to minimise the cost of the Control Program during the Inter-Outbreak phase by standing down the control fleet and relying on monitoring to detect an outbreak. Since Culling and TUVs rely on the same vessels and crews as the control program, this strategy could only be achieved by relying on prediction based on hypothesised pre-conditions (already considered in Strategy 1 above) or on standalone eDNA monitoring. Strategy 2 sets out a monitoring program which uses eDNA methods in isolation to provide early warning of mass spawning, monitoring of outbreak initiation and establishment. The intention is that this would allow for control teams to be stood down while the early warning would allow adequate time for securing new funding and the re-establishment of an on-water control program in time to respond effectively to the outbreak. Experience to date in COTS control and pest species management more generally in Australia indicates that this assumption is unfounded. The very long lead times in securing funding for environmental management and the similarly long lead times in implementing a coordinated and integrated program make it almost inevitable that even very early detection of an incipient outbreak will provide insufficient lead time and the resulting lag will allow the outbreak to establish and spread beyond the capabilities of even an adequately resourced control program. This is a high-risk strategy. While the short-term costs are likely to be low, the probability that it accrues very significant ecological long-term costs and ultimately fails to achieve program objectives is very high. In addition, while eDNA may provide information on increased larval COTS densities, it provides only very coarse information on adult abundance and the location of outbreaks and, currently, no additional information on other assets that might guide the implementation of a control program.

We strongly recommended against this strategy (noting that eDNA tools have utility in other strategies)

Goals:

i) detect incipient outbreaks with sufficient time to trigger a control program.
ii) allow an c. two-year timeframe to fund and establish a control program

Monitoring by Phase:

Inter-Outbreak Phase

- Fixed array of automated or hand collected eDNA sampling locations established and maintained at high connectivity locations (i.e. high chance of detection) in the Initiation and Dispersal boxes.
- Vessel-mounted automated eDNA samplers established and maintained on vessels regularly traversing the Initiation and Dispersal boxes (selected on routes traversed)
- eDNA technologies used to establish baseline and non-outbreak levels of COTS adult and larval DNA
- A network of citizen and professional scientists collecting water and plankton samples.

Initiation and Establishment Phase

- Detection of elevated adult/juvenile abundances – eDNA monitoring (vessel and fixed array of eDNA samplers) across the Initiation and Dispersal Boxes.
- Detection of settlement on and across reefs – settlement traps
- Detect recruitment and initiation – adult eDNA

Outbreak

- Delimit outbreak – vessel-based eDNA sampling, tows
- Control – any control activities will require TUV tows, manual control data to locate COTS for control so this capacity would need to be deployed at least at this stage.

Post-Outbreak

- eDNA monitors densities through decline to baselines
- TUV surveys monitor COTS adults and asset recovery

Innovation Needs/Opportunities:

- Refinement of the eDNA technology
- Development of automated interval or continuous samplers, both fixed and mobile, and for settlement traps
- Development of automated *in situ* analysis and reporting
- Design of robust sampling regimes for fixed array and vessel-based approaches in each phase of the outbreak
- Broadening of analysis and sampling to include metabarcoding coral and reef assemblage assessment

Advantages

- Enables the standing down of the control fleet during the inter-outbreak period thereby reducing costs.
- May provide time for securing funding and mounting a control program.

Disadvantages

- Relies on standing down the control fleet during the inter-outbreak period to reduced costs thereby increasing the risk of a delayed management response before the next outbreak
- Assumes that funding and implementation of a control program is possible in the period between outbreak detection and establishment
- Requires on-going support and maintenance of sampling, analysis and interpretation program. Monitoring programs are usually harder to fund than control programs.
- Time lag between eDNA data collection and information becoming available
- Provides limited information beyond bio-physical monitoring (if included in samplers) and the presence of COTS DNA.
- Provides information to trigger action but not to direct control operations at sub-reef scales, or, where there are few sampling locations per region, where in the region management is required
- Tow surveys are still required divers to confirm or locate source populations
- No data on coral cover, reef community structure or health and the distribution of these assets is collected as part of the current approach.
- Without a combination of mobile and continuous fixed sampling provides coarse-scale information only
- Fine-scale surveys are costly and high resolution limiting the scale on which they can be deployed
- Visual tow methods are subsequently still required for delimitation prior to control

Strategy 3: Cull and Tow-based Strategy

This strategy outlines a two-tier monitoring program based on TUV-tow monitoring with estimates refined by culling at sites where tows indicate COTS densities are of concern, i.e. above baselines or key thresholds. The key objective of this approach would be to detect and control COTS in locations where their densities are considered a risk and might lead to outbreak initiation. This would be achieved by conducting rapid, new-generation TUV tows during the Inter-Outbreak phase to monitor the distribution of COTS densities and COTS feeding scars across reefs and to identify locations where those densities are changing or approaching relevant thresholds, e.g. the reproductive-enhancement threshold of 3 COTS/ha^{-1} (Rogers et al. 2017) or the operational dive threshold (Fletcher et al. 2020). Such detections

would trigger an immediate management response given that cull teams are already present allowing for refinement of the estimate. Recent analyses (Westcott et al. 2021), indicate that the current control fleet's capability is sufficient to comprehensively monitor the Initiation and Dispersal Boxes, to detect population densities below <1 COTS ha^{-1}, and to mount a management response to any incipient outbreak. Additional investment, or less comprehensive monitoring in the Initiation and Dispersal Boxes, would allow for GBR scale monitoring. This would allow time for securing additional resources if necessary. This monitoring approach would allow for a broad range of additional and relevant data to be collect with no extra cost and would provide high locational accuracy.
This strategy is highly recommended if resources are limited.

Goals:

i) Detection during the Inter-Outbreak Period of increases in adult densities that could breach the reproductive threshold of 3 COTS/ha^{-1} (Rogers et al. 2017) or operational threshold (Fletcher et al. 2020), to,
ii) Trigger immediate control action to prevent densities that might breach the reproductive threshold and initiate an outbreak
iii) Maintain a standing fleet capable of continuous COTS monitoring and surveillance and of mounting an immediate COTS control response
iv) Monitoring across the entire Outbreak Cycle of contextual environmental variables, including, coral cover, coral community structure, COTS population dynamics, fish abundance and community structure,
v) Provide on-going, high-resolution reef health monitoring capacity.

Monitoring by Phase:

Inter-Outbreak Phase

- Maintain a standing fleet of control vessels in the Outbreak and Dispersal Boxes, potentially supplemented by smaller monitoring-only vessels.
- Conduct tows at reefs to provide continuous coverage of Outbreak and Dispersal Boxes
- Tows (manta or TUV) conducted on reef, lagoon and bommie perimeters and elsewhere as possible to monitor i) COTS and feeding scars, ii) coral cover and community structure, iii) indices of fish community structure, iv) other aspects of reef health.
- Deep reef TUV-tows conducted in locations modelled to have suitable deep habitat
- Detection of sites with densities of COTS approaching the reproduction threshold triggers control.

Initiation and Establishment Phase

- Tows used to delimit and monitor outbreak progress, assess asset condition, inform design of the control response at the regional scale
- Tows inform response strategy and progress at the reef scale
- Cull program data provides site level monitoring of needs and progress

Outbreak

- Tows used to delimit and monitor outbreak progress, assess asset condition, inform design of the control response at the regional scale
- Tows inform response strategy and progress at the reef scale
- Cull program data provides site level monitoring of needs and progress

Post-Outbreak

- Tows provide assessment of impact of the outbreak through asset monitoring

Innovation Needs

- Development of shallow-water TUVs with appropriate sensor and operational capabilities.
- Development of data management regimes that enable real time feedback to vessels
- Development of data management regimes that optimize information, storage and handling requirements
- Improved AI for measurement of key COTS, COTS feeding scars, and coral metrics.
- Development of data recording tools for control divers
- Development of appropriate spatial sampling strategies for each activity during each phase of the outbreak cycle

Advantages:

- Maintains a ready response for outbreaks, eliminating any delay between detection of an outbreak and the capacity to implement management
- Prevents the development of the COTS population conditions for outbreak development rather than responding an outbreak event.
- Provides rich, comprehensive and on-going monitoring of a broad range of additional reef health attributes, e.g., coral cover, community structure, indices of fish abundance and community structure, bleaching, cyclone damage, etc.
- Assessments of TUV tow data can be automated to provide rapid turnaround to the fleet.

Disadvantages

- Requires on-going funding
- TUV tows produce massive data sets, the management of which would require careful consideration
- Maintaining an operational fleet through the inter-outbreak period is costly. This cost might be offset by maintaining a minimum of control vessels (probably three or four) supplement by smaller "tow" vessels to conduct monitoring only.

Strategy 4: Combined Cull, Tow and eDNA Monitoring

This Option outlines a monitoring program that combines both cull and tow-based methods with eDNA. In this approach, TUV-tow monitoring provides a broad range of detailed monitoring data on COTS and coral condition, where indicated these estimates are refined by culling. eDNA methods would contribute to this task, particularly in terms of early warning, and would be fundamentally important in 'sentinel' and validation roles. The concept of the sentinel role would be that while TUV-based monitoring can cover the Initiation and Dispersal Boxes adequately over time, at any given point in time, its sampling is sparsely distributed, and although capable of detecting the majority of the COTS population at a given site, inevitably will miss some individuals. eDNA methods can plug this gap by sampling water flows over longer time periods that represent a much broader sampling of a region and, at a reef, detect individuals not otherwise monitored almost regardless of their location in the coral matrix. Any eDNA trigger would allow a re-focusing of TUV-based monitoring and its associated culling capability. A key objective of this approach would be to detect and prevent spawning events that might lead outbreak initiation. Monitoring during other phases would be as per the tow-based strategy but would use eDNA monitoring to validate (failsafe) tow monitoring of areas

that have been successfully controlled and are now in maintenance mode and sites assessed as not requiring culling, and to monitor spread ahead of the outbreak.
This strategy is very highly recommended and is the preferred strategy.

Goals:

i) Detection during the Inter-Outbreak Period of increases in adult densities, or the formation of adult aggregations, that could breach the reproductive threshold of 3 COTS/ha^{-1} (Rogers et al. 2017) or operational thresholds (Fletcher et al. 2020), and,
ii) Deploy eDNA at nodes of high connectivity in regions in validation and sentinel roles and to guide to tow-monitoring
iii) Trigger immediate control action to prevent densities that might breach relevant thresholds and initiate an outbreak
iv) Maintain a standing fleet capable of continuous COTS monitoring and surveillance and of mounting an immediate COTS control response
v) Monitoring across the entire Outbreak Cycle of contextual environmental variables, including; coral cover, coral community structure, COTS population dynamics, fish abundance and community structure,
vi) Use eDNA to monitor large-scale patterns of spread and regions that have been successfully controlled and are now in maintenance mode.
vii) Provide on-going, high-resolution reef health monitoring capacity.

Monitoring by Phase:

Inter-Outbreak Phase

- Maintain a standing fleet of control vessels in the Initiation and Dispersal Boxes, potentially supplemented by smaller monitoring-only vessels.
- Conduct tows at reefs in a manner that provides continuous and representative coverage of the Initiation and Dispersal Boxes
- Tows conducted on reef and bommie perimeters and elsewhere as possible to monitor i) COTS and feeding scars, ii) coral cover and community structure, iii) fish community structure, iv) monitor other aspects of reef health.
- Deep TUV-tows (acoustic and video) conducted in locations with suitable deep habitat
- Detection of sites with densities of COTS approaching the reproduction threshold triggers control.
- eDNA surveillance of larvae at sentinel sites
- post-settlement eDNA surveillance used in a sentinel approach or as a validation tool – e.g. vessel based sampling or fixed samplers located at high connectivity points along the reef.

Initiation and Establishment Phase

- Tows and eDNA (larvae and post-settlement) used to delimit and monitor outbreak progress, assess asset condition, inform design of the control response at the regional scale
- Tows inform response strategy and control progress at the site and reef scales
- Cull program data provides site level monitoring of needs and progress

Outbreak

- Tows used to delimit and monitor outbreak progress, assess asset condition, inform

design of the control response at the regional scale
- Tows inform response strategy and progress at the reef scale
- Cull program data provides site level monitoring of needs and progress
- Post-settlement eDNA to monitor spread in dispersal box and reefs that have been successfully controlled and are now in Maintenance Mode.

Post-Outbreak

- Tows provide assessment of impact of the outbreak through asset monitoring
- eDNA monitors background densities

Innovation Needs

- Development of shallow-water TUVs with appropriate sensors, operational capabilities and piloting methods
- Development of deep-water ROVs with appropriate sensors, operational capabilities (e.g. culling) and piloting methods
- Development of data management regimes that enable real time feedback to vessels
- Development of data management regimes that optimize information, storage and handling requirements
- Improved AI for detection of key COTS and coral thresholds
- Development of data recording tools for control divers
- Development of spatial sampling strategies for each activity during each phase of the outbreak cycle

5.3 Diver and Vessel monitoring tools

While overall Monitoring Program design has been the focus of this report, there remain several areas where major improvements in overall program performance could be achieved through targeted research and technology developments.

Divers

All aspects of decision making in the current COTS Control Program are fundamentally based on the monitoring data collected as part of the cull activities. While there will be a shift in emphasis to other data sources as a new monitoring program is implemented, there will remain a strong reliance on cull data collected by divers to inform decision making, e.g. number and size of COTS culled on a dive. This information is currently recorded based on the memory of divers at the end of each dive. This represents a significant opportunity for error to enter decision processes and to do so at the very beginning of the process. Developing tools that improve in-water data collection by cull divers must be an absolute priority.

Vessels

Vessel operations are major determinant of the efficiency of the control program. Data collection on vessel movements and patterns of operation may provide opportunities for streamlining activities and for sharing information across the fleet. Automated processes for collecting and reporting this information should be considered

5.4 Data Management and Analysis

The monitoring outlined in the above scenarios will inevitably result in significant data flows requiring i) appropriate curation and management, ii) analysis and interpretation, and iii) structures for feeding these analyses into the decision process. The magnitude of this task shouldn't be underestimated. For example, individual TUV-tows will be capable of collecting terabytes of data and the need to regularly transfer, curate, analyse and interpret such volumes of data will require a research focus in its own right. Similarly, amassing and managing remotely sensed and automated sampling data from a variety of sources for the analysis of drivers of outbreaks will require a specific focus.

Ensuring monitoring data and information can be curated, analysed, and shared will be necessary, at a minimum, to achieving the goals of a COTS monitoring and surveillance program. Beyond this baseline requirement, however, lies significant opportunity to magnify the impact of monitoring and surveillance beyond current practices. Providing an advanced information infrastructure would allow field data and analyses to flow between field programs, researchers and managers smoothly and automatically, in ways that tracked provenance and maintained appropriate data sharing agreements and security measures where necessary. This would reduce the time and money overheads imposed on researchers and managers seeking to leverage the intelligence provided by monitoring to build our understanding of COTS and make better decisions. Faster data sharing, analysis and interpretation would increase the speed at which we can learn about both COTS and COTS management, which would in turn accelerate future advances in COTS management on the GBR.

The costs of designing and implementing such infrastructure would be low relative to the field components of a monitoring program, but would require work to establish the institutional arrangements to underpin data sharing, and work on the technological infrastructure and systems that would facilitate data flows. To ensure tight integration with field monitoring systems, it would be vital that the design and implementation of the information infrastructure was coordinated from the very start of the monitoring program. Implemented appropriately, this relatively small investment would provide significant returns, magnifying the impact of the rest of the monitoring program, and accelerating advances in science and management.

5.5 Sampling Design

In this report we have reviewed the monitoring needs of the COTS Control Program in the light of its objectives and the tools currently available or that will be available in the near future. In doing so, however, we have not delved into the details of specific sampling designs, i.e. strategies for sampling across reefs and through time. These are critical considerations, and considerations upon which the quality of inferences derived from the program, and ultimately the utility of the monitoring and its companion control program, will ultimately hinge. Consequently, investing in research to ensure the sampling design is robust and fit for purpose is of paramount importance.

Developing the sampling design that is most appropriate for the Control Program is a significant undertaking and one that must take into account not only the management objectives but also our willingness to accept risk, the attributes of the available tools, the relevant ecological processes and logistical constraints. We have not engaged in this task here largely because to do so at this juncture would have been premature. Experimental design for monitoring requires information on the attributes and errors of each of the candidate technologies, an understanding of how errors (or biases) are influenced by sampling conditions and implementation, and how these attributes interact with the questions being addressed and the processes being monitored. While some assessments have been conducted on existing methods (e.g., MacNeil et al. 2016, Westcott et al. 2021), key new technologies, specifically TUVs and eDNA, are still in their development phases. Some assessments have been conducted for these new tools (e.g., Uthicke et al. 2018, Kettle and Babcock, public seminar 4 Feb 2021), however, these were designed to provide confidence in the tools potential rather than to act as formal assessments of their performance in a specific monitoring framework. Such assessments can be conducted in the very near future with candidate TUVs predicted to be ready for formal assessment in the third quarter of 2021 and eDNA potentially soon thereafter. Assessments of the absolute sensitivity and biases of each of the candidate tools will enable determination of how each tool can be most effectively deployed and the key thresholds that the monitoring can reliably detect and the scales at which this can be done.

While the attributes of the monitoring tools are an important consideration for monitoring design, as mentioned above, other factors also come into play. In particular, uncertainties about the relevant ecological processes, and inherent variation in the processes themselves, mean that the design processes is unlikely to be simple and the product unlikely to be a static ‘optimal’ design. Instead we might expect that it will require assessment of a range of scenarios and that the product likely to be one that is designed from the outset to accommodate this variation and uncertainty and to adapt to improved understanding over time.

To illustrate this point, we consider the example of how potential hypotheses about the underlying processes involved in outbreak initiation might result in very different patterns of COTS distribution, and require very different sensitivities and sampling strategies in order to reliably trigger a management intervention. In the first scenario we assume that outbreaks develop as a result of events at a single site. COTS females can be very fecund, producing as many as 100 million eggs in a year (Kettle and Lucas 1987, Babcock et al. 2016b). If a single or a small number of extremely fecund females at a site can trigger an outbreak, then we might expect Outbreak initiation will occur through downstream spread of initially limited geographic scope from a point source. That point source would likely be impossible to detect and the initial spread might also be challenging due to its limited distribution. Reliable early warning of such a situation might require near comprehensive and regular TUV surveys of COTS across most if not all reefs to ensure reliable detection and a regularly monitored array of eDNA sentinel sites at key connectivity nodes. A second scenario might see outbreaks develop because of environmental drivers that are distributed at regional scales, e.g. changes in water quality (Fabricius et al. 2010, Wooldridge and Brodie 2015). Under this scenario we might expect those conditions would be broadly distributed and readily detected. We might also expect to see broadly distributed changes in COTS densities across that region and through the downstream area. Reliable detection under this scenario might require relatively low intensity sampling of relevant environmental variables and of COTS themselves. In a third scenario, outbreaks develop through the dynamics of individual COTS meta-populations in an area coming into synchrony and providing a sufficient pulse of recruits to initiate the outbreak. This might occur by chance or in response to external drivers which could operate at a range of scales, including local scales. Under this scenario we might expect to see fluctuations in COTS densities and trends at sites and reefs through time but that these only presage an outbreak when local synchrony occurs. Detecting such patterns might require a design that sampled reefs comprehensively through time but sampled local areas in close temporal proximity. The monitoring design that gives the greatest chance of timely detection in or any one of these scenario might not be the same as the scenario that performs the best across all scenarios. The final choice of design would depend on the balance of costs, risks and uncertainty. The take home message, however, is that uncertainty about the processes driving outbreaks, the tools being used, and the logistics of control operations will require assessments of a range of scenarios to ensure the monitoring design offers the greatest chance of successfully detecting key triggers.

The design phase also needs to consider that a COTS Monitoring Program would not be operating in isolation. Rather, it would be building on a legacy of past and ongoing monitoring programs such as the AIMS LTMP and MMP and GBRMPA's Eye-on-the-Reef and RHIS surveys. Ensuring that an orderly transition or translation from these methods will be necessary. Similarly, opportunities for leveraging off and contributing to new monitoring programs such as RIMRep should be sought where ever possible.

6.0 SUMMARY

COTS remain a major threat to the health and dynamics of reef ecosystems on the GBR (De'ath et al. 2012, Commonwealth of Australia 2015, State of Queensland 2018, Great Barrier Reef Marine Park Authority 2019). Successful management of COTS is fundamental not only to reducing their direct impacts on hard coral cover but to the success of other reef management interventions that seek to supplement and sustain hard coral cover through the coming decades (Condie et al. 2018). Maintaining readiness to respond to COTS outbreaks, however, is complicated by the cyclic nature of their population dynamics (Uthicke et al. 2009) and the consequent, but fatally lagged, boom-bust cycle of management funding and readiness (Lassig 1993, Pratchett et al. 2014, Pratchett et al. 2017).

A lagged management response has serious consequences. Experience from a range of pest and invasive species studies, including COTS outside Australia, clearly demonstrates that intervention early in an incursion or outbreak is critical for successful management interventions (Yamaguchi 1986). Failing to act early is usually only overcome with massive subsequent investment and often depends on highly favourable circumstances, e.g. rodent eradication is almost exclusively successful on small and isolated islands (Veitch et al. 2019). Furthermore, experience from four COTS outbreaks on the GBR clearly demonstrate that management responses that are not sufficiently scaled to the scale of program objectives and which are implemented too late in the outbreak cycle are doomed to failure (Pratchett et al. 2017, Pratchett and Cumming 2019). As a consequence, while we outline a number of strategies for monitoring COTS population dynamics and reef condition, all of which would support and guide management, we strongly recommend approaches that ensure that monitoring and control capabilities are both combined and sustained.

Of the Monitoring and Surveillance strategies we have suggested, Strategy 3, based on a combination of culling and TUV surveys (replacing manta tows), represents the foundational and minimal recommended design. It is also the design onto which other monitoring components should be added subject to funding. Strategy 3 builds on the existing Control Program’s operations and capability and requires little modification of these, greatly simplifying its implementation. By focusing on the very first stages in the initiation of an outbreak and deploying technologies that maximize the resolution and scope of the data collected during monitoring, Strategy 3 provides: i) early warning of an outbreak, ii) enables an immediate management response at the earliest point in outbreak initiation that COTS are susceptible to control, iii) provides information that not only detects those very early signals but which also directs very precisely where management should be invested, iv) collects information on a broad range of contextual data that is key to decision making, e.g. asset value and distribution, reef condition, and v) has the potential to provide this information across all reefs in the Initiation and Dispersal Boxes on appropriate timeframes. In doing so it vi) maintains a standing control fleet for future outbreak response, and vii) feeds into other monitoring programs.

Strategy 4 represents the preferred and recommended strategy. It builds on Strategy 3 by employing eDNA approaches as part of monitoring but also in sentinel role and validation capacities for the tow-based Strategy 3. To do this it takes advantage of the high sensitivity of eDNA technologies to COTS eDNA in water at locations where currents maximise connectivity and therefore the extent of sampling in regions. In this manner, eDNA sampling could identify key events in COTS dynamics, e.g., larval build up, and COTS detection rates that warrant focused investigation using TUV-tows. This approach can inform on incipient outbreaks but also provide additional confidence around decisions to stop control activities at particular locations.

Should resourcing permit it, combining Strategy 4 with Strategy 1, the monitoring of bio-physical and ecological drivers of COTS outbreaks, represents the ideal approach, providing optimal surveillance to inform direct management decisions while simultaneously testing key hypotheses about the causes of outbreaks and potentially informing indirect management action. There are many synergies of this approach with other monitoring initiatives on the GBR such as RIMRep and it is likely that Strategy 1 would be best implemented as part of that program.

Irrespective of the strategy ultimately adopted in the program, the success of the COTS Control Program in achieving its objectives will ultimately be determined by the quality of the information on which decisions are made and this, in turn, will be determined by the quality of the sampling design that underpins the strategy. Funding the development of a sampling design to specifically inform COTS monitoring must be a priority.

While every opportunity to align and work with other monitoring programs should be exploited to maximum mutual benefit, the very specific data requirements and spatial and temporal scales of monitoring required for a COTS monitoring program all point to a need for a specific COTS monitoring program that, while aligned with these other programs, is fully integrated into the COTS Control Program and independent of other monitoring programs in terms of its management, funding and operations.

REFERENCES

Alexander, J. B., M. Bunce, N. J. White, and e. al. 2020. Development of a multi-assay approach for monitoring coral diversity using eDNA metabarcoding. Coral Reefs **39**:159–171.

Babcock, R. and C. Mundy. 1992. Reproductive biology, spawning and field fertilization rates of Acanthatser planci. Marine and Freshwater Research **43**:525-533.

Babcock, R., C. Mundy, and D. Whitehead. 1994. Sperm diffusion models and in situ confirmation of long-distance fertilization in the free-spawning asteroid Acanthaster planci. The Biological Bulletin **186**:17-28.

Babcock, R., E. Plaganyi, E. B. Morello, and W. Rochester. 2014. What are the important thresholds and relationships to inform the management of COTS? Draft report, 30 June 2014. Report ER, CSIRO, Australia.

Babcock, R. C., J. M. Dambacher, E. B. Morello, É. E. Plagányi, K. R. Hayes, H. P. A. Sweatman, and M. S. Pratchett. 2016a. Assessing Different Causes of Crown-of-Thorns Starfish Outbreaks and Appropriate Responses for Management on the Great Barrier Reef. PLoS ONE **11**:e0169048.

Babcock, R. C., D. A. Milton, and M. S. Pratchett. 2016b. Relationships between size and reproductive output in the crown-of-thorns starfish. Marine Biology **163**:7.

Babcock, R. C., É. E. Plagányi, S. A. Condie, D. A. Westcott, C. S. Fletcher, M. C. Bonin, and D. Cameron. 2020. Suppressing the next crown-of-thorns outbreak on the Great Barrier Reef. Coral Reefs **39**:1233-1244.

Beeden, R. J., M. A. Turner, J. Dryden, F. Merida, K. Goudkamp, C. Malone, P. A. Marshall, A. Birtles, and J. A. Maynard. 2014. Rapid survey protocol that provides dynamic information on reef condition to managers of the Great Barrier Reef. Environmental Monitoring and Assessment **186**:8527-8540.

Birkeland, C. and J. S. Lucas. 1990. Acanthaster planci: major management problem of coral reefs. CRC press, Boca Raton, Florida.

Caballes, C. F., M. Byrne, V. Messmer, and M. S. Pratchett. 2021. Temporal variability in gametogenesis and spawning patterns of crown-of-thorns starfish within the outbreak initiation zone in the northern Great Barrier Reef. Marine Biology **168**:1-13.

Claar, D. C., L. Szostek, J. M. McDevitt-Irwin, J. J. Schanze, and J. K. Baum. 2018. Global patterns and impacts of El Niño events on coral reefs: A meta-analysis. PLoS ONE **13**:e0190957.

Commonwealth of Australia. 2015. Reef 2050 Long-Term Sustainability Plan.

Condie, S. A., K. R. N. Anthony, R. C. Babcock, R. Beeden, C. S. Fletcher, R. Gorton, D. Harrison, H. A. J., E. E. Plaganyi, and D. A. Westcott. submitted. Large-scale interventions may delay decline of the Great Barrier Reef. Royal Society Open Science.

Condie, S. A., É. E. Plagányi, E. B. Morello, K. Hock, and R. Beeden. 2018. Great Barrier Reef recovery through multiple interventions. Conservation Biology **32**:1356-1367.

De'ath, G., K. E. Fabricius, H. Sweatman, and M. Puotinen. 2012. The 27-year decline of coral cover on the Great Barrier Reef and its causes. Proceedings of the National Academy of Sciences **109**:17995-17999.

Doyle, J. and S. Uthicke. 2020. Sensitive environmental DNA detection via lateral flow assay (dipstick)—A case study on corallivorous crown-of-thorns sea star (Acanthaster cf. solaris) detection. Environmental DNA.

Doyle, J. R., A. D. McKinnon, and S. Uthicke. 2017. Quantifying larvae of the coralivorous seastar Acanthaster cf. solaris on the Great Barrier Reef using qPCR. Marine Biology **164**:12.

Endean, R. and W. Stablum. 1973. A study of some aspects of the crown-of-thorns starfish (Acanthaster planci) infestations of reefs of Australia's Great Barrier Reef. Atoll Research Bulletin **167**:1-62.

Engelhardt, U. 1999. Fine-scale surveys of crown-of-thorns starfish (Acanthaster planci) in the central Great Barrier Reef region. Townsville, Australia, CRC Reef Research Centre Technical Report No. 30.

Engelhardt, U., N. Taylor, J. Brent, D. Engelhardt, M. Russell, D. Williamson, D. Wiseman, and R. Australia. 2002. Fine-scale Surveys of Crown-of-thorns Starfish, Acanthaster Planci, in the Cairns Section of the Great Barrier Reef Marine Park: Status Report 2000-01. CRC Reef Research Centre.

Fabricius, K. E., K. Okaji, and G. De'ath. 2010. Three lines of evidence to link outbreaks of the crown-of-thorns seastar Acanthaster planci to the release of larval food limitation. Coral Reefs **29**:593-605.

Fernandes, L., H. Marsh, P. J. Moran, and D. Sinclair. 1990. Bias in manta tow surveys of Acanthaster planci. Coral Reefs **9**:155-160.

Fisk, D. A. and M. C. Power. 1999. Development of cost-effective control strategies for crown-of-thorns starfish. CRC Reef Research Centre.

Fletcher, C. S., M. C. Bonin, and D. A. Westcott. 2020. An ecologically-based operational strategy for COTS Control: integrated decision making from the site to the regional scale. A Report to the NESP Tropical Water Quality Hub. Cairns, Australia.

Fletcher, C. S., C. Castro-Sanguino, S. Condie, Y.-M. Bozec, K. Hock, D. W. Gladish, P. J. Mumby, and D. A. Westcott. 2021. Regional-scale modelling capability for assessing Crown-of-thorns starfish control strategies on the Great Barrier Reef. Reef and Rainforest Research Centre Limited, Cairns.

Fletcher, C. S. and D. A. Westcott. 2013. Dispersal and the design of effective management strategies for plant invasions: matching scales for success. Ecological Applications **23**:1881-1892.

Fletcher, C. S., D. A. Westcott, H. T. Murphy, A. C. Grice, and J. R. Clarkson. 2015. Managing breaches of containment and eradication of invasive plant populations. Journal of Applied Ecology **52**:59-68.

Gardner, T. A. 2003. Long-Term Region-Wide Declines in Caribbean Corals. Science **301**:958-960.

Gladstone, W. 1993. The history of crown-of-thorns starfish controls on the Great Barrier Reef and an assessment of future needs for controls. Pages 147 - 156 *in* U. Engelhardt and B. Lassig, editors. The Possible cause and consequences of outbreaks of the crown-ofthorns starfish. . Great Barrier Reef Marine Park Authority, Proceedings of a workshop held in Townsville, Queensland, Australia.

Great Barrier Reef Marine Park Authority. 2019. Great Barrier Reef Outlook Report 2019. GBRMPA, Townsville.

Haywood, M. D. E., D. P. Thomson, R. C. Babcock, R. D. Pillans, J. K. Keesing, M. Miller, W. A. Rochester, A. Donovan, R. D. Evans, G. Shedrawi, and S. N. Field. 2019. Crown-of-thorns starfish impede the recovery potential of coral reefs following bleaching. Marine Biology **166**:15.

Hock, K., N. H. Wolff, S. A. Condie, K. R. N. Anthony, and P. J. Mumby. 2014. Connectivity networks reveal the risks of crown-of-thorns starfish outbreaks on the Great Barrier Reef. Journal of Applied Ecology **51**:1188-1196.

Hoegh-Guldberg, O. 1999. Climate change, coral bleaching and the future of the world's coral reefs. Mar. Freshwater Res. **50**:839.

Hoj, L., M. Byrne, F. Kroon, and D. Westcott. 2020. A Review of Biolgically Based Control Technologies of the Crown-of-Thorns Starfish: Options for Enhancing the Integrated Pest Management Approach. Report to the National Environmental Science Program.. Cairns.

Hughes, T. P. 2003. Climate Change, Human Impacts, and the Resilience of Coral Reefs. Science **301**:929-933.

Hughes, T. P., K. D. Anderson, S. R. Connolly, S. F. Heron, J. T. Kerry, J. M. Lough, A. H. Baird, J. K. Baum, M. L. Berumen, T. C. Bridge, D. C. Claar, C. M. Eakin, J. P. Gilmour, N. A. J. Graham, H. Harrison, J.-P. A. Hobbs, A. S. Hoey, M. Hoogenboom, R. J. Lowe, M. T. McCulloch, J. M. Pandolfi, M. Pratchett, V. Schoepf, G. Torda, and S. K. Wilson. 2018a. Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. Science **359**:80-83.

Hughes, T. P., J. T. Kerry, M. Álvarez-Noriega, J. G. Álvarez-Romero, K. D. Anderson, A. H. Baird, R. C. Babcock, M. Beger, D. R. Bellwood, R. Berkelmans, T. C. Bridge, I. R. Butler, M. Byrne, N. E. Cantin, S. Comeau, S. R. Connolly, G. S. Cumming, S. J. Dalton, G. Diaz-Pulido, C. M. Eakin, W. F. Figueira, J. P. Gilmour, H. B. Harrison, S. F. Heron, A. S. Hoey, J.-P. A. Hobbs, M. O. Hoogenboom, E. V. Kennedy, C.-y. Kuo, J. M. Lough, R. J. Lowe, G. Liu, M. T. McCulloch, H. A. Malcolm, M. J. McWilliam, J. M. Pandolfi, R. J. Pears, M. S. Pratchett, V. Schoepf, T. Simpson, W. J. Skirving, B. Sommer, G. Torda, D. R. Wachenfeld, B. L. Willis, and S. K. Wilson. 2017. Global warming and recurrent mass bleaching of corals. Nature **543**:373.

Hughes, T. P., J. T. Kerry, and T. Simpson. 2018b. Large-scale bleaching of corals on the Great Barrier Reef. Ecology **99**:501-501.

Hulme, P. E. 2006. Beyond control: wider implications for the management of biological invasions. Journal of Applied Ecology **43**:835-847.

Kenchington, R. A. 1977. Growth and recruitment of Acanthaster planci (L.) on the great barrier reef. Biological Conservation **11**:103-118.

Kettle, B. T. and J. S. Lucas. 1987. Biometric relationships between organ indices, fecundity, oxygen consumption and body size in Acanthaster planci (L.) (Echinodermata; Asteroidea). Bulletin of Marine Science **41**:541–551.

Lassig, B. 1991. Final report on the results of COTSAC management related research: 1985–1989. Great Barrier Reef Marine Park Authority, Townsville, Australia.

Lassig, B. 1993. The need for a crown-of-thorns starfish contingency plan. Pages 161 - 168 *in* U. Engelhardt and B. Lassig, editors. The Possible cause and consequences of outbreaks of the crown-ofthorns starfish. . Great Barrier Reef Marine Park Authority, Proceedings of a workshop held in Townsville, Queensland, Australia.

Lindenmayer, D. B. and G. E. Likens. 2018. Effective ecological monitoring. 2nd edition. CSIRO Publishing, Collingwood, Victoria.

MacNeil, M. A., C. Mellin, M. S. Pratchett, J. Hoey, K. R. N. Anthony, A. J. Cheal, I. Miller, H. Sweatman, Z. L. Cowan, S. Taylor, S. Moon, and C. J. Fonnesbeck. 2016. Joint estimation of crown of thorns (Acanthaster planci) densities on the Great Barrier Reef. PeerJ **4**:e2310.

Mapstone, B. D. 1995. Scalable Decision Rules for Environmental Impact Studies: Effect Size, Type I, and Type II Errors. Ecological Applications **5**:401-410.

Mellin, C., S. Matthews, K. R. N. Anthony, S. C. Brown, M. J. Caley, K. A. Johns, K. Osborne, M. Puotinen, A. Thompson, N. H. Wolff, D. A. Fordham, and M. A. MacNeil. 2019. Spatial resilience of the Great Barrier Reef under cumulative disturbance impacts. Global Change Biology **25**:2431-2445.

Miller, I. R., M. Jonker, and G. Coleman. 2009. Crown-of-thorns starfish and coral surveys using the manta tow and SCUBA search techniques. Australian Institute of Marine Sciences, Townsville.

Moran, P. and G. De'ath. 1992. Suitability of the manta tow technique for estimating relative and absolute abundances of crown-of-thorns starfish (<I>Acanthaster planci</I> L.) and corals. Marine and Freshwater Research **43**:357-379.

Ortiz, J. C., N. H. Wolff, K. R. Anthony, M. Devlin, S. Lewis, and P. J. Mumby. 2018. Impaired recovery of the Great Barrier Reef under cumulative stress. Science Advances **4**:(7), p.eaar6127.

Plagányi, É. E., R. C. Babcock, J. Rogers, M. Bonin, and E. B. Morello. 2020. Ecological analyses to inform management targets for the culling of crown-of-thorns starfish to prevent coral decline. Coral Reefs **39**:1483-1499.

Pratchett, M., C. Caballes, J. Wilmes, S. Matthews, C. Mellin, H. Sweatman, L. Nadler, J. Brodie, C. Thompson, J. Hoey, A. Bos, M. Byrne, V. Messmer, S. Fortunato, C. Chen, A. Buck, R. Babcock, and S. Uthicke. 2017. Thirty Years of Research on Crown-of-Thorns Starfish (1986–2016): Scientific Advances and Emerging Opportunities. Diversity **9**:41.

Pratchett, M. S. 2005. Dynamics of an outbreak population of Acanthaster planci at Lizard Island, northern Great Barrier Reef (1995–1999). Coral Reefs **24**:453-462.

Pratchett, M. S. 2010. Changes in coral assemblages during an outbreak of Acanthaster planci at Lizard Island, northern Great Barrier Reef (1995–1999). Coral Reefs **29**:717-725.

Pratchett, M. S., C. F. Caballes, J. A. Rivera-Posada, and H. P. A. Sweatman. 2014. Limits to Understanding and Managing Outbreaks of Crown-of-Thorns Starfish (*Acanthaster* spp.). Oceanography and Marine Biology: An Annual Review **52**:133-200.

Pratchett, M. S. and G. S. Cumming. 2019. Managing cross-scale dynamics in marine conservation: Pest irruptions and lessons from culling of crown-of-thorns starfish (Acanthaster spp.). Biological Conservation **238**:108211.

Price, M. 2018. New starfish-fighting fleet on the horizon. Press Release by The Hon. Melissa Price MP.

Reichelt, R. E. 1990. Dispersal and Control Models of Acanthaster Planci Populations on the Great Barrier Reef. Pages 6-16 *in* R. Bradbury, editor. Acanthaster and the Coral Reef: A Theoretical Perspective. Springer Berlin Heidelberg.

Rivera-Posada, J. and M. Prattchet. 2012. A review of existing control efforts for *Acanthaster planci*; limitations to successes, Report to the Department of Sustainability, Environment, Water, Population & Communities,.*in* NERP Tropical Environmental Hub, editor., Townsville, June 5 2012.

Rogers, J. G. D., E. Pláganyi É, and R. C. Babcock. 2017. Aggregation, Allee effects and critical thresholds for the management of the crown-of-thorns starfish Acanthaster planci. Marine Ecology Progress Series **578**:99-114.

Stat, M., M. J. Huggett, R. Bernasconi, J. D. DiBattista, T. E. Berry, S. J. Newman, E. S. Harvey, and M. Bunce. 2017. Ecosystem biomonitoring with eDNA: metabarcoding across the tree of life in a tropical marine environment. Scientific Reports **7**:12240.

State of Queensland. 2018. Reef 2050 Water Quality Improvement Plan 2017 – 2022 Australia.

Stuart-Smith, R. D., C. J. Brown, D. M. Ceccarelli, and G. J. Edgar. 2018. Ecosystem restructuring along the Great Barrier Reef following mass coral bleaching. Nature **560**:92-+.

Uthicke, S., J. Doyle, S. Duggan, N. Yasuda, and A. D. McKinnon. 2015. Outbreak of coral-eating Crown-of-Thorns creates continuous cloud of larvae over 320 km of the Great Barrier Reef. Scientific Reports **5**:7.

Uthicke, S., E. E. Fisher, F. Patel, B. Diaz-Guijarro, J. R. Doyle, Messmer, V., and M. S. Pratchett. 2019. Spawning time of Acanthaster cf. solaris on the Great Barrier Reef inferred using qPCR quantification of embryos and larvae: do they know it's Christmas? Marine Biology **166**:133.

Uthicke, S., M. Lamare, and J. R. Doyle. 2018. eDNA detection of corallivorous seastar (Acanthaster cf. solaris) outbreaks on the Great Barrier Reef using digital droplet PCR. Coral Reefs **37**:1229-1239.

Uthicke, S., B. Schaffelke, and M. Byrne. 2009. A boom-bust phylum? Ecological and evolutionary consequences of density variations in echinoderms. Ecological Monographs **79**:3-24.

Vanhatalo, J., G. R. Hosack, and H. Sweatman. 2017. Spatiotemporal modelling of crown-of-thorns starfish outbreaks on the Great Barrier Reef to inform control strategies. Journal of Applied Ecology **54**:188-197.

Veitch, C. R., M. N. Clout, A. R. Martin, J. C. Russell, and C. J. West, editors. 2019. Island invasives: scaling up to meet the challenge. IUCN, Gland, Switzerland.

Westcott, D. A., P. Caley, D. K. Heersink, and A. McKeown. 2018. A state-space modelling approach to wildlife monitoring with application to flying-fox abundance. Scientific Reports **8**:4038.

Westcott, D. A., C. Fletcher, D. Gladish, S. Condie, S. Uthicke, and B. R.C. 2021. Integrated Pest Management Crown-of-Thorns Starfish Control Program on the Great Barrier Reef: Current Performance and Future Potential. Report to the National Environmental Science Program.. Cairns.

Westcott, D. A. and C. S. Fletcher. 2018a. How Effective Are Management Responses In Controlling Crown-of-Thorns Starfish and their Impacts On The Great Barrier Reef? Report to the National Environmental Science Program. Reef and Rainforest Research Centre Limited. Cairns.

Westcott, D. A. and C. S. Fletcher. 2018b. How effective are management responses in controlling crown of-thorns starfish and their impacts on the Great Barrier Reef? A Report for NESP Tropical Water Quality Hub Integrated Pest Management Program. NESP Tropical Water Quality Hub, Cairns.

Westcott, D. A., C. S. Fletcher, R. Babcock, and E. Plaganyi-Lloyd. 2016a. A Strategy to Link Research and Management of Crown-of-Thorns Starfish on the Great Barrier Reef: An Integrated Pest Management Approach, Report to the National Environmental Science Programme. Reef and Rainforest Research Centre Limited, Cairns.

Westcott, D. A., C. S. Fletcher, R. Babcock, and E. Plaganyi-Lloyd. 2016b. A Strategy to Link Research and Management of Crown-of-Thorns Starfish on the Great Barrier Reef: An Integrated Pest Management Approach. Report to the National Environmental Science Programme. . Cairns.

Westcott, D. A., C. S. Fletcher, F. J. Kroon, R. C. Babcock, E. E. Plaganyi, M. S. Pratchett, and M. C. Bonin. 2020. Relative efficacy of three approaches to mitigate Crown-of-Thorns Starfish outbreaks on Australia's Great Barrier Reef. Scientific Reports **10**:12.

Williams, I. D., C. S. Couch, O. Beijbom, T. A. Oliver, B. Vargas-Angel, B. D. Schumacher, and R. E. Brainard. 2019. Leveraging Automated Image Analysis Tools to Transform Our Capacity to Assess Status and Trends of Coral Reefs. Frontiers in Marine Science **6**.

Wilmes, J. C., C. F. Caballes, Z.-L. Cowan, A. S. Hoey, B. J. Lang, V. Messmer, and M. S. Pratchett. 2018. Contributions of pre- versus post-settlement processes to fluctuating abundance of crown-of-thorns starfishes (Acanthaster spp.). Marine Pollution Bulletin **135**:332-345.

Wilmes, J. C., D. J. Schultz, A. S. Hoey, V. Messmer, and M. S. Pratchett. 2020. Habitat associations of settlement-stage crown-of-thorns starfish on Australia’s Great Barrier Reef. Coral Reefs **39**:1163-1174.

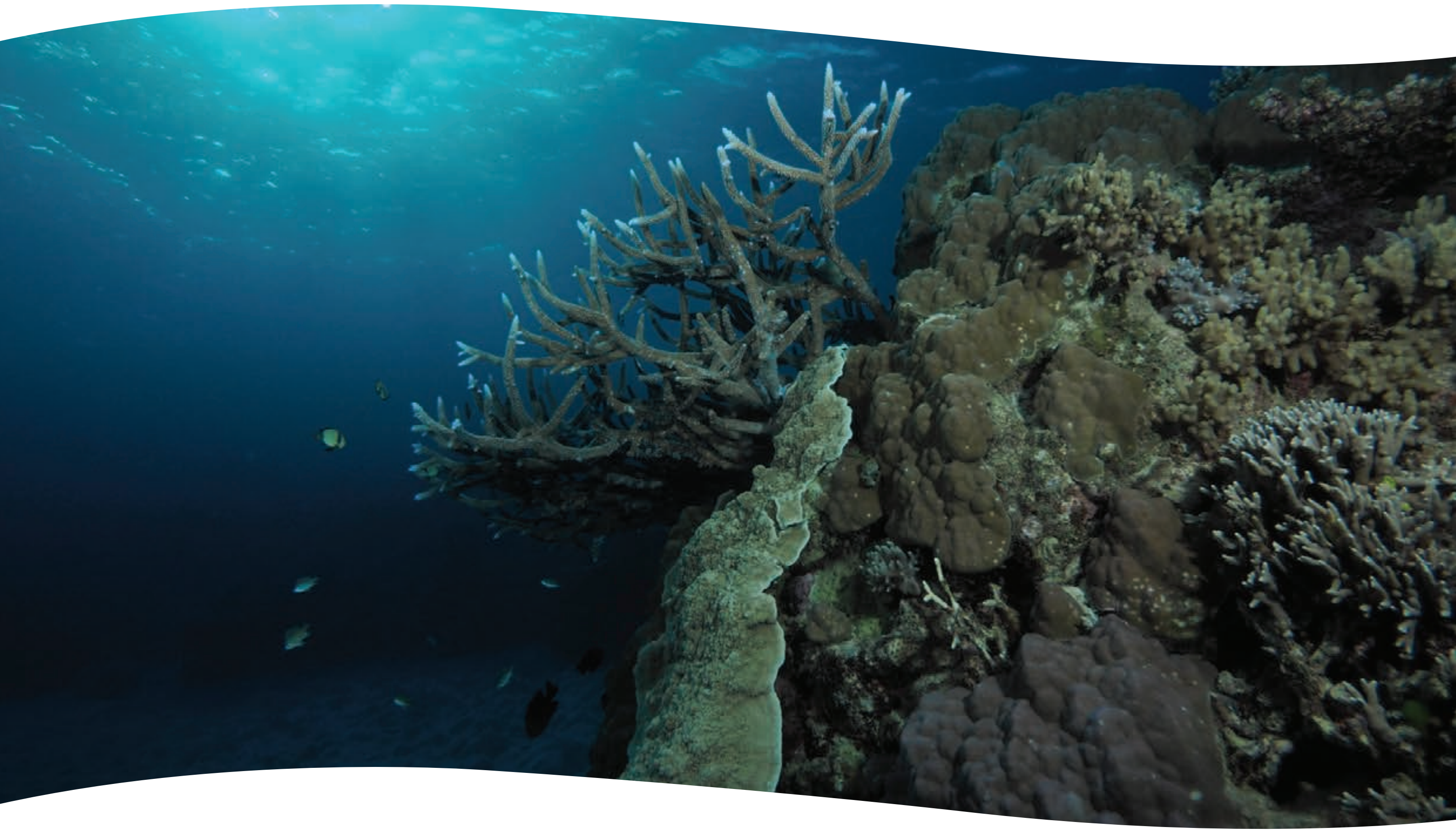
Wooldridge, S. A. 2009. Water quality and coral bleaching thresholds: Formalising the linkage for the inshore reefs of the Great Barrier Reef, Australia. Marine Pollution Bulletin **58**:745-751.

Wooldridge, S. A. and J. E. Brodie. 2015. Environmental triggers for primary outbreaks of crown-of-thorns starfish on the Great Barrier Reef, Australia. Marine Pollution Bulletin **101**:805-815.

Yamaguchi, M. 1986. Acanthaster planci infestations of reefs and coral assemblages in Japan: a retrospective analysis of control efforts. Coral Reefs **5**:23-30.

Zann, L. and K. Weaver. 1988. An evaluation of crown-of-thorns starfish control programs undertaken on the Great Barrier Reef.*in* J. H. Choat, D. Barnes, M. Borowitzka, J. C. Coll, P. J. Davies, P. Flood, B. G. Hatcher, D. Hopley, P. A. Hutchings, D. Kinsey, G. R. Orme, M. Pichon, P. F. Sale, P. Sammarco, C. C. Wallace, C. Wilkinson, E. Wolanski, and O. Bellwood, editors. Proceedings of the 6th International Coral Reef Symposium International Coral Reef Society, Townsville, Australia.

Zhai, F. G., D. X. Hu, Q. Y. Wang, and F. J. Wang. 2014. Long-term trend of Pacific South Equatorial Current bifurcation over 1950-2010. Geophys Res Lett **41**:3172-3180.



Reef & Rainforest
RESEARCH CENTRE