Tropical Water Quality Hub

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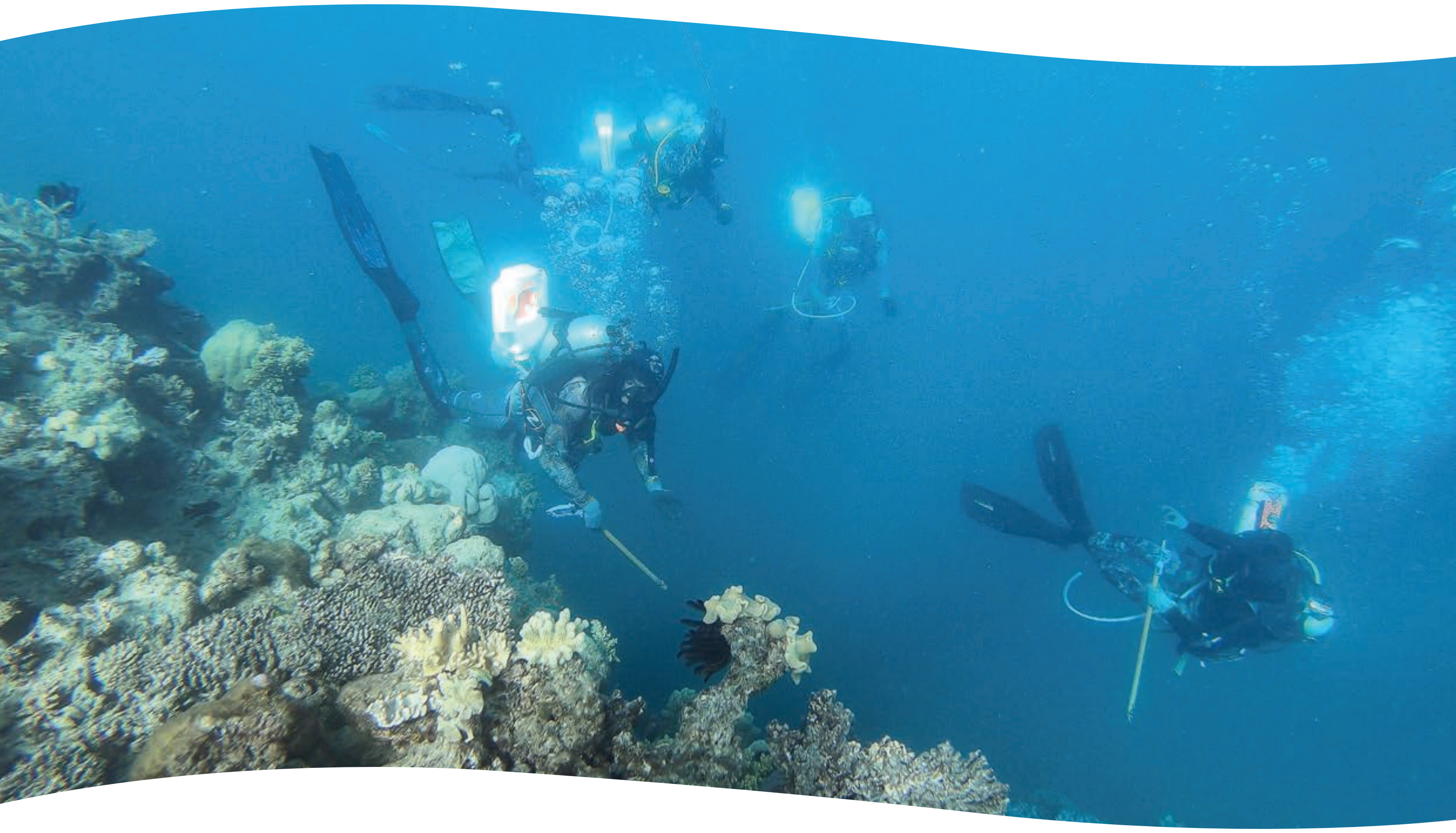
Technical Report

An ecologically-based operational strategy for COTS Control

Integrated decision making from the site to the regional scale

Cameron S. Fletcher, Mary C. Bonin and David A. Westcott



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Integrated decision making from the site to the regional scale

Cameron S. Fletcher[1], Mary C. Bonin[2] and David A. Westcott[1]

[1] CSIRO Land & Water

[2] Great Barrier Reef Marine Park Authority

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Cover photographs: COTS control by scuba (Front); Injecting a COTS (Back). Images courtesy of Cameron Fletcher.

This report is available for download from the NESP Tropical Water Quality Hub website:
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GLOSSARY

AMPTO .... Association of Marine Park Tourism Operators
Control Program..................... A coordinated COTS Control Program run on the GBR
COTS....................................... Crown-of-thorns starfish (*Acanthaster* cf. *solaris*)
COTS Control Centre .... Advanced tablet-based DSS being developed for the NESP COTS IPM Research Program
CPUE....................................... Catch-per-unit-effort, in COTS per minute bottom time
Dive .... A single control dive at a Site on a Reef, typically of 40 minutes bottom time duration
DSS.. Decision Support System
Ecological Threshold .... The COTS density below which coral growth can outpace COTS damage at a Site, in this report typically expressed in units of CPUE
Expanded Control Program ... The new Expanded Control Program run since November 2018
GBR... Great Barrier Reef
GBRMPA .... Great Barrier Reef Marine Park Authority
Historical Control Program.... The Control Program delivered between 2012 – 2018
Intensive Control.................... Reef above the Ecological Threshold, revisited frequently for cull actions
IPM.. Integrated Pest Management
Maintenance Mode .... Reef below the Ecological Threshold, revisited periodically for manta tow
NESP .... National Environmental Science Program
Priority Reef............................ A Reef selected for control actions due to its high ecological and/or economic value
Reef .... A single reef on the GBR, typically with its own unique identification code
RRRC....................................... Reef and Rainforest Research Centre
Site .... A single site on a single Reef in the GBR, typically 10ha in size
Vessel...................................... Boat of contractor employed to undertake COTS control
Voyage .... A single Control Program voyage, typically lasting 10 days
Voyage Plan .... List of Reefs, in order, to be visited on the current Voyage

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EXECUTIVE SUMMARY

This report outlines an ecologically-informed framework for the management of day-to-day operations of the Expanded Crown-of-Thorns Starfish (*Acanthaster* cf*. solaris,* hereafter COTS) Control Program on the Great Barrier Reef. This framework links COTS ecology to Control Program decisions by providing a structured decision process within and amongst reefs in a local area of control vessel operation. It does this based on specified priorities at the regional scale over a single year and multi-year resourcing constraints across the GBR. The framework leverages our best current understanding of the management and ecological processes driving the system and, importantly, is also designed to collect information at management-relevant scales to fill key knowledge gaps and improve the performance of the Control Program in future.

The primary goal of COTS control is the mitigation of COTS impacts on natural coral dynamics. On short timescales, this requires that COTS populations are reduced to a density where the amount of coral consumed is less than or equal to the amount of coral that regenerates through growth. It has been estimated that this Ecological Threshold in COTS density is reached when control actions achieve a Catch-Per-Unit-Effort (CPUE) of 0.04 COTS per minute dive bottom time in locations where coral cover is lower than 40%, and 0.08 where coral cover is greater than or equal to 40% (Babcock et al., 2014).

The key principles of ecologically informed management and control at the local scale of Control Program vessel operations are that effort will be focused on ecologically or economically important Priority Reefs, and that: 1) these Reefs will be managed as a whole; 2) once Intensive Control at a Priority Reef is started, it will be continued until the Ecological Threshold has been reached and the Reef is moved to Maintenance Mode; and 3) only then will those Control Program resources be redirected to another nearby Priority Reef. Periodic manta tow surveillance will be used to structure control actions during intensive culling at a Reef and, once COTS density at the Reef is reduced to the Ecological Threshold, to ensure that density is maintained.

This report describes three decision trees designed to ensure that key decision making processes in the Expanded COTS Control Program are informed by these ecological principles. The first two decision trees are designed to inform day-to-day decisions made on-water during a scheduled Voyage, based on the status of the Reef being controlled, prior information collected during previous Voyages, and new information collected once staff arrive at the Reef. The final tree is designed to aid managers in choosing how to sequence on-water control actions across the portfolio of Intensive Control and Maintenance Mode Reefs as COTS densities change as a result of Control Program activities.

The decision trees are designed to ensure that an ecologically meaningful outcome will be reached at every Priority Reef that is actioned by the Control Program. They couple Reef-scale manta tow surveillance with Site-scale intensive cull to efficiently reduce COTS densities at a Priority Reef as quickly as possible. They automatically scale the scope of management within each region of the GBR to the scale of the COTS outbreak there, ensuring that management resources are never stretched across so many Reefs that control becomes ecologically ineffective. They provide checks and balances to compensate for uncertainty and ensure that when ecologically meaningful outcomes are achieved at a Reef, they are maintained over time.

The first of these decision trees was rolled out to managers in mid-2018 and on-water operators in late-2018. The first eight months of data from the Expanded Control Program show that the decision criteria being employed in the process are reliable. The analysis also shows that the decisions being recommended by the simplified decision tree process have led to desired outcomes in terms of recommending where on-water vessel operators should target their activities, adaptably covering Priority Reefs identified by GBRMPA in each region, and in reducing COTS densities at managed Reefs. Finally, the data show that the simplified decision tree process has also been successful when it has been implemented in regions with very low COTS densities, such as those that may be found in the initiation box prior to a new primary outbreak. This report outlines the ecological foundation of the Integrated Pest Management (IPM) approach to the control program and how this has been used to structure the decision trees, reflects on refinements implemented following feedback from reef managers and on-water operators, and provides key recommendations for the current and future implementation of the Expanded Control Program.

GBRMPA's *Integrated Pest Management Operations Manual for Crown-of-Thorns Starfish Control Program Vessels* (GBRMPA, unpublished) is a companion publication to this report and its guidelines have been developed in the light of the strategy outlined in this report.

1.0 INTRODUCTION

Crown-of-Thorns Starfish (COTS) are one of the major threats to coral on the Great Barrier Reef (GBR) and around the globe (Bruno & Selig, 2007; De'ath, Fabricius, Sweatman, & Puotinen, 2012; Pearson, 1981; Pratchett, Caballes, Rivera-Posada, & Sweatman, 2014; Yamaguchi, 1986). They have been estimated to be responsible for 42% of coral loss across the GBR between 1985 and 2012 (De'ath et al., 2012). However, unlike the other identified significant threats to coral reefs, such as cyclone damage (Gardner, Côté, Gill, Grant, & Watkinson, 2003; Pratchett et al., 2014) and bleaching (Claar, Szostek, McDevitt-Irwin, Schanze, & Baum, 2018; Hoegh-Guldberg, 1999; Hughes, 2003; Terry P. Hughes et al., 2018; Hughes, Kerry, & Simpson, 2018), COTS can be managed to provide immediate protection of coral on the GBR (Westcott & Fletcher, 2018). This makes an effectively structured and coordinated COTS management strategy a key component of any strategy aiming to conserve coral cover on the GBR over short, medium and long timescales (Westcott, Fletcher, Babcock, & Plaganyi-Lloyd, 2016).

Accordingly, significant resources have been invested in attempting to reduce COTS populations across the GBR (Gladstone, 1993; Price, 2018; J Rivera-Posada & Prattchet, 2012; Westcott et al., 2016). The primary direct method of COTS control on the GBR is, and for the foreseeable future will remain, manual culling of individual starfish by divers (Firth & McKenzie, 2015; Westcott et al., 2016). Manual control has been employed at local scales at key reefs or dive sites on the GBR since the 1960s, with varying levels of success (Gladstone, 1993; Pratchett et al., 2014; J Rivera-Posada & Prattchet, 2012; Westcott & Fletcher, 2018). Beginning in 2012, the first coordinated and strategic manual Control Program was launched on the GBR, with a dedicated vessel working to protect coral from COTS impacts at high value tourism sites. An evaluation of the data collected from that initial Control Program showed that manual control could be effective at reducing COTS densities and their impacts on coral at these sites (Westcott & Fletcher, 2018). In 2018, the Australian Government provided funding to expand the Control Program, in recognition that COTS control provided a feasible on-water action to enhance the resilience of the GBR (GBRPMA, 2017; Price, 2018). This has allowed the control fleet to expand to six vessels during 2018 - 2019, significantly increasing the potential for achieving program objectives at larger spatial scales. However, the extent of COTS damage across the GBR still far exceeds the resources available to manage it, a common situation in pest management. Making the most of the resources available for COTS control requires that efforts are invested in high priority locations at an intensity that allows an ecologically meaningful reduction in coral damage to be achieved, and that decisions made across the fleet are underpinned by a solid ecological understanding of the system being managed (Westcott et al., 2016).

The goal of this report is to lay out an ecologically-informed decision making framework for the new Expanded Control Program. The key principals and decision tree process were developed in consultation with reef managers in mid-2018, provided to on-water COTS control vessel operators when the expanded program was mobilised in late-2018, and have since been refined in response to their feedback. Section 2 of the report describes three decision trees to inform decisions at the local area, reef and site scales during a scheduled Voyage. These decision trees represent a staged and adaptive approach to the development of the Expanded Control Program's operations. The first is a simplified decision tree to inform day-to-day on-water management decisions without requiring detailed analysis, based on the ecological status of a Reef, data from previous Voyages, and information collected during the current Voyage. This is the decision tree that has informed the Expanded Control Program since it began, and which has been incorporated into GBRMPA's operational guidelines for the Control Program (GBRMPA, unpublished). This approach is then refined to propose an advanced on-water decision tree, incorporating detailed computational analysis and adaptive management, and a separate voyage planning decision tree. These are designed to be implemented via the COTS Control Centre tablet-based Decision Support System over the coming months. In Section 3, we analyse the first eight months of data from the Expanded Control Program, which has run using the simplified on-water decision tree, to examine the reliability of the criteria used to make key decisions and to assess how the program has reduced COTS populations at reefs. Section 4 reflects on these results and incorporates feedback from on-water control staff to present a series of recommendations for managers. Finally, Appendix 1 presents a detailed example of how the decision tree has informed on-water decisions and management actions at John Brewer Reef.

A note on terminology: where words such as Reef, Site, Dive, and Voyage appear capitilised throughout this report, they refer to their formal definition in the context of the decision tree framework, as defined in the Glossary at the beginning of this document.

1.1 Recent historical context (2012 – 2018)

Between 2012 and 2018, on-water COTS control was implemented on the GBR by the Association of Marine Park Tourism Operators (AMPTO) (Firth & McKenzie, 2015), coordinated by the Great Barrier Reef Marine Park Authority (GBRMPA) and the Reef and Rainforest Research Centre (RRRC). Over this time, AMPTO operated either one or two vessels, depending on funding availability. Each vessel typically completed 25 ten-day voyages per year, each consisting of up to 36 cull dives. Voyages visited established "control sites" at reefs across the Cairns region of the GBR. Control sites were located at specific locations on economically or ecologically important reefs and invariably represented a small proportion of the total area of any reef. The target area of each voyage was planned up to a year in advance in conjunction with GBRMPA and RRRC, and the reefs visited within that local area were determined by the on-water operators during the voyage.

The historical Control Program was based around dives of 40 minutes bottom time duration up to a maximum depth of 15 m, for logistical and Occupational Health and Safety reasons (Firth & McKenzie, 2015). Historical Control Program data suggests that the associated spatial scale for a single dive was approximately 450 m of reef edge. COTS were culled at each site by a dive team of 4 – 8 people using single-shot bile salt injection technique (Firth & McKenzie, 2015; J. A. Rivera-Posada, Pratchett, Cano-Gómez, Arango-Gómez, & Owens, 2011). During COTS cull activities, every COTS encountered by dive crews was injected (Firth & McKenzie, 2015).

Analysis of historical Control Program data suggests that control was effective at sites that were visited intensively (Westcott and Fletcher 2018). That study found that sites that were visited more frequently had higher coral cover at the end of the program, and sites that received more control were more likely to show larger and positive changes in hard coral cover. However, at sites that were visited infrequently, data and on-water crew experience showed that COTS catch-per-unit efforts persisted at levels almost as high as prior to culling, and that coral cover tended to decline (Westcott & Fletcher, 2018). This suggests that effective control at a site benefited from repeated intensive revisitation.

1.2 Overview of an ecologically-informed underpinning for control

The ecologically-informed approach to COTS control outlined in this document is based on a set of principles derived from analysis of the historical Control Program, and the ecological and management dynamics of COTS populations and control actions. These principles and the logic that drives them can be summarised as seven broad rules-of-thumb:

Prioritise Reefs for control: The scale of COTS outbreaks on reefs across the GBR far exceeds the resources that are available, so it is necessary to prioritise a subset of Reefs for management. The identity of these Reefs and the order in which they are managed should be determined from regional management priorities based on protecting key ecological (coral sources) and economic (tourism sites) assets, and disrupting the spread of COTS larvae on ocean currents by controlling reefs that are important sources of COTS larvae. In order to generate ecologically meaningful outcomes, the number of Reefs under active control at any point in time should be limited to a number that can be comprehensively managed with the Control Program resources available. This is achieved automatically in the decision process outlined below, which scales the number of Reefs managed by the Control Program to the resources available.

Cull entire Reefs: Once Priority Reefs are identified, they should be managed at the whole-of-reef scale. Our understanding of how ocean currents distribute larvae between reefs on the GBR is currently modelled between entire reefs, and we do not yet have detailed sub-reef scale habitat data, nor detailed habitat preference data that would allow us to estimate where COTS were likely to aggregate within a Reef, nor how fast they may move between different parts of a Reef. This means that each high Priority Reef selected for control should be controlled across its entire extent, not just at one or two high value Sites on the Reef, until the COTS densities at all Sites are reduced below ecologically meaningful thresholds.

Prioritise Sites at Reefs: Although we cannot currently predict where exactly COTS will congregate on a Reef, we can be certain that they will aggregate. Historical Control Program data shows that sub-reef COTS aggregations are often highly localised, and that the efficiency of control actions is largely determined by how effectively these aggregations are located and targeted for cull (Fletcher & Westcott, 2016). High density aggregations of COTS can be efficiently located using manta tow surveillance (Fletcher & Westcott, 2016). Reefs under control should be periodically manta towed and control actions targeted at the Sites with the highest density aggregations on a reef, gradually moving cull efforts towards progressively lower density Sites until the whole Reef is maintained below Ecological Threshold densities. Operationally, a Reef-scale manta tow threshold below which no cull is considered necessary is also implemented: that no COTS or COTS scars are detected across manta tows encompassing the entire circumference of the reef (GBRMPA, unpublished).

Cull Sites to below the Ecological Threshold: Mitigating the impact of COTS on coral cover requires that COTS densities are reduced to a point where the amount of coral they consume is less than or equal to the amount of coral that regenerates through growth. It has been estimated that this Ecological Threshold is reached when control activities exhibit a Catch-Per-Unit-Effort (CPUE) of 0.04 COTS per minute dive bottom time on Reefs where coral cover is lower than 40%, and 0.08 where coral cover is greater than or equal to 40% (Babcock et al., 2014). On any one Voyage, each Site that is dived should be controlled until there are no COTS available to cull. The total number of COTS controlled at a Site during the Voyage should then be used to provide the most up-to-date estimate of CPUE to inform decisions about subsequent control requirements. Sites and Reefs may need to be managed repeatedly until these ecologically-informed CPUE thresholds are achieved.

Revisit at Voyage intervals: To minimise coral loss once control actions begin, Reefs under Intensive Control should be revisited as frequently as operational considerations allow – every Voyage if possible. Sites within a Reef that are above the Ecological Threshold should be re-culled frequently, while allowing sufficient time for previously culled COTS to disintegrate (Firth & McKenzie, 2015; Jairo Rivera-Posada, Caballes, & Pratchett, 2013), and for cryptic individuals inaccessible during the prior cull to emerge. Current data indicates that these processes are likely to occur over a period of several to c. 10 days.

Maintain surveillance after Ecological Threshold reached: Even once a Reef has been reduced to below the Ecological Threshold, surveillance needs to continue to detect possible re-emergence of COTS at densities higher than the Ecological Threshold. Current control methods cannot access deep water below 15m (Westcott et al., 2016), and cannot reliably detect small COTS with the same certainty as large COTS (MacNeil et al., 2016; Westcott & Fletcher, 2018). Current ecological knowledge of COTS movement and behaviour at scales relevant to management is limited (Bos, Gumanao, Mueller, & Saceda-Cardoza, 2013; Pratchett et al., 2017). This critical maintenance surveillance step ensures that the long-term ecological goals of the program can be maintained, despite limitations in our current control methods, and uncertainties in our ecological understanding of the system. Ongoing surveillance also improves understanding and appropriate response to other impacts to coral cover (e.g. cyclones, bleaching) that may occur on Reefs where COTS are being controlled. The data collected will be used to improve control activities in future.

Collect data: The largest source of data on COTS abundance and distribution and the effectiveness of control actions now comes from the Expanded Control Program itself. This data must be systematically and rigorously collected and curated, actively analysed to update empirical estimates of the key parameters that inform decision points, and used to assess Control Program performance. This approach can be improved significantly using an adaptive management framework that temporarily uses intensive structured monitoring on some of the Reefs being controlled to gain better insights into the outcomes of control. The decision process laid out below is explicitly designed to simultaneously use our best management-ecological understanding of the system as it stands now, and collect the data we need to improve our understanding of key management relevant drivers of COTS population dynamics into the future.

1.3 The decisions that need to be made

Based on the ecological and management drivers outlined above, there are several temporal and spatial scales at which decisions need to be made by different decision makers in the system. These scales can be broadly characterised as:

i) the GBR / entire Control Program scale,
ii) the region / Control Program Vessel scale,
iii) the local area / Voyage scale,
iv) the Reef scale,
v) the Site / Dive scale.

In this document we lay out a structure for making ecologically informed decisions at the v) Site / Dive; iv) Reef; and iii) local area / Voyage scales, given specified priorities and constraints at the ii) regional / Control Program Vessel scale, and the GBR / entire Control Program scale.

These priorities and constraints include overall resourcing constraints, which determine the total number of Control Program Vessels distributed across the GBR. They also include the region in which each Vessel operates and the Priority Reefs to be managed within each Region. These decisions at the GBR and regional scale will be informed by NESP4 and NESP5 COTS IPM Research Programs (Westcott & Fletcher, 2019; Westcott et al., 2018). Informing the selection of Priority Reefs within each region has been a primary goal of the NESP3 COTS IPM Research Program (Westcott et al., 2017), and the expertise from this effort has already been incorporated into priority lists developed by GBRMPA. Further work on how best to distribute Vessels across a suite of Priority Reefs is a topic of ongoing research. The current document does not delve into the details of how this prioritisation list is developed; it simply assumes that GBRMPA managers have supplied a list of Priority Reefs to be managed within each Region.

For the sake of simplicity, the decision trees presented below focus on the decisions that must be made for the operation of a single Vessel, assuming that Vessels are operating on an assigned set of Reefs unique to that Vessel. This matches how Vessels have been assigned to regions in the current iteration of the Expanded Control Program. However, the underlying ecological-management principles presented are general, and could be readily adapted to coordinate flexible actions across a fleet of Vessels operating across a common set of Reefs, as discussed in the recommendations to managers at the end of the report.

With the structure laid out above, there are two levels of decisions remaining to implement the Expanded Control Program in an ecologically-informed manner:

i) the decision about how frequently Vessel Voyages should revisit each Reef; and
ii) the decision about how to carry out control actions once a Vessel arrives at a Reef

In addition, there are two qualitatively distinct “Control Program” states a reef can be in:

i) Intensive Control Mode while COTS densities are above the Ecological Threshold
ii) Maintenance Mode once COTS densities have been reduced below the Ecological Threshold

The decision trees provide an ecologically-informed framework to address these decisions, a structure to ensure that the data to inform these decisions can be collected at the scales required, and a logical sequence to ensure that ecologically-meaningful outcomes are achieved.

2.0 THE DECISION TREES

The decision making process may be structured as a “tree” that presents a flow of data collection, analysis, decision points, and resultant actions (Fig. 1). The tree structure ensures that the sequence of these events proceeds in a consistent order, while the fact that management continues until each Site is measured to drop below the relevant Ecological Threshold guarantees that the outcome is ecologically meaningful.

The tree structures developed below are designed to be logically complete, in that if they were followed explicitly, the deterministic outcome would be a series of controlled Reefs with COTS densities below the Ecological Threshold at which, all else being equal, coral growth would outpace COTS damage. In the real world, however, decision making is hampered by uncertainty. There are three key types of uncertainty in the COTS control system: uncertainty in sampling techniques; uncertainty in the effectiveness of control actions; and uncertainty in our knowledge of the ecological processes that drive COTS population dynamics.

The decision trees provide a framework for responding to these uncertainties and ensuring that ecologically informed decisions can be made in spite of uncertainty. They do this by ensuring that the necessary data is collected to inform decisions at the time and place that they need to be made, by collecting both fine scale (cull) and whole-of-reef (manta tow) surveillance estimates at ecologically meaningful intervals relevant to decision making (Fletcher & Westcott, 2016), and by only ceasing active control actions at a Site once it is observed that COTS densities there are below the Ecological Threshold (Babcock et al., 2014).

Furthermore, although there are a range of ecological processes which we know must occur in the managed populations, such as movement of COTS within Reefs over time and the emergence of cryptic individuals within a Site following control actions, there currently exist no reliable estimates of the relative scale of these processes at the time and spatial scales relevant to the Control Program (Westcott et al., 2016). Field studies as part of the NESP COTS IPM Research Program aim to improve our fundamental ecological understanding of these processes (Westcott et al., 2017), but the data collected by the Control Program itself can be used to provide preliminary estimates and, more importantly, make the ecologically-informed decisions required to coordinate the Control Program at the day-to-day level.

This approach combines the principles of targeted data collection to inform decision making in the short term, with an adaptive management approach that both allows us to improve the efficiency of the Control Program and better understand the system we are managing over the medium term. The simplified on-water decision tree facilitates ecologically-informed decision making using targeted data collection focussed on key processes, without requiring detailed analysis of the data collected on-water. The full decision tree process includes adaptive tuning of three key parameters of the Control Program to generate optimal ecological effectiveness and management efficiency based on the data collected by the Control Program itself.

2.1 A simplified on-water decision tree for manual implementation

The simplified decision tree is designed to be implemented immediately and manually (i.e. without the use of bespoke software) by on-water Control Program Vessel operators. It employs simplified decision points and uses Control Program data directly, rather than requiring detailed analysis prior to decision making. This is the decision tree that has informed the new Expanded Control Program from mid-2018 up to the current time.

Figure 1 defines a decision tree to ensure that the decisions that must be made during a Voyage are made in a manner that is: 1) consistent with ecological principles, in that Reefs are managed as-a-whole and COTS densities are reduced to meaningful Ecological Thresholds; 2) efficient, in that the Sites with the highest density aggregations of COTS are managed first to protect the greatest amount of coral; and 3) rigorous, in that COTS densities are monitored over time and this information is used to update control tactics.

Each Vessel is provided with a list of Priority Reefs for their region by program managers at the GBRMPA. The GBRMPA program managers also provide named Site polygons in a KML file that encompass the circumference of each Priority Reef. When the Control Program began in mid-2018, all Priority Reefs were in Intensive Control management mode, but control actions can move a reef from Intensive Control to Maintenance Mode by either: 1) completing a comprehensive manta tow survey showing that no COTS or COTS scars are detected around the circumference of the reef (GBRMPA, unpublished); or 2) controlling all Sites around the reef in which manta tows detected COTS or scars, until the CPUE at each is below the Ecological Threshold (Babcock et al., 2014).

By the time it is leaving port, a Vessel will have an agreed Voyage Plan, which is determined in consultation with program managers at the GBRMPA based on review of data from the set of potential Reefs to be visited by that Vessel. The Voyage Plan defines which Reefs are to be visited during the Voyage, and in which order. The order is based on operational constraints (related to, for example, weather forecasts), and the following rules-of-thumb: Maintenance Mode Reefs requiring manta tow are visited first; then Intensive Control Reefs at which control actions have already begun are visited in the order that control actions began there; and if control actions at all those Reefs are completed during the Voyage, then control begins at an operationally accessible, Intensive Control Priority Reef at which control actions have not yet begun.

If the first Reef to be visited is a Maintenance Mode Reef that requires manta tow surveillance, the on-water decision process is relatively direct: travel to the Reef, manta tow the entire circumference of the Reef; if any sign of COTS is detected in any individual manta tow, move the Reef from Maintenance Mode to the top of the Intensive Control list; and in either case, update the most recent date of manta tow and move to the next Reef on the Voyage Plan.

If the first Reef to be visited is an Intensive Control Reef that has never been visited for control previously, or if it has been visited for control previously but the last manta tow at the Reef was performed more than 42 days ago, then the Vessel begins by performing a comprehensive manta tow around the circumference of the Reef. If no sign of COTS is found across any manta tow, the Reef is moved from Intensive Control mode to Maintenance Mode; and in either case, the most recent date of manta tow is updated and the Vessel moves to the next Reef on the Voyage Plan.

If COTS are detected during the manta tow of the entire Reef, then any Site at which COTS were detected is targeted for control. This can be summarised as the rule “Dive a Site if one or more COTS or feeding scars are observed”. The Site with the highest number of COTS detections is controlled first. A crew Dives at the Site, starting at one end of the Site and comprehensively searching the Site, injecting any COTS they detect. If they don’t reach the other end of the Site in a single 40-minute bottom time dive, they perform further Dives there until they have covered the entire Site or run out of Dives on the current Voyage. Once the Site has been comprehensively covered by a dive team, divers are redirected to the Site on the Reef with the next highest manta tow COTS detections.

Divers continue culling at all Sites on a Reef at which COTS were detected during the manta tow until either every such Site has been culled, in which case the Vessel moves to the next Reef on the Voyage Plan, or until it is time to return to port. If all Sites on a Reef at which COTS were detected during the manta tow are culled and achieve CPUEs less than the Ecological Threshold, the Reef is moved from Intensive Control to Maintenance Mode, otherwise it remains in Intensive Control mode.

If the Reef being visited is an Intensive Control Reef that has been manta towed within the past 42 days, then no new manta tow is required, and divers begin culling: first, at any Site that was only partially completed during the previous Voyage; then at the Sites controlled during the previous Voyage for which the CPUE was above the Ecological Threshold, starting with the Site that produced the highest CPUE; and finally at any Sites that were not previously visited (due to the Voyage ending), but at which COTS were detected during the previous manta tow. Again, once every such Site has been culled, the Vessel moves to the next Reef on the Voyage Plan, and if all Sites on a Reef at which COTS were detected during the manta tow are culled and achieve CPUEs less than the Ecological Threshold, the Reef is moved from Intensive Control to Maintenance Mode.

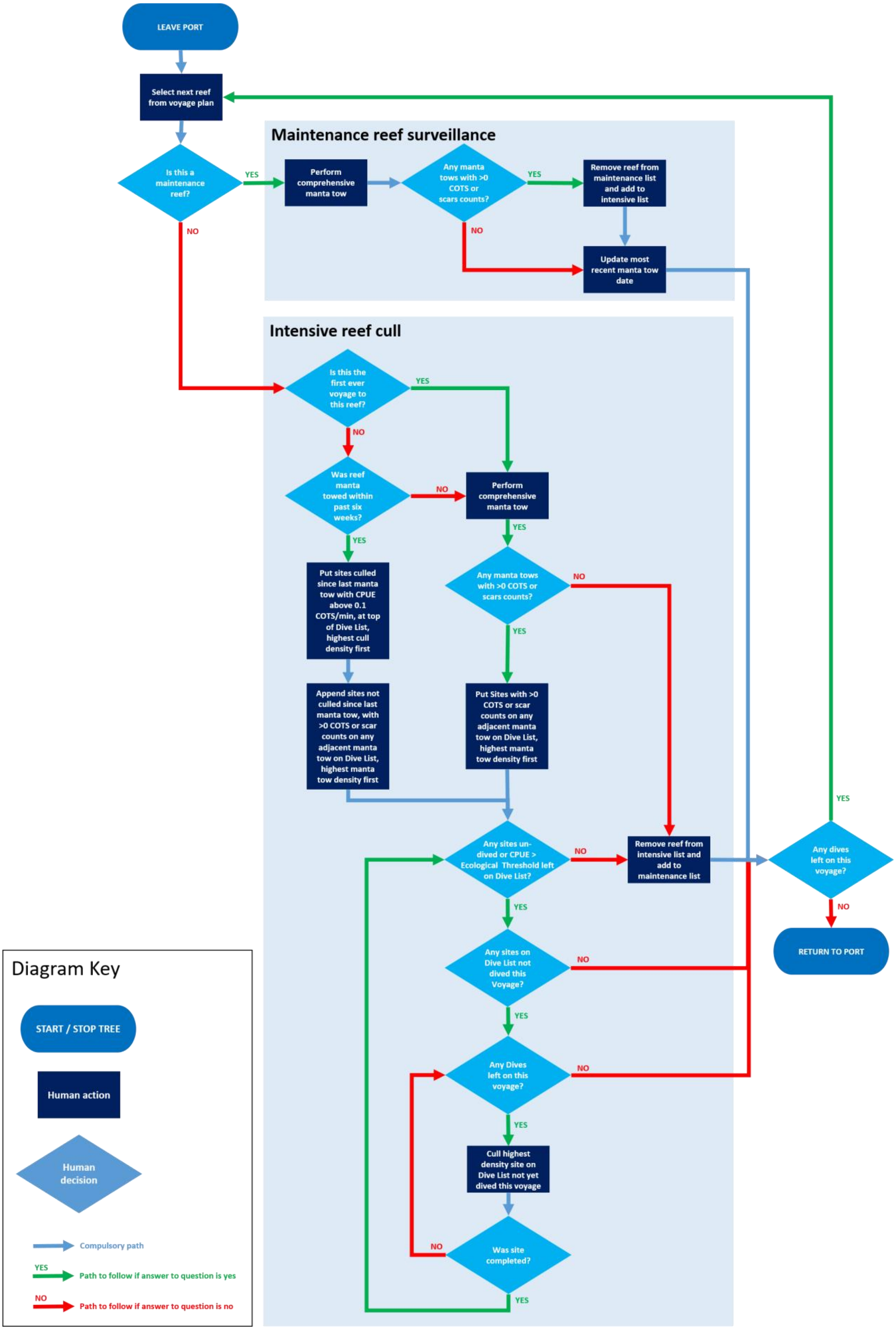


Figure 1: The simplified on-water decision tree

2.2 An advanced on-water decision tree leveraging data analysis and adaptive management

The decision tree illustrated in Figure 1 employs a number of simplifications to provide actionable rules-of-thumb and simplify decision making on-water without requiring detailed data analysis. It provides a decision flow that, if implemented rigorously, will guarantee ecologically meaningful outcomes at the Reefs controlled. On the other hand, it is possible to structure a more efficient local scale management program using a less simplified ecological underpinning and a combination of advanced analysis and adaptive management. This approach requires a decision support system (DSS) capable of coordinating and analysing Control Program manta tow and cull data as it is collected across the fleet of control Vessels operating within a region. This advanced decision tree approach is being delivered as part of the COTS Control Centre under the NESP COTS IPM Research Program (Westcott & Fletcher, 2019).

This DSS system will facilitate two key improvements. First, it will use adaptive management to refine three key adaptive management variables: a) the optimum amount of time between manta tows of Maintenance Mode Reefs; b) the optimum amount of time between manta tows of Intensive Control Reefs; and c) the optimum time between subsequent Dives at Sites. Second, it will use ecological modelling and analysis of Control Program data to select which Sites should be managed by simultaneously analysing manta tow and cull data between the time Intensive Control begins at a Reef and the time it is moved to Maintenance Mode. Implementing this DSS requires advanced analysis and computational capacity on-water, but this investment should generate significant increases in Control Program efficiency and effectiveness. This capacity is currently being developed based on the advanced decision trees shown in Figure 2 and Figure 3, and outlined in this Section and Section 5 of this report.

Advanced on-water decision tree

By the time it is leaving port, a Vessel will have a Voyage Plan, ideally designed using the Voyage Planning decision tree described in the Section 3.3 below. The Voyage Plan defines which Reefs are to be visited and in which order. For Maintenance Mode Reefs that need to be manta towed, it provides an estimate of the amount of time that will be required to complete the manta tow. For Intensive Control Reefs it provides a maximum amount of time during the Voyage that can be invested at that Reef, in order that other commitments can still be met during the Voyage. The order in which Reefs are then visited is optimised by the DSS based on logistical considerations and operational constraints.

If the first Reef to be visited is a Maintenance Mode Reef that requires manta tow surveillance, the on-water decision process is relatively direct. First, the Vessel is directed to travel to the Reef and manta tow its entire circumference. If the COTS density estimated from the manta tow data by the DSS at any of the control Sites exceeds the Ecological Threshold, the DSS will move the Reef from Maintenance Mode to the top of the Intensive Control list. In either case, the DSS will update the most recent date of manta tow and direct the Vessel to move to the next Reef on the Voyage Plan.

If the first Reef to be visited is an Intensive Control Reef that has never been visited for control previously, or if it has been visited for control previously but the last manta tow at the Reef was performed more than some initially defined number, Y, days ago, then the DSS will advise the Vessel to begin by performing a comprehensive manta tow around the circumference of the Reef. The current Control Program, running on the simplified decision tree in Figure 1, aims to manta tow Intensively controlled Reefs every 42 days, or roughly once every fourth voyage, based on expert ecological opinion and operational constraints. Ecologically, however, the optimal frequency of manta tow will be driven by factors such as the speed with which COTS move into a recently controlled Site, the detectability of COTS at the Site, and the performance of the predictive model on which the decision support system is based. The DSS will adaptively refine the optimal frequency (Y days) of manta tow, such that it provides the information required to make effective on-water decisions with the least investment, while simultaneously improving our understanding of these important ecological drivers of COTS population dynamics at management-relevant scales.

The DSS will then generate an estimate of COTS density at each Site on the Reef by combining available manta tow and cull data for the Reef into an ecological model. Sites will be ranked according to estimated density to create a Ranked Reef Site List for the current Voyage. Those Sites that are estimated to have a density greater than the Ecological Threshold density will be added to a Reef Over-Threshold List. If none of the Sites are estimated to have a density greater than the Ecological Threshold density, then the Reef will be moved from Intensive Control mode to Maintenance Mode, and if there are still Dives left on the current Voyage then the DSS will direct the Vessel to move to the next Reef on the Voyage Plan.

If there are Sites estimated to have COTS densities greater than the Ecological Threshold on the Reef Over-Threshold List, then those Sites that were last culled longer than the frequency of site revisitation (X) days ago will be added to a Site Work List. The current Control Program, running on the simplified decision tree, aims to revisit Sites once per voyage, roughly every 12 days, an operationally simple approximation based on expert opinion. Ecologically, the optimal Site revisitation frequency will be driven by needing to allow sufficient time, up to 36 hours, for previously culled COTS to disintegrate (Jairo Rivera-Posada et al., 2013), and for cryptic individuals inaccessible during the prior cull to emerge. The DSS will test a range of frequencies of Site revisitation to adaptively refine the optimal frequency, while providing the first estimates of the magnitude of those ecological processes, information crucial to effective management. In future, this may allow Sites to be re-culled within a Voyage, significantly increasing Control Program efficiency.

The highest density Site at the top of the Site Work List will then be selected for control. A Dive crew will be dropped at one end of the Site, based on prevailing conditions, and comprehensively search the Site, injecting any COTS they detect. If they don't reach the other end of Site in a single 40-minute bottom time Dive, they will perform further Dives there until they have covered the entire Site or run out of Dives on the current Voyage. Once the Site has been completed, the DSS will update its most recent visit date to the current date, and then use the cull numbers recorded at the Site to update the ecological model and generate a new COTS density estimate for the Site.

If this new density estimate is lower than the Ecological Threshold density, then the DSS decision tree checks whether all Sites at the Reef are now estimated to be below the Ecological

Threshold density, and if so, the Reef is removed from the Intensive Control list and added to the Maintenance Mode list. If it isn't, then the DSS will generate an updated Site Work List from the estimated densities, but the Site just managed will be omitted because its most recent visitation date will be the current date. By this process, the DSS will direct a cull crew to Dive at the next highest density Site on the Reef.

The DSS decision tree will repeat this process until either all Sites at a Reef are below the Ecological Threshold density, all possible Dives at a Reef are complete, or there are no further Dives remaining within the Voyage Plan at that Reef. This decision tree ensures that control is ecologically meaningful by providing only a single path via which a Reef can be moved from Intensive Control to Maintenance Mode: when the estimated COTS density at all Sites within a Reef is below the Ecological Threshold where damage due to COTS is less than the growth rate of coral.

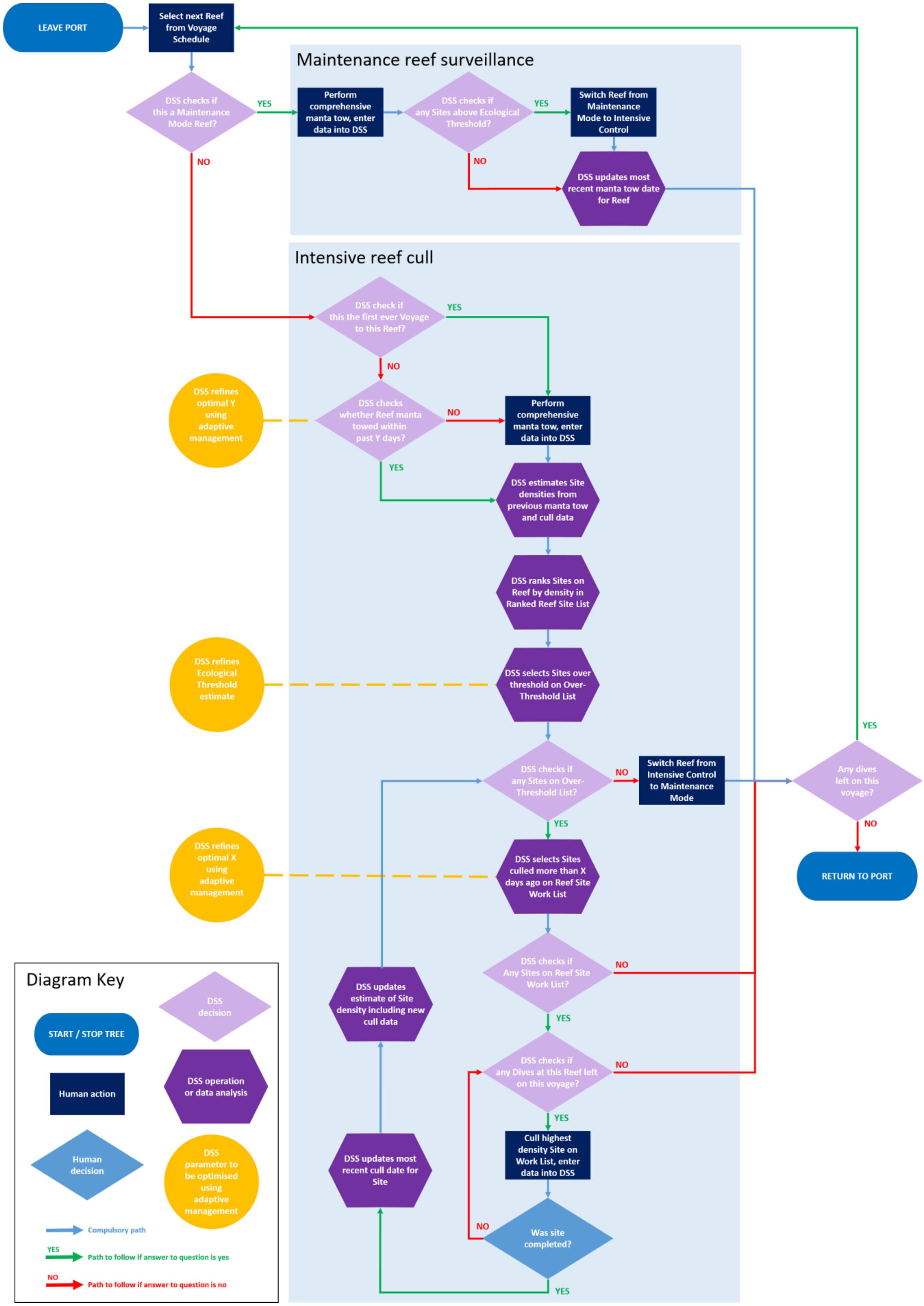


Figure 2: The advanced on-water decision tree

2.3 An advanced Voyage Plan decision tree leveraging adaptive management to structure voyages within a region

The simplified decision tree process illustrated in Figure 1 and outlined in Section 3.1 contains an implicit Voyage Planning process, based on on-water controllers balancing operational constraints with three rules-of-thumb for the order in which Reefs on the next Voyage should be visited: first, Maintenance Mode Reefs requiring manta tow; then Intensive Control Reefs at which control actions have already begun; and then Intensive Control Reefs at which control actions have not yet begun. All Reefs in this process come from GBRMPA's Priority Reef list within the relevant operational region, and operators are encouraged to select Priority Reefs closer to the top of the priority list before moving to Reefs lower on the list. This simplified process can be refined with the DSS to provide more guidance to operators about Voyage Plan sequencing, whilst also using advanced analysis techniques and adaptive management to increase Control Program efficiency.

In theory, the on-water decision process outlined in the previous section is self-scaling. When the first Vessel left port at the very start of the Expanded Control Program, it would have visited one of the highest Reefs on GBRMPA's regional priority list, performed a manta tow and begun cull activities. If, on this first or subsequent Voyages, the operator managed to finish work at the Reef, by completing a cull at every Site on the Reef estimated to have COTS density higher than the Ecological Threshold in less than the "frequency of Site revisitation (X)" time, then the Vessel would have temporarily finished work at that Reef for the current Voyage, and would therefore have moved to another Priority Reef. It would continue managing this Priority Reef until the "frequency of site revisitation" period on the first Priority Reef had elapsed, then it would head back there to continue control activities. It would focus on the first Priority Reef even at the expense of the second Priority Reef based on the principle that once work begins on a Reef it should continue until ecologically meaningful control is achieved. As control activities at the first Priority Reef started to get the COTS population under control at Sites across the Reef, relatively fewer resources (in this case, Dives) would have been required to control it and more resources would have been redirected to the second Priority Reef, and eventually a third Priority Reef and so on. Eventually, all Sites at the first Priority Reef would have been reduced below the Ecological Threshold, and it would be switched to Maintenance Mode, after which it would be visited with the frequency of re-manta towing maintenance reefs (Z)".

This on-water framework provides a simple "earliest-priority-to-completion" rule-of-thumb that says we begin with a Priority Reef, and only move on from it when it has been managed to an ecologically meaningful degree. It is not, however, designed to coordinate the actions of multiple Vessels or take into account external factors such as weather. It therefore risks inefficiency because Reefs with similar levels of priority, which will tend to be managed simultaneously, may be located far from each other. It also says nothing about how to distribute resources between culling at Intensively Controlled Reefs and surveillance at Maintenance Mode Reefs as the Control Program continues, or how best to sequence multiple tasks during a single Voyage. This is the role of the Voyage Plan decision tree.

The Voyage Plan decision tree

The Voyage Plan decision tree shown in Figure 3 illustrates how this process will be implemented by the COTS Control Centre DSS as part of the NESP5 COTS IPM Research Program (Westcott & Fletcher, 2019). Each vessel has been provided with a list of approximately 30 Priority Reefs for their Operational Region by GBRMPA, classed into the ten Priority Reefs to be targeted first, if possible, ten Priority Reefs to be targeted once the first ten have been completed, and the ten remaining Priority Reefs. When the Control Program began in mid-2018, all Priority Reefs were in Intensive Control mode, but control actions have since moved a number of reefs from Intensive Control to Maintenance Mode (see Section 4). The goal of the Voyage Plan decision tree is to plan which Reefs will be visited on the next Voyage in a way that maintains the ecological structure of the on-water decision tree, while simultaneously ensuring the long-term ecological outcomes of the Control Program and also maximising efficiency. It maintains the ecological structure of the on-water decision tree by revisiting the Reefs currently being controlled as frequently as possible until they are reduced below the Ecological Threshold. It guarantees that the long-term ecological outcomes of the program are maintained by ensuring that Maintenance Mode reefs are re-manta towed on ecologically meaningful timeframes. It maximises efficiency by ensuring that as control resources are freed up at currently controlled Reefs, the next Priority Reef selected for control is both one of those targeted for initial control and logistically and operationally accessible.

Determining how many and which reefs can be visited during a Voyage requires knowing what actions are required at each Reef. The management process of moving a Reef with an outbreaking COTS population from Intensive Control to Maintenance Mode is likely to take an indeterminate but repeated (e.g. > 3) number of Voyages, while culling at a single Site on the Reef is likely to take an indeterminate but small (e.g. < 3) number of Dives within a Voyage. In contrast, providing a whole-reef snapshot to inform decisions requires that an entire Reef is manta towed during a single Voyage. The time required for this can be reliably estimated based on the Reef's circumference and the length of a standard two-minute manta tow. These observations give us a simple "packing rule" for our Voyage Plan: choose the indivisible but known-time manta tows for the upcoming Voyage first, then fill in the remaining time in the Voyage with divisible and unknown-time cull actions. Note that this order-of-sequencing does not prioritise Maintenance Mode surveillance over the culling of Intensive Control Reefs; the frequency of both control activities is independently determined by their respective ecological drivers. Instead, it facilitates Voyage planning that automatically balances short-term cull needs and long-term surveillance requirements.

The Voyage Plan decision tree combines the "earliest-priority-to-completion" rule of thumb with the "packing" rule of thumb, and incorporates it into an adaptive management framework and a logistical sequencing module to maximise efficiency. The goal is to design the optimal Voyage for the next Vessel to leave port, without necessarily knowing exactly how long that Vessel will spend at each Reef it visits.

First, if any Maintenance Mode Reefs in the operational region were last manta towed more than Z days ago and are likely to be operationally accessible during the upcoming Voyage, then the one surveyed longest ago will be added to the Voyage Plan. The current Control Program aims to manta tow Maintenance Mode Reefs every three to six months, based on expert opinion and operational constraints. Ecologically, however, the optimal value will be driven by factors such the speed with which COTS move between managed Reefs, and the rate at which juvenile COTS grow and become accessible for control. The DSS will adaptively refine the optimal frequency of manta tow by comparing projected model estimates with observed densities, to maximise the amount of time between manta tows at Maintenance Mode Reefs while minimising coral damage due to re-emerging or immigrating COTS populations. Vitally, this will improve our understanding of these important ecological drivers of COTS population at the scale of management.

The DSS will then estimate the time required to manta tow the Maintenance Mode Reef based on the size of the Reef and previous Voyages to it, and from that the remaining time during the upcoming Voyage will be determined. If there is another Maintenance Reef to be surveyed, and enough estimated time remaining in the Voyage to survey it, then that Reef, too, will be added to the Voyage Plan, and the remaining time in the Voyage estimated.

Once there are no more Maintenance Mode Reefs requiring surveillance, then the Reef that has currently been under Intensive Control for the longest will be added to the Voyage Plan. Additional Reefs currently under Intensive Control will be added to the Voyage Plan in the order in which they began Intensive Control. Finally, Reefs from GBRMPA's Priority Reefs that are scheduled for Intensive Control but at which control has not yet been started will be added, based on a balance of: a) their sequence on GBRMPA's Priority List; b) their operational accessibility; and c) the distance from the current Reefs on the Voyage Plan and logistical overheads in travelling between Reefs.

At this point, the list of Reefs in the upcoming Voyage is finalised. The DSS will then optimise the sequence of Reef visitations to minimise travel time overheads, along with the amount of time available to be spent at each Reef based on the work to be conducted there. That is, to minimise logistical overheads, the Voyage Plan may direct a Vessel to visit an Intensively Controlled Reef at the beginning of the Voyage, but will direct the Vessel to leave that Reef with sufficient time remaining to perform manta tow surveillance at any Maintenance Mode Reefs planned for the Voyage, independent of how much of the task at the Intensively Controlled Reef is completed at that point in the Voyage.

At several points throughout the Voyage Planning decision process, and at any point during on-water activities, on-water operators can override the automated Voyage Plan based on their expert opinion on operational accessibility to certain Reefs given prevailing weather conditions or other operational concerns.

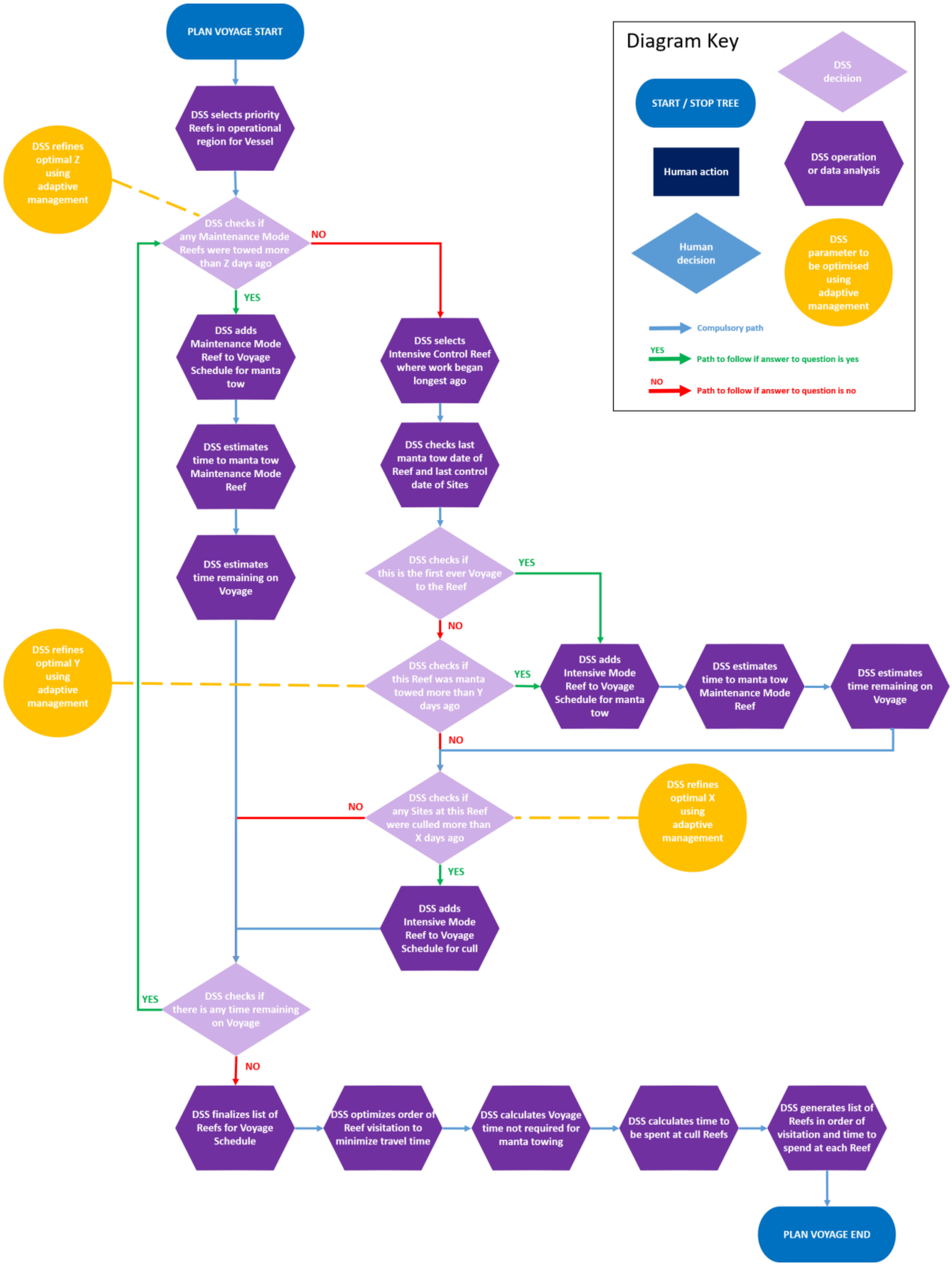


Figure 3: The advanced Voyage Planning decision tree

2.4 Further considerations

The decision trees are designed to provide a self-scaling logical structure ensuring that COTS densities at all Maintenance Mode Reefs are reduced to a point where coral growth can outpace COTS damage. They do this while accounting for uncertainty in the way we detect COTS through repeated surveillance, and in our understanding of how managed COTS populations recover and spread, through intensive revisitation until Ecological Thresholds are demonstrably achieved. The simple decision tree is designed to be implemented on-water without requiring advanced analysis, by making simplifying assumptions and collecting all the data required to inform decision making during control activities. The advanced decision trees are designed to use increasingly sophisticated analysis to provide significant further improvements to the efficiency of the Control Program, while ensuring the same strict ecological outcomes are met.

The structure provided by the decision trees, however, does not explicitly consider some edge cases that may prove important as data about the operation of the program starts to become available. For instance, as the Control Program progresses, more and more Reefs will be shifted to Maintenance Mode, and servicing them with regular surveillance visits will require significant Control Program resources. There may be a temptation to focus on culling Intensive Control reefs, but surveilling Maintenance Mode Reefs will be vitally important to ensuring that the Control Program is maintaining ecologically meaningful COTS densities across the Reefs being managed. It may eventually become necessary to shift the responsibility for the ongoing surveillance of Maintenance Mode Reefs to other operators geared up specifically for this task. Because surveillance requires a lower investment in equipment and training, this might provide an opportunity for smaller operators to participate in the program, e.g. Traditional Owner groups involved in management on their sea-country.

The decision processes outlined can guide the independent decisions of multiple Vessels within a fleet but does not provide explicit guidance on how to make simultaneous decisions when multiple Vessels are on-water at the same time, nor how best to provide coverage across a region. High priority, very large Reefs with high densities of COTS may be best managed by directing multiple Vessels from the fleet to operate there simultaneously. Where Vessels operate at a Reef at the same time, a manual Voyage Planning decision process may need to put one Vessel in charge of the operations of all Vessels at the Reef to ensure they are synchronised, until the more advanced DSS comes online.

The frequency of Site revisitation, a key Control Program variable, is currently fixed to once per Voyage, but in future will be refined using adaptive management techniques and the data from the Expanded Control Program. If this process recommends revisitation at intervals shorter than a single Voyage then, in future, the DSS may direct either a single Vessel to revisit a Site within a single Voyage, or a second Vessel to follow the path of the first a few days later. In such a case, it would be important that the second Vessel knows the order of operation of the first Vessel in order to sequence its actions correctly and ensure that all Sites are visited at the appropriate frequency of Site revisitation. This capability will be provided by the COTS Control Centre DSS, but if this principle is to be tested in the meantime, manual communication may be needed to sequence control efforts across Vessels.

At all points throughout the decision making process, ultimate responsibility for on-water staff health and safety must rest with on-water, human decision makers. The decision tree process outlined has no capacity to judge ocean or weather conditions, but instead relies on the expert opinion of Vessel Captains and Dive Masters to judge to what degree the recommended strategies can be followed. At no point should on-water safety be compromised to adhere to the decisions recommended.

Finally, while the decision trees presented in this report have been developed in the context of the management of an existing secondary outbreak, they provide the structure and processes required for responding with manual control to the detection of a primary outbreak.

3.0 HOW HAS THE SIMPLIFIED DECISION TREE PROCESS PERFORMED TO DATE?

At the time of writing, the newly Expanded Control Program has been operating for approximately eight months (November 2018 to June 2019). This provides an initial data set with which to assess the performance of the Expanded Control Program. Over this period, the Expanded Control Program visited 140 Reefs across 10° of latitude (12° - 22° S), with decisions about the management status made at 113 of these. At the remaining 27 Reefs work had begun but conditions (weather, crocodile risk, etc) had prevented assessment as work could not be completed around the entirety of these Reefs. At the 113 Reefs with assessments, the management status at the end of June 2019 was:

- 12.4% (14 Reefs) currently under Intensive Control, i.e. surveillance revealed COTS present and culling is underway to reduce their density
- 29.2% (33 Reefs) transitioned to Maintenance Mode, i.e. surveillance revealed COTS present and culling was undertaken to reduce their densities to below the Ecological Threshold
- 58.4% (66 Reefs) in Maintenance Mode – surveillance revealed no need for culling

On the face of it, this summary of the status of Reefs eight months into the new Expanded Control Program suggests that the Program is operating effectively in terms of: detecting Reefs that require control; in successfully reducing COTS densities at those Reefs requiring control to below the Ecological Threshold; and in keeping COTS densities at those Reefs low. The data from this work also allows us to examine the Expanded Control Program's performance around a number of key decision points in more detail.

3.1 Are the decision criteria effective and efficient?

The first of these decision points is the question of how reliably the program is identifying Reefs that do not require control. This is an important question because if the indicators used by the program are inadequate then there will be a tendency to: i) identify Reefs as having low COTS densities when they are in fact high (false negatives); or ii) identify Reefs as having high densities when in fact they are low (false positives). False negatives would result in Reefs needing management being ignored, with resultant coral loss and COTS spread – a matter of significant concern. False positives are of less concern, given that subsequent Dives would quickly identify actual densities, however they do result in unnecessary investment of Dives at a Reef. The key decision criteria the program currently uses to determine if a Reef requires control is "Dive a Reef if one or more COTS or feeding scars are observed", and it is of immediate interest to assess the appropriateness of this decision criteria.

At 88 Reefs manta tows reported zero COTS observed and, following the decision making framework, no control Dives were conducted at those Reefs (Table 1, '0 COTS observed' column, 'No cull undertaken' row). However, at an additional 32 Reefs manta tows reported zero COTS observed but, despite this, control Dives were subsequently conducted (Table 1, '0 COTS observed' column, '0', '< 4 ha^{-1}' and '> 4 ha^{-1}' rows). This provides data for assessing the performance of the decision criteria "Dive a Reef if one or more COTS or feeding scars are observed" is effective and efficient.

No COTS were found at 15 of these Reefs while at 15 Reefs COTS were found but at densities below the Ecological Threshold (4 ha^{-1}). At two Reefs (6%) the COTS density was found to be above the Ecological Threshold. This means that manta tow observations of COTS only (not feeding scars) correctly identified Reefs as below the Ecological Threshold 94% of the time.

Table 1: Performance of the number of COTS observed during manta tow as an indicator of the need to undertake culling in the new Expanded Control Program. Values in table are the number of individual Reefs actioned that fall into each manta tow category, and the outcome of subsequent culling activity, if undertaken

		Number of Reefs Manta Towed			
		0 COTS observed	1 COTS observed	>1 COTS observed	TOTAL
COTS Culled	No cull undertaken	88	0	0	88
	0	15	2	0	17
	< 4 ha^{-1}	15	2	3	20
	> 4 ha^{-1}	2	0	13	15
	TOTAL	120	4	16	140

Recording of feeding scars alone during manta tows correctly identified 100% of Reefs above the Ecological Threshold as requiring control Dives. Feeding scars were recorded at all but four of the Reefs (22%) with COTS present but at densities below the Ecological Threshold (Table 2, 'Scars Absent' column, '< 4 ha^{-1}' row). Critically, in the two instances where manta tows reported zero observations of COTS, but where subsequent culling identified densities above the Ecological Threshold, those Reefs had been identified as requiring control Dives based on the presence of feeding scars during the manta tows.

Table 2: Performance of the presence of COTS feeding Scars observed during manta tow as a suitable indicator of the need to undertake culling in the new Expanded Control Program. Values in table are the number of individual Reefs actioned that fall into each manta tow category, and the outcome of subsequent culling activity, if undertaken. 'Scars Absent' indicates 0 scars detected, 'Scars Present' 1 – 10 scars detected, and 'Scars Common' > 10 scars detected.

		Number of Reefs Manta Towed			
		Scars Absent	Scars Present	Scars Common	TOTAL
COTS Culled	No cull undertaken	83	4	1	88
	0	1	5	11	17
	< 4 ha^{-1}	4	2	14	20
	> 4 ha^{-1}	0	0	15	15
	TOTAL	88	11	41	140

Based on these results, we would expect that 80% of the 88 Reefs that were manta towed and reported zero COTS and zero feeding scars would have had COTS present, but at densities lower than the Ecological Threshold. Vitally, 0% would have had COTS at densities above the Ecological Threshold. In the context of this Control Program, we are trying to avoid false negatives, i.e. concluding that a Reef is below the threshold when in fact it is above the threshold. These results suggest that the rule currently being employed, "Dive a Reef if one or more COTS or scars are observed", is sufficiently conservative to avoid false negatives. At Reefs where a false positive occurred, it appears that limited numbers of Dives ($\bar{x}$ = 3.4, range 2 – 8) were required to ascertain that further Dives were not required. In short, the decision criteria currently employed in the new Control Program minimize the risk of false negatives without overly inflating the costs associated with false positives.

3.2 Does the program reduce COTS densities, and do they remain low?

Given a decision to control at a Reef, the next key question is whether the decision tree-informed IPM process is achieving its goal of reducing COTS densities to below the Ecological Threshold at the scale of the Reef. By the end of May 2019, the Expanded Control Program had Dived thirty Reefs during a single Voyage only, with between 1 and 33 Dives conducted ($\bar{x}$ = 7.1 Dives). Four Reefs were Dived on two Voyages, one on three, two on four, two on seven, one on eight and one on ten Voyages. These Reefs received between 23 and 612 Dives (mean 115 Dives).

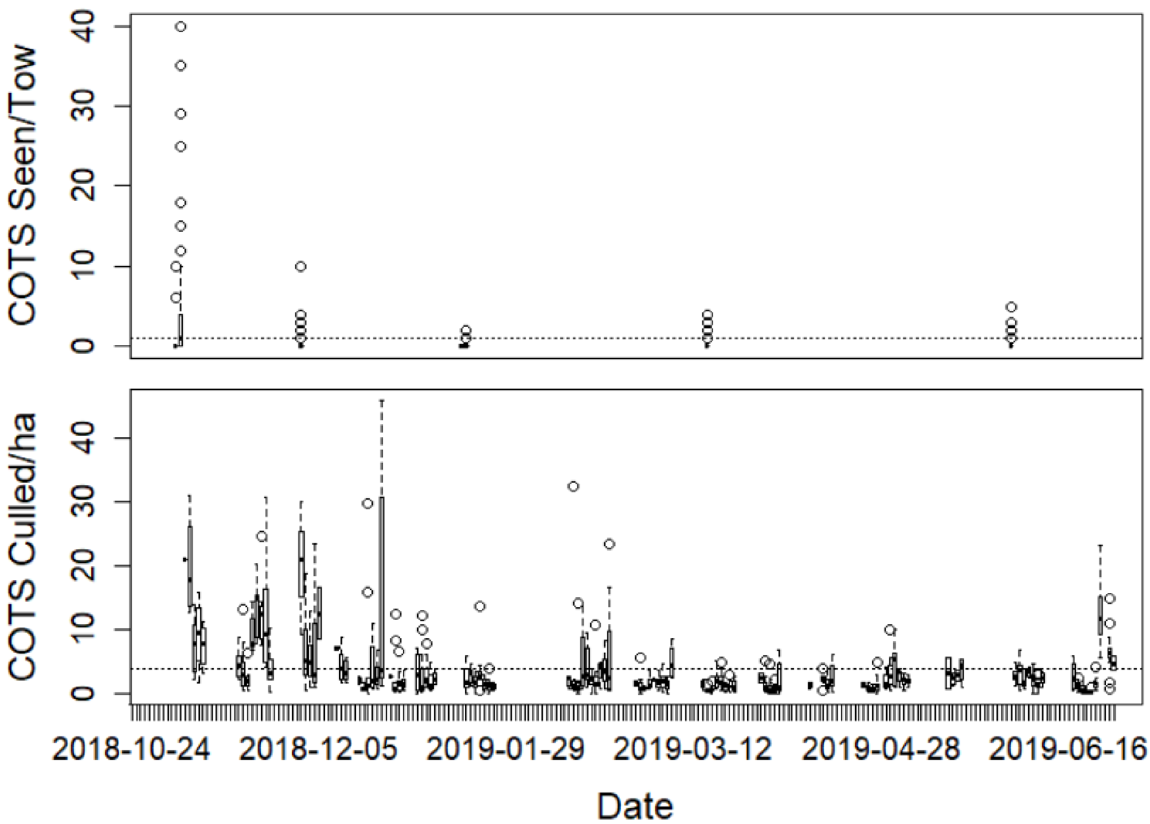


Figure 4: Progress of the Expanded Control Program at John Brewer Reef. The top panel shows the number of COTS and feeding scars observed in manta tows plotted against the date on which the tow occurred. The lower panel shows the median number of COTS culled at Sites on the Reef plotted against the date on which the cull occurred. Clusters of data indicate individual Voyages. In both panels the dark horizontal bar represents the median, the box the 25th and 75th quartiles, whiskers the outliers and circles extreme values. When most values are zero only the extreme values are clearly visible (e.g. in top panel). In the top panel the dotted line represents the manta-tow threshold for instigating control dives (1 COTS or feeding scar observed) and in the bottom panel it represents the Ecological Threshold (4 COTS/ha).

Overall, 36 (± 8.4 S.D.) Dives were conducted at the average Reef, and 115 (± 170 S.D.) Dives at Reefs which required multiple Voyages. Control at a number of Reefs in this summary is on-going and, as a consequence, not all have moved to Maintenance Mode or have yet received multiple Voyages. The number of Voyages required to move a Reef from Intensive Control to Maintenance Mode appears to have been dependent on a range of factors, including the Reef's size and complexity, the density and distribution of the COTS population at the Reef, crew size, and conditions at the time of culling. Describing these determinants is a current focus of ongoing research.

In previous work, we showed that focused control at individual Sites at a Reef was capable of reducing COTS densities to below the Ecological Threshold (Westcott & Fletcher, 2018), i.e. the point where coral cover is at equilibrium with COTS predation (Babcock et al., 2014). The data from the initial months of the Expanded Control Program indicate that a sustained and strategic approach to control results in similar outcomes at the scale of entire Reefs, including at Reefs where outbreaks were widely distributed across the Reef and at high densities.

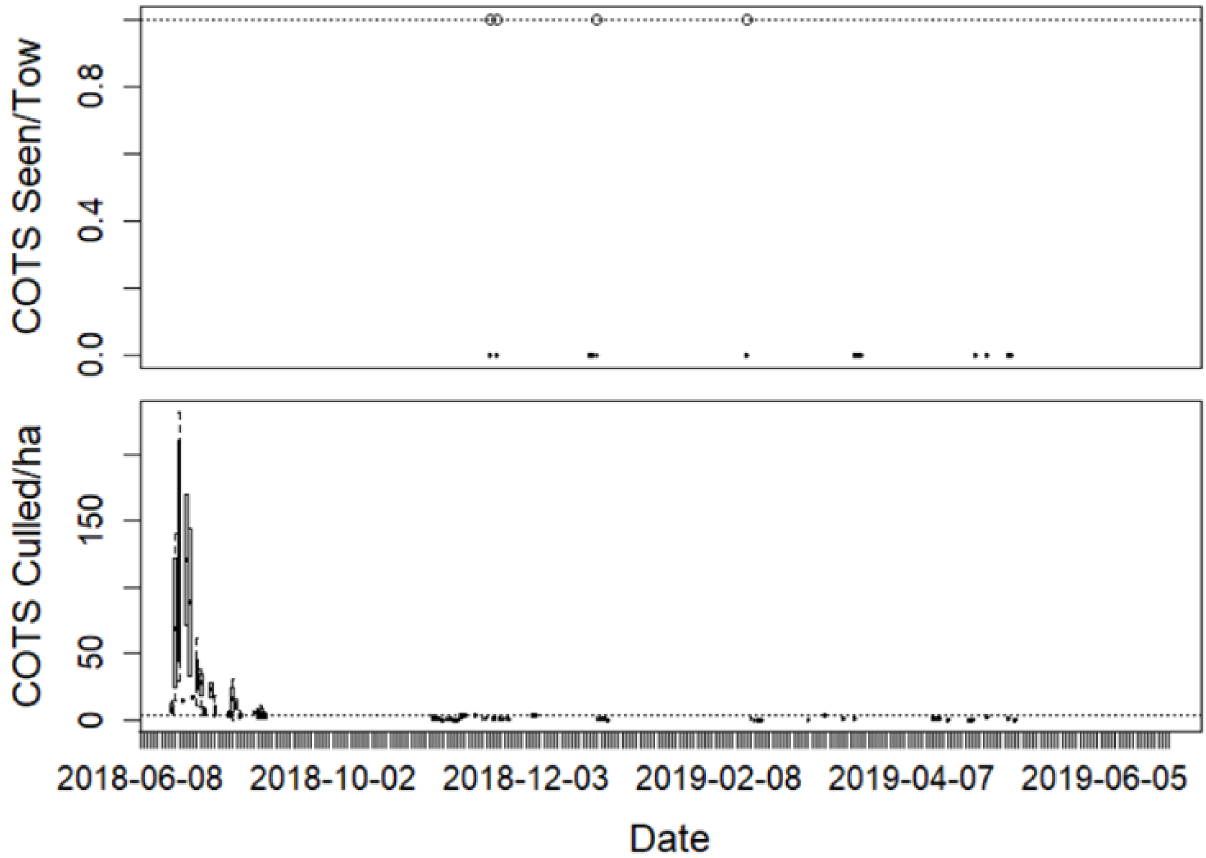


Figure 5: Progress of the Expanded Control Program at Farquharson Reef. The top panel shows the number of COTS and feeding scars observed in manta tows plotted against the date on which the tow occurred. The lower panel shows the median number of COTS culled at Sites on the Reef plotted against the date on which the cull occurred. Clusters of data indicate individual Voyages. In both panels the dark horizontal bar represents the median, the box the 25th and 75th quartiles, whiskers the outliers and circles extreme values. When most values are zero only the extreme values are clearly visible (e.g. in top panel). In the top panel the dotted line represents the manta-tow threshold for instigating control dives (1 COTS or feeding scar observed) and in the bottom panel it represents the Ecological Threshold (4 COTS/ha).

Figures 4 - 6 show data from three Reefs visited by multiple Voyages in the Expanded Control Program. In each example, the densities of COTS remained high during the initial visits but with repeated Voyages declined to the Ecological Threshold. These Reefs illustrate a number of key results from the new Program. The first and most basic of these is that successfully reducing COTS densities requires multiple Voyages, 10 or more in these examples. This suggests that either COTS immigrate into previously culled Sites, and / or not all COTS are available to cull on any single Voyage and multiple Voyages are required to allow 'unavailable' COTS to move back out into the open.

A second and related point is that the number of COTS encountered on subsequent Voyages are often similar to those encountered on the previous Voyage. This suggests that the scheduling of revisitation at Voyage intervals, i.e. once every 10-15 days, is sufficient to make subsequent culls worthwhile and efficient.

Third, declines in the number of COTS encountered are not uninterrupted. Each of these examples includes at least one instance where a period of decline is followed by a sudden increase in numbers culled. There are two likely reasons for this. The first is a function of the way the Expanded Control Program currently operates, informed by the simplified decision tree. Sites with the highest densities during the manta tow are culled down, repeatedly if necessary, until they reach the Ecological Threshold before control moves on to other Sites or a new manta tow is completed. As new Sites are included in the cull roster and are culled for the first time, we could expect some to have higher densities than were recorded in the last visits to the previously culled Sites, resulting in an apparent increase in CPUE.

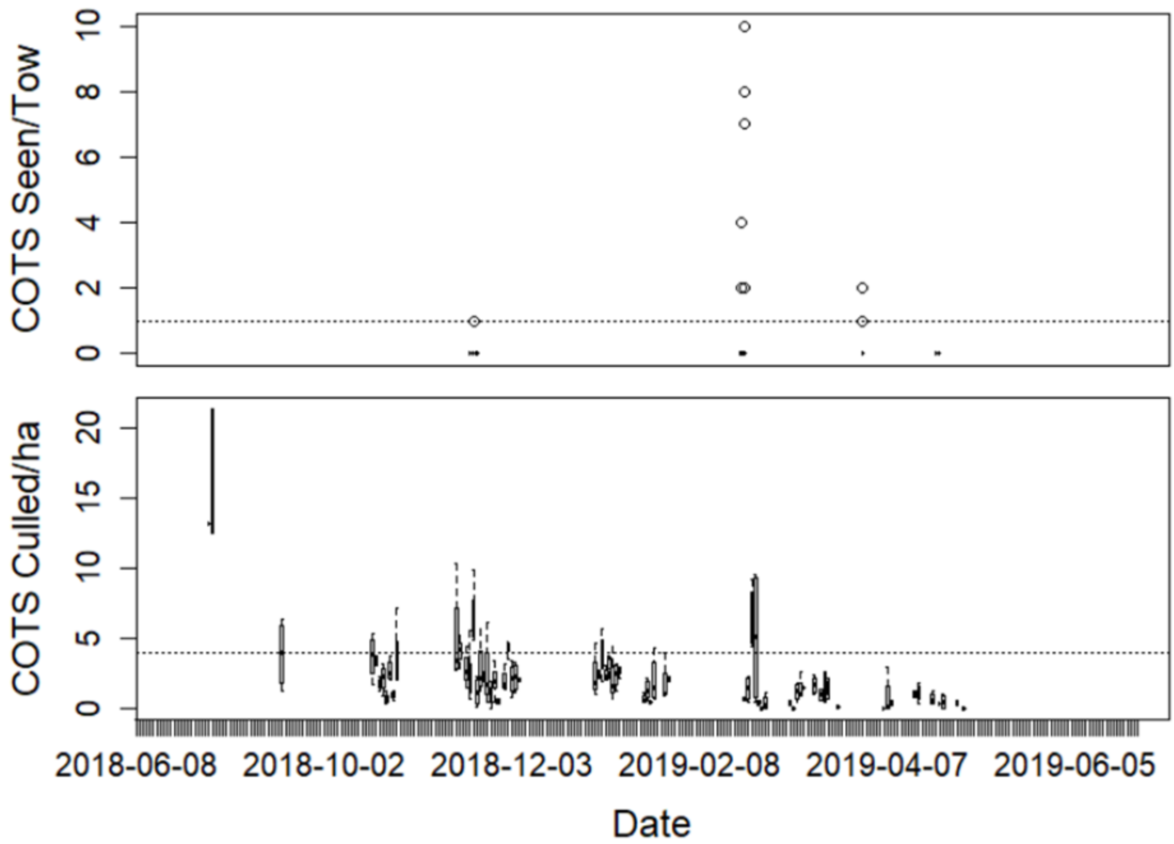


Figure 6: Progress of the Expanded Control Program at Eddy Reef. The top panel shows the number of COTS and feeding scars observed in manta tows plotted against the date on which the tow occurred. The lower panel shows the median number of COTS culled at Sites on the Reef plotted against the date on which the cull occurred. Clusters of data indicate individual Voyages. In both panels the dark horizontal bar represents the median, the box the 25th and 75th quartiles, whiskers the outliers and circles extreme values. When most values are zero only the extreme values are clearly visible (e.g. in top panel). In the top panel the dotted line represents the manta-tow threshold for instigating control dives (1 COTS or feeding scar observed) and in the bottom panel it represents the Ecological Threshold (4 COTS/ha).

The second reason is due to COTS immigrating into previously culled Sites from surrounding areas, resulting in an increase in density. We know that COTS are capable of moving hundreds of metres over the course of several days, and we would expect movement into culled Sites, both from nearby Sites not yet culled, and from areas that are not currently accessible to Divers (e.g. below 15 m depth). This highlights the need to continue visitation of Reefs once they have been switched from Intensive Control to Maintenance Modes, to identify and rectify any resurgence in COTS populations. It also underlines the importance of structuring the Control Program to collect data at the relevant management and ecological scales to improve our understanding of these processes and improve control strategies in future.

Finally, as was noted in our previous work (Westcott & Fletcher, 2018), Figures 7 and 8 show that culling-induced declines occur and lowered densities are maintained for the largest COTS size classes. This is vital, because it confirms that significant numbers of the most damaging and the most fecund individuals are being removed from the populations, and indicates that the Expanded Control Program is an effective means of minimizing damage and spread.

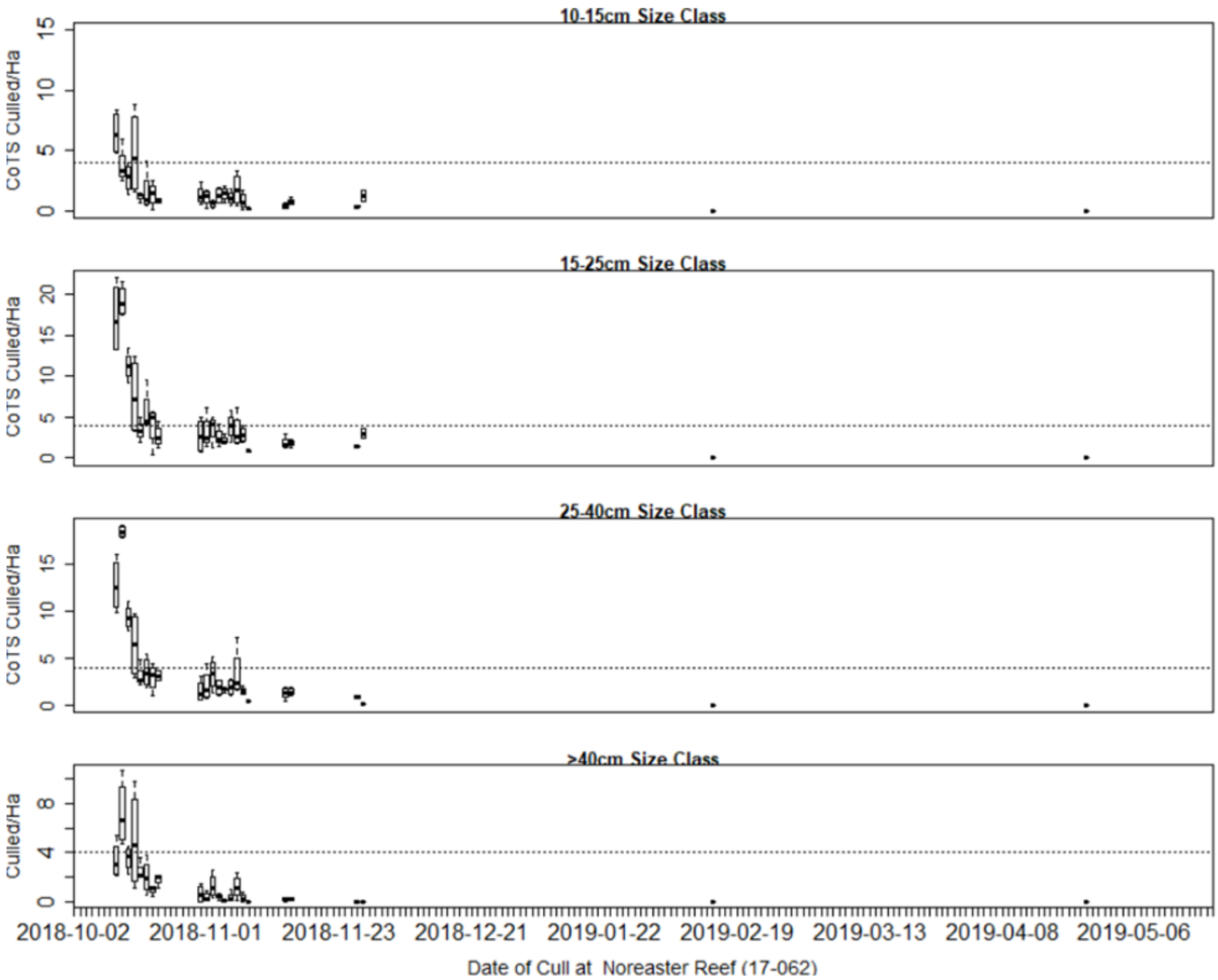


Figure 7: COTS in each of the four size classes culled per hectare at sites on Noreaster Reef plotted against the date of each cull. Six months after the reef was placed in maintenance mode COTS densities remained close to zero

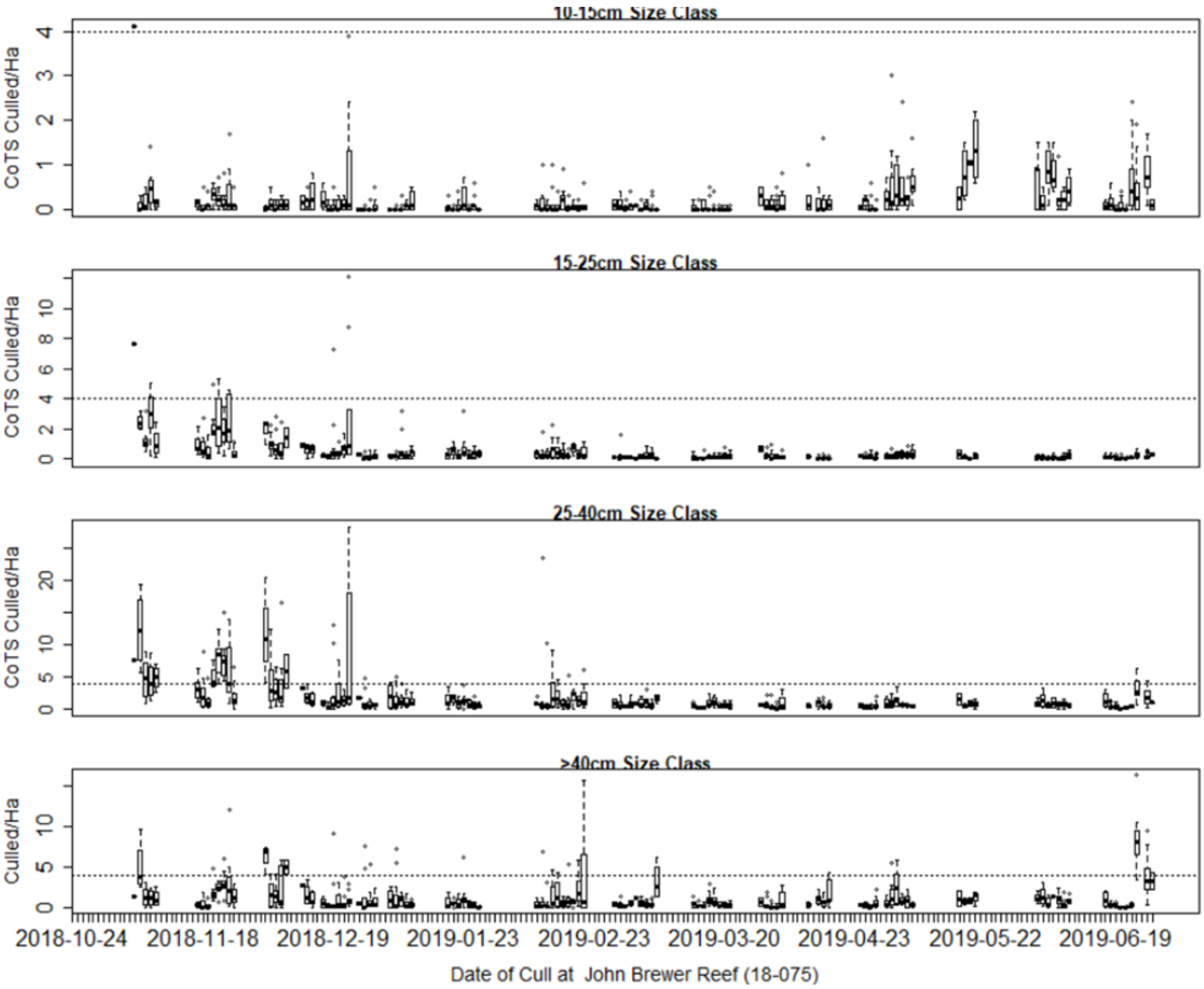


Figure 8: COTS in each of the four size classes culled per hectare at sites on John Brewer Reef plotted against the date of each cull. At John Brewer Reef while the density of the larger size classes was reduced over time the occasional jumps in the density of the largest size class highlight the need for ongoing surveillance once a reef has been placed into Maintenance mode. Immigration from outside the control area is a likely explanation for these sudden increases, a hypothesis that can be tested as data collection across the Control Program continues.

3.3 Do the decision trees self-scale control actions relative to COTS densities across region?

A key principle of ecologically-informed management is that the management goal is scaled to achieve ecologically meaningful outcomes given the resources available. The decision trees are explicitly designed to ensure this outcome, by: 1) continuing Intensive Control at a Reef until COTS densities have demonstrably been reduced to a level at which coral growth can outpace COTS damage; and 2) only once resources are available beginning control actions at the next Priority Reef. When a Reef has low COTS densities, few Voyages will be required to demonstrate that it is below the Ecological Threshold and control operators can quickly move to the next Priority Reef. When a Reef has high COTS densities, many Voyages may be required to achieve the same ecologically-scaled outcome.

This simple approach allows the decision tree to efficiently scale control actions to the density of COTS found at both individual Reefs, and more broadly across operating regions. It also provides targeted data collection at the ecological and management scales important to inform future control decisions and strategies. It provides repeated spatial and temporal manta tow and fine-scale cull data at Priority Reefs with high COTS densities to improve our understanding of outbreaking COTS population processes and control actions. It also provides wide-scale manta tow data for surveillance across large numbers of Reefs in regions with low COTS densities, to improve our understanding of regional distribution of COTS during non-outbreak periods and to provide an early warning capability.

The preliminary data from the first eight months of the Expanded Control Program demonstrates the scalability of the decision tree process across the six Vessels of the Control Program (Table 3). In the far northern part of the GBR, Vessel 1 detected only 0.01 COTS per manta tow on average, and as a result invested most of its effort in manta tow surveillance of over 90 Reefs, completing almost 7,000 manta tows in eight months, but only performing 179 cull Dives and removing approximately 7,000 COTS. In contrast, near the current COTS outbreak front Vessel 5 detected a mean of over 1.3 COTS per manta tow, and invested most effort in completing cull Dives. During 15 Voyages 925 cull Dives removed over 32,000 COTS, but only 500 surveillance manta tows were completed. In each region, the decision tree is driving operators to adopt an approach that ensures that ecological outcomes are reached, while efficiently distributing resources to new Reefs as they become available.

This demonstrates that the decision trees automatically direct available Control Program effort to appropriate management actions given the COTS densities observed at each Reef, and that this process, repeated over many Reefs, scales these operations to the regional scales covered by each Vessel. Where COTS densities are high, Reefs are being revisited and culled intensively until the Ecological Threshold is achieved, and where COTS densities are low, many Reefs are being surveyed quickly and then those resources efficiently deployed to the next Priority Reef.

Table 3: Distribution of Regional COTS effort in the new Expanded Control Program

Vessel	Number of Voyages	Mean manta tow density (COTS/tow)	Number of manta tows	Number of cull Dives	Manta tows per cull Dive	Total COTS culled
Vessel 1	16	0.01	6,950	179	38.8	7,065
Vessel 2	16	0.06	3,199	252	12.7	18,676
Vessel 3	15	0.2	2,065	242	8.5	7,264
Vessel 4	15	0.03	1,969	270	7.3	9,974
Vessel 5	15	1.37	521	925	0.6	32,085
Vessel 6	11	1.24	1,055	832	1.3	37,732

3.4 How did the program perform at Lizard Island? A case study.

While the analyses presented above indicate that the surveillance and control methods used in the field and the decision trees which their data inform are performing effectively, an opportunity arose in August 2019 to conduct additional tests based on independent surveillance. This opportunity arose when researchers surveyed the northern and western sections of Lizard Island reef using personal underwater scooters and SCUBA equipment. It has been suggested that this surveillance approach would provide a more accurate picture than could be achieved with manta tows, because it provides greater capacity to search for cryptic individuals. Based on their surveys, the researchers reported significant densities of COTS and expressed concern that the program had missed a problem situation. This suggested either that the situation at Lizard Island had changed since the last visit by the Expanded Control Program or that the assessment had not accurately represented the situation there. Irrespective, their report provided an opportunity to: i) qualitatively assess the performance of manta tow surveillance against an alternative method, ii) determine whether the situation had changed significantly since the previous surveillance, and, iii) test the performance of the method at low densities (similar to those of a pre-outbreak population). Below, we review the results of initial assessments of the Expanded Control Program of Lizard Island Reefs and a subsequent visit by the Expanded Control Program, and qualitatively compare these to observations from researchers using a different surveillance methodology.

In November 2018, COTS Control Program Vessel crews visited Lizard Island reefs in the area generally considered to be part of the initiation box for primary COTS outbreaks. At that time, comprehensive manta tow surveillance across 92 tows revealed minimal signs of COTS presence or activity. Some COTS scars were observed on 2 manta tows along the reef located on the North West side of the Island, and at that time cull divers were deployed to one cull site where they spent 24.3 dive hours searching and culled 4 COTS (CPUE = 0.003 COTS per minute). Based on this outcome, and in line with current decision tree framework, Lizard Island reefs were placed in ‘Maintenance Mode’ with the intention to re-visit and continue to monitor COTS activity at this high value location as frequently as resources allowed (aiming for revisitation every 3-6 months if possible).

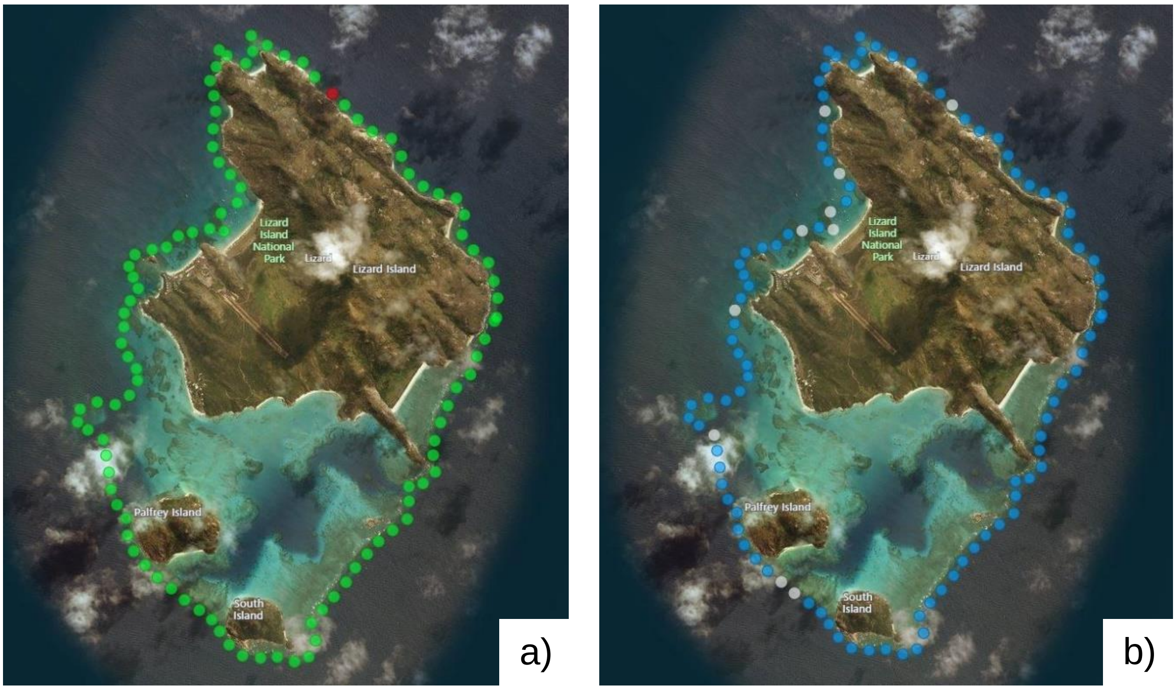


Figure 9: Spatial locations of a) COTS and b) COTS scars observed during manta tow surveillance around Lizard Island reefs in September 2019.

In January 2019, a COTS Control Program vessel returned to Lizard Island Reefs and conducted repeat surveillance. No COTS or COTS scars were detected across 92 manta tows, and as a result no cull divers were deployed during that visit. Again, Lizard Island Reefs were placed in ‘Maintenance Mode’ with the intention to continue monitoring this high value location.

On 29 August 2019, researchers at a NESP IPM COTS Working Group meeting advised of COTS sightings in significant numbers at Lizard Island reefs during a recent research trip. The surveillance was conducted using personal underwater scooters and SCUBA equipment, methods that allowed for greater mobility over and around reef structure than manta tows, including searching in locations where the animals might be obscured from above. Using this method both scars and feeding COTS were observed in ‘significant’ numbers.

Given this new intelligence, and the fact that Lizard Island Reefs had been placed in Maintenance Mode in January, a COTS Control Program Vessel visited Lizard Island again in September 2019. Upon arrival, the Vessel crew began by conducting manta tow surveillance around Lizard Island Reefs. This showed an average of 0.01 COTS counted per tow (i.e. 1 COTS counted across 101 tows). According to standard reef outbreak status thresholds developed by the Australian Institute of Marine Science and used by the Great Barrier Reef Marine Park Authority, this suggested that the reef as-a-whole was not currently experiencing a Potential, Established or Severe outbreak.

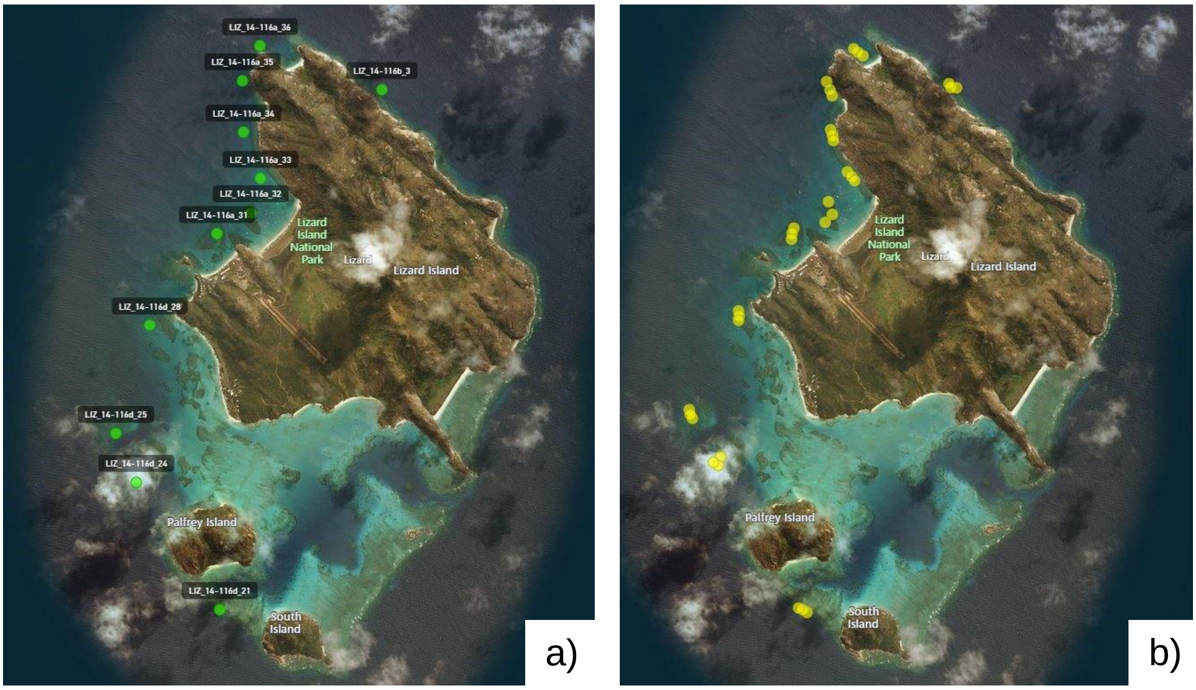


Figure 10: a) Locations of the 11 cull sites around Lizard Island that were actioned by cull divers based on the outcome of manta tow surveillance in September 2019. Green icons indicate ecologically sustainable thresholds for culling have been achieved. Red icons would indicate further culling is required to achieve ecologically sustainable thresholds. b) Locations of the 33 replicate RHIS surveys to estimate coral cover and inform target thresholds for culling. Three replicate RHIS, spaced ~50m apart, are conducted in each cull site prior to the start of culling.

Although the overall outbreak status of Lizard Island reefs was considered 'No Outbreak', the surveillance undertaken by the COTS Control Program crew in September 2019 revealed increasing signs of COTS activity compared to previous visits. One COTS was observed on a manta tow at Lizard Island Reef (North East) 14-116b (Figure 9a) and the presence of fresh COTS feeding scars were observed across 10 manta tows at several reefs around the island i.e. Lizard Island Reef (North West) 14-116a, Lizard Island Reef (North East) 14-116b, and Lizard Island Reef (Lagoon) 14-116d. The highest clusters of scarring were observed across the patch reefs of Lizard Island Reef (North West) 14-116a (Figure 9b).

Following the decision tree framework, cull divers were deployed at all locations where manta tows detected COTS and/or COTS scars (Figure 10a). In total, 11 cull sites (each approximately 10 hectares) were opened and searched for COTS by control divers based on the outcomes of surveillance. Over the course of the September 2019 voyage, the control team culled a total of 34 COTS across 5,520 minutes (92 dive hours) spent searching the 11 cull sites that were opened based on surveillance (Table 4). The highest numbers of COTS were located and injected at cull site 31 (LIZ_14-116a_31) in Lizard Island Reef (North West) 14-116a, with 20 individuals culled over 1,280 minutes (~21 dive hours) spent searching, which equated to a CPUE = 0.016. Note that this cull site is directly adjacent to the cull site where COTS activity was first detected by Control Program crews during their previous assessment of this reef in November 2018 (i.e. LIZ_14-116a_32).

Control divers also conducted 3 replicate Reef Health Information Surveys at each of the 11 cull sites (Figure 10b). The average hard coral cover was 13.36% (+/-1.73 SE), which suggested that COTS Control Program teams should aim to achieve a CPUE of 0.04

Table 4: Culling effort across 11 cull sites actioned due to signs of COTS activity from surveillance around Lizard Island reefs in September 2019.

Reef Section	Site Name	Date	Total COTS Culled	Total Effort (mins)	Catch Per Unit Effort (COTS / min)	Below Threshold?
North East	LIZ_14-116b_3	19/09/2019	1	640	0.002	Yes
Lagoon	LIZ_14-116d_21	19/09/2019	2	640	0.003	Yes
Lagoon	LIZ_14-116d_24	23/09/2019	0	400	0	Yes
Lagoon	LIZ_14-116d_25	22/09/2019	2	320	0.006	Yes
Lagoon	LIZ_14-116d_28	22/09/2019	3	320	0.009	Yes
North West	LIZ_14-116a_31	22/09/2019	20	1280	0.016	Yes
North West	LIZ_14-116a_32	21/09/2019	0	320	0	Yes
North West	LIZ_14-116a_33	21/09/2019	0	320	0	Yes
North West	LIZ_14-116a_34	20/09/2019	2	320	0.006	Yes
North West	LIZ_14-116a_35	20/09/2019	2	320	0.006	Yes
North West	LIZ_14-116a_36	20/09/2019	2	640	0.003	Yes
		TOTAL	34	5520	0.006	

COTS/minute bottom time at cull sites around Lizard Island Reefs in order to minimise the impact of COTS feeding on coral growth. Based on the outcome of the cull efforts, all sites had CPUE below 0.04 (Table 4) indicating that numbers of COTS were sustainable for coral growth at the time. According to the decision tree framework, there was no need for further revisitation to achieve cull thresholds and the Lizard Island Reefs will now be placed back into 'Maintenance Mode', with another round of surveillance scheduled in 3-6 months (i.e. Jan-Mar 2020) in order to re-assess outbreak status and conduct preventative culling if any signs of COTS activity are observed.

Both surveillance and control data collected through the Expanded COTS Control Program in September 2019 suggest that there had been a change in the situation at Lizard Island since the previous visits in November 2018 and January 2019, though the activity was in the same area where indications of COTS had previously been detected. The observed increase in COTS activity over successive visits to Lizard Island qualitatively supports the independent observations of researchers who used an alternative method for surveillance and noted concerning levels of COTS activity in August 2019. These results add to the confidence that can be placed in the combination of manta tow and control dives used in the Expanded COTS Control Program to detect changes in COTS activity over time. While manta tows do not allow for detailed searches, and therefore have potential to underestimate COTS numbers when compared directly to alternative methods such transect surveys using SCUBA, their use in combination with control dives (which do allow for detailed searches) appears sufficiently sensitive to detect increased COTS activity and guide action to effectively mitigate COTS impacts, even when these changes occur at low levels (i.e. prior to outbreaks developing).

This case study also highlights the importance of repeated visitation of reefs in Maintenance Mode, in order to periodically evaluate changes in COTS activity. In the decision tree framework, this revisitation is currently meant to occur at an interval of approximately 3 – 6 months where possible. In the case of Lizard Island, the actual revisitation interval achieved was 3 months in the first instance (November to January), and then 9 months in the second instance (January to September), with the increase in COTS activity detected after the second interval. This suggests that the revisitation schedule of once every 3 – 6 months during Maintenance Mode is not too long, and could perhaps be extended slightly in situations where previous surveillance has detected very little or no COTS activity. Additional data collection over the operation of the program will be used to further test this conclusion. This is important since this is a key decision in the framework and is vital in providing early detection of recovering COTS populations, to ensure the timely protection of coral in outbreaking areas, and potentially to prevent or reduce the severity of primary or secondary outbreaks.

Finally, these results demonstrate that the decision tree framework can effectively direct the distribution of effort and resources at individual Reefs when the density of COTS is very low, such as prior to a primary outbreak in the initiation box.

4.0 SUMMARY AND RECOMMENDATIONS FOR IMPLEMENTATION

The three decision trees described in this Report have been designed to ensure that key decision making processes in the Expanded COTS Control Program are informed by the ecology of the system being managed. The first and second decision trees inform fine-scale decisions made on-water during a scheduled Voyage, based on the status of the Reef being controlled, prior information collected during previous Voyages, and new information collected once staff arrive at the Reef. The third Voyage Planning decision tree informs how best to sequence control actions across the portfolio of Intensive Control and Maintenance Mode Reefs as COTS densities change as a result of Control Program activities.

This framework provides an ecologically-informed structure to manage day-to-day operations of the COTS Control Program. It links COTS ecology to Control Program decisions around cull Dives at Sites each day, at Reefs throughout a Voyage, and across a group of Reefs over several months. The decision trees are logically complete, in that if they were followed explicitly, the deterministic outcome would be a series of controlled Reefs with COTS densities below the Ecological Threshold at which coral growth would outpace COTS damage. They are also self-scaling to the COTS densities encountered and the resources available, ensuring that sufficient effort is invested at Reefs with high COTS densities to reach the Ecological Threshold, but also that operators can identify and manage Reefs with low COTS densities efficiently and move on to invest Control Program resources where they are most needed.

The decision trees provide an ecological foundation to decision making based on the most up-to-date ecological and management understanding of COTS control as it stands today, while recognising and making allowances for the parts of the system we don't yet fully understand, as well as the uncertainties and logistical constraints that come with any real-world pest control program. The system links Reef-scale surveillance and fine-scale cull data during Intensive Control to efficiently structure actions at the Reef scale in a way that both: i) allows for large uncertainties in how COTS utilise Reef habitat on timescales of weeks and months; and ii) provides the data to improve our understanding of this key ecological process to improve the Control Program in future. It also implements long-term monitoring of managed Reefs successfully moved to Maintenance Mode, to improve our understanding of both "known unknowns", such as how COTS move between unmanaged deep-water habitat and Reef Sites, as well as any to-date unidentified "unknown unknowns" that may also contribute to how outbreaking COTS populations recover following control actions.

The decision tree structures have been strongly informed by historical literature, ecological research conducted as part of the NESP COTS IPM Research Program, and extensive engagement with GBR managers and on-water contractors. The core concepts have been ground-truthed and tested over the first eight months of the new Expanded Control Program, and the scientific details of this report have been synthesised into practical guidance for on-water contractors by our partners at GBRMPA (GBRMPA, unpublished). Feedback from on-water crews and GBR managers has, in turn, been used to refine the structure of the decision trees to more accurately reflect how decision making occurs on-water.

Below, we present a list of key recommendations for managers coming from this work. Some of these have already been implemented by managers and on-water contractors, as indicated. Other recommendations are longer-term aspirations, to be gradually implemented or considered for inclusion as refinements to the current Expanded Control Program, or as part of the roll out of the COTS Control Centre Decision Support System.

4.1 Ecological Thresholds

The primary goal of COTS control on timescales from a week to a year is the maintenance of coral cover. This requires that COTS densities are reduced to a point where the amount of coral consumed is less than or equal to the amount of coral that regenerates through growth. Babcock *et al.* (2014) identified an approximate COTS control program Catch-Per-Unit-Effort (CPUE) Ecological Threshold capable of maintaining coral cover and simple enough to inform tactical COTS control operations: 0.04 COTS per minute Dive bottom time in Sites where coral cover was lower than 40%, and 0.08 where coral cover was greater than or equal to 40%.

Achieving this threshold is critical to achieving the ecological outcome desired, but the overall efficiency of the Control Program will be sensitive to the exact value of the Ecological Threshold. This is because, like other pest management systems, marginal culling efficiency is likely to decline as pest densities are reduced and more time must be spent searching for COTS to cull. As a result, it is highly likely that proportionally more time and Control Program resources would be required to reduce the CPUE at a Site from 0.08 to 0.04 than from 0.12 to 0.08. Each additional reduction in the target threshold beyond that strictly necessary to ensure net coral growth at a Site will incur disproportionately greater costs.

This makes accurate identification of the Ecological Threshold at the Reef scale and even the Site scale a key determinant of both Control Program effectiveness and efficiency. The decision tree structure on which the Expanded Control Program is based is explicitly designed to collect the information required to estimate the Ecological Threshold more accurately in future.

Immediate recommendation (already implemented by the Expanded Control Program as part of rolling out the decision tree process): The Control Program should adopt the current best estimate of the threshold at which coral growth can outpace COTS damage: 0.04 COTS per minute Dive bottom time at Sites where coral cover is lower than 40%, and 0.08 where coral cover is greater than or equal to 40%.

Potential for future refinement: As data from the new Expanded Control Program structure becomes available, direct refinements of the Ecological Threshold should be estimated from the Control Program data itself. Future refinements could use both broad-scale (manta tow) and fine-scale (RHIS) coral cover surveys over extended periods, collected as part of the Intensive Control and Maintenance Mode operations of the Control Program, to refine estimates of the Ecological Threshold, including in relation to COTS age-size class, and across a range of coral covers and COTS densities at Reefs and Sites.

4.2 Control at Reefs

With the information currently available, there is little ecological reason to manage systems at less than the Reef scale. Our current understanding of ocean current connectivity is based on entire Reefs, and we do not have detailed sub-Reef scale habitat data for the Reefs being managed, nor detailed habitat preference data that would allow us to estimate where COTS were likely to aggregate at the Site scale. For the moment, each area of high-density COTS on a single Reef should be treated as equally important.

However, in future, if analysis of the new Expanded Control Program data or field studies occurring as part of the NESP COTS IPM Research Program show that COTS movement rates are very low under certain coral cover conditions, it may be possible to target control actions on each localised high-density aggregation of COTS within a single Reef at a scale smaller than the entire Reef, increasing efficiency.

Immediate recommendation (already implemented by the Expanded Control Program as part of rolling out the decision tree process): The Control Program should comprehensively control entire Priority Reefs until CPUEs below the current best estimate of the Ecological Threshold are achieved. Within a Reef, control should be targeted at Sites with high-density aggregations of COTS using regular manta-tow surveillance of the entire Reef boundary.

Potential for future refinement: Data collected during the first year of operation of the Expanded COTS Control Program should be used to infer currently unknown bounds on the movement rate of COTS between Sites on outbreaking Reefs with high densities of COTS over management-relevant timescales. Combined with the spatial structure of Sites on Priority Reefs, this upper bound of COTS movement rate should be simulated to virtually test the potential for sub-Reef scale targeted control actions. If sub-Reef scale control is likely to provide efficiency improvements, the performance of the DSS's internal predictive ecological model at the sub-Reef scale should be tested against the observed cull data from the Expanded COTS Control Program.

4.3 Cull Sites and Dive structure

The Historical Control Program was based around Dives of 40-minute bottom time duration up to 15 m depth for logistical and Occupational Health and Safety reasons related to commercial SCUBA operations. Many Dives were completed on snorkel, but still worked to 40-minute bottom time durations. In a 40-minute bottom time dive an average-sized Dive team of 6 to 8 divers could cull an average non-outbreaking density of COTS over an area approximately 500 m long and 200 m wide. Control Sites were historically defined by polygons designed to be covered by a team of eight divers in two 40-minute bottom time duration dives. The average historical control polygon had a mean area of 22.5 ha (S.D. 25.5 ha), mean maximum length of 897 m (S.D. 535 m), and inferred mean width 251 m.

The size of average Site polygons is a key management system parameter, because it defines the smallest scale at which resources can be distributed and data recorded. Small polygons allow aggregations to be targeted more accurately when COTS densities are high, and resources distributed over wider areas once COTS densities are reduced through management action, but risk increasing logistical and data management overheads if they become too small.

Immediate recommendation (already implemented by the Expanded Control Program as part of rolling out the decision tree process): The average size of control Site polygons should be halved from historical norms, to an area of approximately 10 hectares, with a length of approximately 500 m and width of approximately 200 m. This is the natural quantum at which data is generated and on-water decisions are currently made on-water, so it represents a simple improvement to Control Program efficiency without incurring additional overheads.

Potential for future refinement: Future refinements could test the performance of more flexible Dive structures, including smaller Dive crews (2-person) at Sites with very low estimated COTS densities, Dive durations of less than 40-minute bottom time, or coverage of more than one Site within a single Dive. Advanced refinements could include recording actual Dive start and end points or GPS tracks, and mapping results onto Sites in software, rather than defining Dives within rigidly defined polygons.

4.4 Site revisitation frequencies

The Historical Control Program targeted control actions at Sites rather than entire Reefs. It aimed to revisit Sites as often as every six weeks, but revisitation frequency was highly variable between Sites, and when resources were strained revisitation frequency often extended to 12 weeks or longer. Our analysis of the Historical Control Program showed that the Sites that were visited more frequently maintained or increased their coral cover, and sites that received more control were more likely to show larger and positive changes in hard coral cover (Westcott & Fletcher, 2018). This suggests that effective control at a Site is dependent on intensive and repeated revisitation.

Site revisitation frequency matters because if the time between Voyages to a Reef is too long, COTS populations remaining there can consume significant amounts of coral. However, because control actions at a Site aim to cull every COTS detected there, if the time between Voyages is too short, there are likely to be few COTS newly available since the previous cull, making control investment inefficient. The ecological processes determining the optimal rate of Site revisitation are: i) the rate at which injected COTS disintegrate and the rate at which fresh feeding scars become distinguishable from pre-cull scars allowing detection of unculled COTS; ii) the rate at which cryptic COTS that are undetectable and therefore not available to be culled during a specific Dive at a Site emerge and become available for future culls; and iii) the rate at which COTS immigrate into a Site from surrounding regions following control. There currently exist no reliable estimates of the relative scale of the latter two processes at the time and spatial scales relevant to the Control Program (Westcott et al., 2016). However, we can put an upper bound on the revisitation frequency from Historical Control Program data, and then use the Extended Control Program to collect data at the scale relevant to management to refine this parameter in future.

Immediate recommendation (already implemented by the Expanded Control Program as part of rolling out the decision tree process): Sites should be revisited once per Voyage, roughly every 12 days. Each Voyage, each Site selected for control should be covered completely, by: dropping a Dive crew at one end of the Site; who then comprehensively search the Site, injecting any COTS they detect; if they don't reach the other end of Site in a single 40-minute bottom time Dive, they should perform further Dives there until they have covered the entire Site. Once the Site is covered, it should not be Dived again until the following Voyage.

Potential for future refinement: Preliminary results from the Expanded Control Program suggest that a Site revisitation frequency every Voyage or 12 days is sufficient for COTS populations at individual Sites to recover and be efficiently culled using the standard Dive process. Future refinements could leverage the COTS Control Centre DSS to test adaptively shortening this revisitation schedule even further, so that a single Site could be Dived to completion more than once on a Voyage. This may require refinements to Voyage Planning and to on-water techniques for distinguishing recently culled COTS from newly emerged COTS.

4.5 Intensive Control manta tow frequencies

Early NESP COTS IPM research on the Historical Control Program showed that: i) sub-reef COTS aggregations are often highly localised; ii) that the efficiency of control actions is largely determined by how effectively these aggregations are located and targeted for culling; and iii) that high density aggregations of COTS can be efficiently located using manta tow surveillance (Fletcher and Westcott 2015). It recommended that all control visits to a Reef begin with manta tow surveillance in order to efficiently target Dives at Sites with high COTS densities. A preliminary implementation of this approach was rolled out and tested in the last 12 months of the Historical Control Program.

Because the Expanded Control Program aims to revisit Reefs and Sites at much shorter intervals (~ 2 weeks) than the Historical Control Program (6 weeks minimum, more than 12 weeks maximum), it will not be necessary to manta tow a Reef at the beginning of every Voyage in order to effectively target Sites. Ecologically, the frequency with which Intensive Control Reefs should be manta towed will be determined by how quickly COTS populations move around the Reef and how well the ecological model on which the decision trees are based can predict changes in COTS populations. The new Expanded Control Program, using the simplified on-water decision tree, effectively uses surveillance data directly without a predictive model of COTS populations, so will require relatively frequent manta tows. The COTS Control Centre DSS will use an advanced management-population model incorporating the Control Program data itself to inform decision making, which may allow less frequent manta towing in future.

Immediate recommendation (already implemented by the Expanded Control Program as part of rolling out the decision tree process): Each Intensive Control Reef should be manta towed approximately every 42 days, roughly every fourth Voyage. This is similar to the frequency of manta tow tested in the final months of the Historical Control Program. It strikes a balance between collecting timely data to inform decision making and using resources efficiently, while collecting the baseline data required to improve the ecological models on which the DSS is based and the future efficiency of the Control Program.

Potential for future refinement: As the COTS Control Centre DSS is rolled out, variations in the Intensive Control manta tow frequency should be gradually iterated and tested using an adaptive management approach. This will allow us to empirically determine the manta tow frequency necessary to accurately drop divers at COTS aggregations while minimising resource requirements. This dynamic process should be implemented into the DSS so that it can be lengthened as the predictive models in the DSS are refined.

4.6 Maintenance Mode manta tow frequencies

Manta towing Reefs that have been transitioned to Maintenance Mode is a crucial part of the decision tree system. It is designed to compensate for current limitations in our understanding of the ecological processes driving the system, the effectiveness of management, and the effect of large but unpredictable external factors such as cyclones and bleaching on the Control Program. Vitally, it also allows us to collect data at scales that can help improve our understanding of these factors in future.

The optimal frequency of manta tow at Maintenance Mode Reefs will depend on ecological factors accumulating over timescales of months. Very little data at these timescales is currently available, because previous studies have predominantly focussed on hourly to daily movements of COTS individuals (Pratchett et al., 2017) or population dynamics over years (Lawrey, 2015). The manta tow frequency for Maintenance Mode Reefs in the Expanded Control Program aims to balance the resource requirements of repeatedly manta towing an increasing portfolio of Reefs that have successfully been moved to Maintenance Mode against the need to ensure that these reefs remain below the Ecological Threshold.

Immediate recommendation (already implemented by the Expanded Control Program as part of rolling out the decision tree process): Reefs in Maintenance Mode should be manta towed every three to six months. This is likely to represent a manageable surveillance load for operators focussed primarily on culling down high COTS densities on Reefs near the current outbreak front, with relatively few Reefs moved from Intensive Control to Maintenance Mode. It will also allow vital data to be collected about re-emergence of outbreaks at previously controlled Reefs to inform future refinements to the Control Program.

Potential for future refinement: The optimal frequency to repeat manta tows at Reefs in Maintenance Mode should be estimated directly from the data collected during the first year of operation of the Expanded Control Program. Because there are two distinct management-ecological drivers of Reefs in Maintenance Mode, creating two classes of Maintenance Mode Reefs should be considered: i) those Reefs that were immediately moved into Maintenance Mode because there were a very low background density of COTS there on first visitation, and so are unlikely to spontaneously outbreak; and ii) those Reefs that were outbreaking on first visitation, and were subsequently successfully controlled from Intensive Control to Maintenance Mode, where the risk of re-emergent outbreak may be higher.

In theory, manta towing reefs is a simpler task than culling operations as it does not involve scuba diving and can be conducted with smaller teams operating from smaller vessels. In some areas these vessels could be land-based rather than operating over voyages lasting ten days. This may provide the opportunity for divesting responsibility for Maintenance Mode manta towing to other operators, including Traditional Owner groups wishing to play an active role in the management of their sea country.

4.7 Voyage Planning

The Historical Control Program involved a single contractor using either one or two Vessels to control a relatively constrained geographic region, with a single dedicated program manager coordinating the actions of all Vessels. This allowed Voyage Plans to be manually optimised across the fleet. The Expanded COTS Control Program, in contrast, involves multiple contractors operating Vessels with different crews and capabilities across a wide geographic scale, encompassing Reefs experiencing very different phases of the outbreak.

This increase in the scale of management introduces significant opportunities to improve efficiency through smart scheduling of Voyages, but also difficulties in ensuring that data and control actions are sequenced between Vessels at sea quickly and reliably enough to consistently apply ecological management principles. The simplest way of manually scheduling operations across the fleet to ensure ecologically meaningful outcomes at each controlled Reef is to assign a unique set of Priority Reefs to each Vessel, even if Vessels' operational regions overlap. In future, a dynamic scheduling approach across the fleet could refine this further. It could focus more resources on high density infestations at the regional scale by moving Vessels between regions in response to an increased understanding of regional COTS densities as the Expanded COTS Control Program collects more data. It could also focus resources at the Reef scale by sequencing Vessels to visit the same Reef one after another to reduce the time between Dives at Sites.

Immediate recommendation (already implemented by the Expanded Control Program as part of rolling out the decision tree process): Each Vessel should be assigned a unique set of Priority Reefs, even if their operational regions overlap. This will allow each Vessel to implement the decision tree process independently, ensuring ecologically meaningful outcomes at each Reef managed, independent of the speed and reliability of data sharing between Vessels.

Potential for future refinement: As automated and connected data collection across the fleet matures, the COTS Control Centre DSS should be used to test whether dynamically scheduling Voyages to Reefs between Vessels can improve Control Program efficiency through more frequent Site revisitation or temporary redistribution of Vessels between regions.

REFERENCES

Babcock, R., Plaganyi, E., Morello, E., Rochester, W., Hoey, J., Pratchett, M., & Anthony, K. (2014). *What are the important thresholds and relationships to inform the management of COTS? Draft report, 30 June 2014*. Retrieved from Australia: http://hdl.handle.net/11017/2955

Bos, A. R., Gumanao, G. S., Mueller, B., & Saceda-Cardoza, M. M. E. (2013). Management of crown-of-thorns sea star (Acanthaster planci L.) outbreaks: Removal success depends on reef topography and timing within the reproduction cycle. *Ocean & Coastal Management, 71*, 116-122. doi:http://dx.doi.org/10.1016/j.ocecoaman.2012.09.011

Bruno, J. F., & Selig, E. R. (2007). Regional Decline of Coral Cover in the Indo-Pacific: Timing, Extent, and Subregional Comparisons. *PLoS ONE, 2*(8), e711. doi:10.1371/journal.pone.0000711

Claar, D. C., Szostek, L., McDevitt-Irwin, J. M., Schanze, J. J., & Baum, J. K. (2018). Global patterns and impacts of El Niño events on coral reefs: A meta-analysis. *PLoS ONE, 13*(2), e0190957. doi:10.1371/journal.pone.0190957

De'ath, G., Fabricius, K. E., Sweatman, H., & Puotinen, M. (2012). The 27-year decline of coral cover on the Great Barrier Reef and its causes. *Proceedings of the National Academy of Sciences, 109*(44), 17995-17999. doi:10.1073/pnas.1208909109

Firth, S., & McKenzie, C. (2015). *Crown-of-thorns starfish (COTS) control program : Voyage data - Catch per Unit of Effort (CPUE), Eradicated COTS size and coral cover from July 2013 - Jan 2015 (AMPTO)*. Retrieved from: http://eatlas.org.au/geonetwork/srv/eng/metadata.show?uuid=fe100cb3-9b29-4e6b-a8e1-0434631064fa&currTab=complete

Fletcher, C. S., & Westcott, D. A. (2016). *Strategies for Surveillance and Control: Using Crown-of-Thorns Starfish management program data to optimally distribute management resources between surveillance and control. Report to the National Environmental Science Programme. Reef and Rainforest Research Centre Limited*. Retrieved from Cairns:

Gardner, T. A., Côté, I. M., Gill, J. A., Grant, A., & Watkinson, A. R. (2003). Long-Term Region-Wide Declines in Caribbean Corals. *Science, 301*(5635), 958-960. doi:10.1126/science.1086050

GBRMPA. (unpublished). *Integrated pest management operations manual for crown-of-thorns starfish control program vessels*. Townsville: Great Barrier Reef Marine Park Authority

GBRPMA. (2017). *Great Barrier Reef blueprint for resilience*. Townsville: Great Barrier Reef Marine Park Authority

Gladstone, W. (1993). *The history of crown-of-thorns starfish controls on the Great Barrier Reef and an assessment of future needs for controls*. Paper presented at the The Possible cause and consequences of outbreaks of the crown-ofthorns starfish. , Proceedings of a workshop held in Townsville, Queensland, Australia.

Hoegh-Guldberg, O. (1999). Climate change, coral bleaching and the future of the world's coral reefs. *Mar. Freshwater Res., 50*(8), 839. doi:10.1071/mf99078

Hughes, T. P. (2003). Climate Change, Human Impacts, and the Resilience of Coral Reefs. *Science, 301*(5635), 929-933. doi:10.1126/science.1085046

Hughes, T. P., Anderson, K. D., Connolly, S. R., Heron, S. F., Kerry, J. T., Lough, J. M., . . . Wilson, S. K. (2018). Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science, 359*(6371), 80-83. doi:10.1126/science.aan8048

Hughes, T. P., Kerry, J. T., & Simpson, T. (2018). Large-scale bleaching of corals on the Great Barrier Reef. *Ecology, 99*(2), 501-501. doi:10.1002/ecy.2092

Lawrey, E. (2015). Crown-of-thorns starfish (Acanthaster) statistical modelled distribution from LTMP Manta Tow Data (NERP TE 13.1, AIMS). Retrieved from http://eatlas.org.au/data/uuid/84bcf698-569b-4907-958a-974c262a363c

MacNeil, M. A., Mellin, C., Pratchett, M. S., Hoey, J., Anthony, K. R. N., Cheal, A. J., . . . Fonnesbeck, C. J. (2016). Joint estimation of crown of thorns (Acanthaster planci) densities on the Great Barrier Reef. *PeerJ, 4*, e2310. doi:10.7717/peerj.2310

Pearson, R. G. (1981). Recovery and Recolonization of Coral Reefs. *Marine Ecology Progress Series, 4*, 105-122. doi:10.3354/meps004105

Pratchett, M. S., Caballes, C. F., Rivera-Posada, J. A., & Sweatman, H. P. A. (2014). Limits to Understanding and Managing Outbreaks of Crown-of-Thorns Starfish (*Acanthaster* spp.). *Oceanography and Marine Biology: An Annual Review, 52*, 133-200. doi:doi:10.1201/b17143-4

10.1201/b17143-4

Pratchett, M. S., Cowan, Z.-L., Nadler, L. E., Caballes, C. F., Hoey, A. S., Messmer, V., . . . Ling, S. D. (2017). Body size and substrate type modulate movement by the western Pacific crown-of-thorns starfish, Acanthaster solaris. *PLoS ONE, 12*(9). doi:10.1371/journal.pone.0180805

Price, M. (2018). New starfish-fighting fleet on the horizon [Press release]. Retrieved from https://web.archive.org/web/20180911124438/https://www.environment.gov.au/minister/price/media-releases/mr20180613.html

Rivera-Posada, J., Caballes, C. F., & Pratchett, M. S. (2013). Lethal doses of oxbile, peptones and thiosulfate-citrate-bile-sucrose agar (TCBS) for Acanthaster planci; exploring alternative population control options. *Marine Pollution Bulletin, 75*(1-2), 133-139. doi:10.1016/j.marpolbul.2013.07.053

Rivera-Posada, J., & Prattchett, M. (2012). *A review of existing control efforts for Acanthaster planci; limitations to successes, Report to the Department of Sustainability, Environment, Water, Population & Communities,*. Townsville, June 5 2012

Rivera-Posada, J. A., Pratchett, M., Cano-Gómez, A., Arango-Gómez, J. D., & Owens, L. (2011). Injection of Acanthaster planci with thiosulfate-citrate-bile-sucrose agar (TCBS). I. Disease induction. *Diseases of Aquatic Organisms, 97*(2), 85-94. doi:10.3354/dao02401

Westcott, D. A., & Fletcher, C. S. (2018). *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*. Retrieved from Cairns:

Westcott, D. A., & Fletcher, C. S. (2019). NESP Project 5.1: Matching the Crown-of-Thorns Starfish Integrated Pest Management to the scale of the new Control Program. In.

Westcott, D. A., Fletcher, C. S., Babcock, R., Hoj, L., Kroon, F., Uthicke, S., . . . Hock, K. (2018). NESP Project 4.1: Crown-of-thorns starfish: surveillance and life history.

Westcott, D. A., Fletcher, C. S., Babcock, R., & Plaganyi-Lloyd, E. (2016). *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*. Retrieved from

Westcott, D. A., Fletcher, C. S., Babcock, R., Plaganyi, E., Pratchett, M., Messmer, V., . . . Doyle, J. (2017). NESP Project 3.1.1, Regional Scale Integrated Pest Management of Crown-of-Thorns Starfish. In.

Yamaguchi, M. (1986). Acanthaster planci infestations of reefs and coral assemblages in Japan: a retrospective analysis of control efforts. *Coral Reefs, 5*(1), 23-30. doi:10.1007/bf00302168

APPENDIX 1: IMPLEMENTING THE SIMPLE DECISION TREE

On November 1st 2018, an on-water contractor was directed to John Brewer Reef for the first time, with instructions to follow the simplified decision tree to implement control at the Reef. The worked example below shows how data collected during on-water control activities was employed, using the decision tree, to influence decisions made at the Reef in a step by step manner.

At the beginning of control actions, John Brewer Reef was covered by 28 Sites predefined by GBRMPA staff (Figure 11a). Between November 1st 2018 and June 30th 2019, fifteen Voyages of approximately nine days' duration were conducted to the Reef. Five of these Voyages involved comprehensive manta tows. Each Voyage typically conducted just under 12000 minutes bottom-time cull Dives on Voyages that did not involve a manta tow, and 8000 minutes on those that did. This is consistent with Historical Control Program voyages, which typically conducted 36 dives of 40 minutes bottom time duration with up to 8-person dive crews. Vessels typically spent at least 5 days in port between Voyages, although occasionally spent longer.

Figure 11 shows the number of COTS of each size class culled each Voyage (Figure 11c) and cumulatively (Figure 11d). This shows that when control first began the bulk of starfish controlled were in the two largest size classes, but that the relative proportion of the catch in these large size classes decreased over each Voyage. This is important because large starfish consume the most coral. An approximate estimate of the cumulative amount of coral saved each day by these control actions is shown in Figure 11d. Note that this represents an instantaneous estimate of the amount of coral that the number and size of starfish controlled could consume in a single day, but does not take into account population growth over the 34 week period of the data presented, which could be significant.

Below, we show how the control program staff used the data collected during each Voyage to structure the on-water decisions leading to these excellent outcomes.

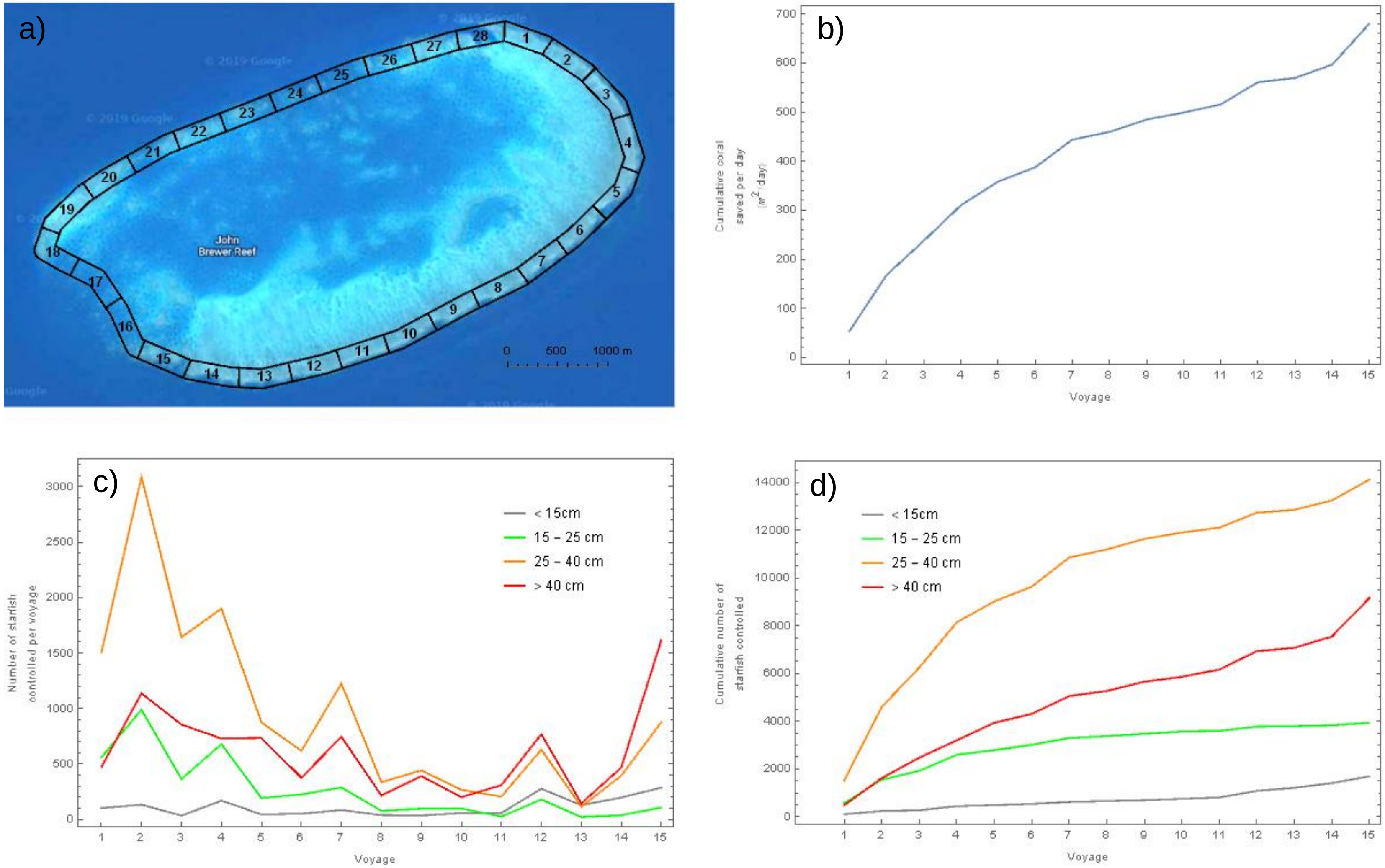


Figure 11: Summary Control Program results from John Brewer reef, with 28 control sites marked

Voyage 1

The first time John Brewer Reef was visited, the on-water decision tree directed control program staff to perform a manta tow. The result of the comprehensive series of manta tows is shown in the solid coloured lines in Figure 12a, and Table 5 (columns ‘COTS Count’ and ‘Scar Category’). In Figure 12a, manta tows are shown as red if more than 10 COTS and/or scars were recorded within the two-minute tow; orange for 3 – 10 COTS and/or scars, green for 1 – 3 COTS and/or scars, and grey for no COTS or scars present. In Table 5, “Scar Category” is a categorical variable in which category “a” or “absent” represents 0 scars counted; “p” or “present” represents 1 – 10 scars counted; and “c” or “common” represents > 10 scars counted

The simplified decision tree then directed that the operator use these tows to estimate the relative density of COTS across each of the GBRMPA-defined sites, and rank Sites in order of largest estimated COTS density to lowest. On-water this was done by-eye from observation of manta tow results, and as a result, on-water operators focussed cull activities during Voyage 1 across Sites 1 – 5 and Site 7. With the benefit of hindsight and advanced analysis, we can (Table 5, ‘Rank Before’ column):

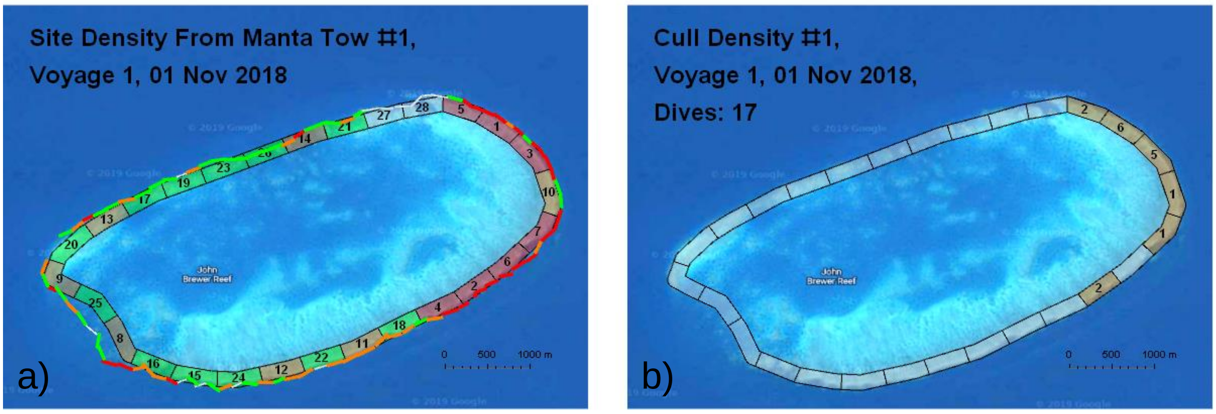
- Assign each manta tow to the closest Site
- Calculate the mean COTS Count and Scar Category across manta tows assigned to each Site
- Colour each Site in Figure 1 using the same categories as the manta tows themselves
- Rank each Site from highest estimated COTS density to lowest

The calculated Rank Before score provides recommendations about which six Sites should be controlled first that are broadly similar (Sites 1, 2, 3, 6, 7, 8) to those used by on-water controllers (Sites 1, 2, 3, 4, 5, 7).

The on-water decision tree then instructed staff to begin cull actions at the highest ranked Sites first, diving repeatedly at a Site until it had been comprehensively covered from one end to the other. During the first Voyage to John Brewer Reef, on-water staff accordingly began control actions at the highest ranked Sites, as illustrated in Figure 12b and Table 5 (‘Cull’ columns). Due to the high densities of COTS found at these Sites, they all required multiple Dives to complete a single comprehensive cull (Figure 12b, numbers inside Site polygons, and Table 5 ‘Number of Dives’ column). For instance, Site 2 was Dived during the first full day of culling. Due to the density of COTS found and culled there, the Site was not completed within a single 40 minute bottom time Dive, and so was Dived again. It eventually took eight Dives across two days to cover the entire Site, and the total CPUE achieve over those Dives was 0.80 COTS per minute bottom time.

After completing the comprehensive manta tow and 25 Dives, the Vessel headed back to port. The CPUEs achieved at the six culled Sites were significantly higher than the Ecological Threshold. Interestingly, looking at the relative rank of the culled Sites based on CPUE achieved (Table 5 ‘Rank After’ column), shows that relative abundance of COTS at several Sites differed from that estimated from manta tow (Table 5 ‘Rank Before’ column).

Figure 12 and Table 5: Voyage 1



Site	Manta tow			Cull						
	COTS Count	Scar Category	Above Threshold?	Rank From	Rank Before	Number of Dives	CPUE	Above Threshold?	Rank After	Rank From
1	40, 0	p, p	Y	M	3	2	0.77	Y	3	C
2	18, 4, 35, 29	c, p, p, p	Y	M	1	8	0.80	Y	1	C
3	9, 4, 7, 0	c, c, c, p	Y	M	6	7	0.44	Y	5	C
4	0, 0, 7	p, p, c	Y	M	8	2	0.64	Y	4	C
5	1, 5, 3	p, c, c	Y	M	7	2	0.43	Y	6	C
6	2, 7, 7	c, c, c	Y	M	5				8	M
7	25, 12, 8	c, c, c	Y	M	2	4	0.79	Y	2	C
8	3, 15, 10	p, c, c	Y	M	4				7	M
9	4, 2, 0	p, p, p	Y	M	17				17	M
10	0, 2, 2	c, p, p	Y	M	10				10	M
11	0, 7	a, p	Y	M	19				19	M
12	2, 0, 2, 4	p, p, p, p	Y	M	18				18	M
13	2, 0, 0	p, a, p	Y	M	26				26	M
14	0, 0, 0, 2, 0	a, p, a, c, p	Y	M	22				22	M
15	1, 1, 0	p, p, c	Y	M	15				15	M
16	2, 1, 0, 0	c, c, p, p	Y	M	9				9	M
17	0, 0, 2	a, p, p	Y	M	25				25	M
18	6, 0, 0, 1	c, p, p, p	Y	M	11				11	M
19	0, 6	p, p	Y	M	14				14	M
20	10, 0, 0	p, p, p	Y	M	13				13	M
21	0, 0, 0	c, p, p	Y	M	16				16	M
22	0, 0, 0	p, a, c	Y	M	20				20	M
23	0, 0, 0	p, p, p	Y	M	24				24	M
24	0, 0	p, p	Y	M	23				23	M
25	1, 2, 0	p, c, p	Y	M	12				12	M
26	2, 0, 0	p, p, p	Y	M	21				21	M
27	0, 0, 0	a, a, a	N	M	28				28	M
28	0, 0, 0	a, a, a	N	M	27				27	M

Voyage 2

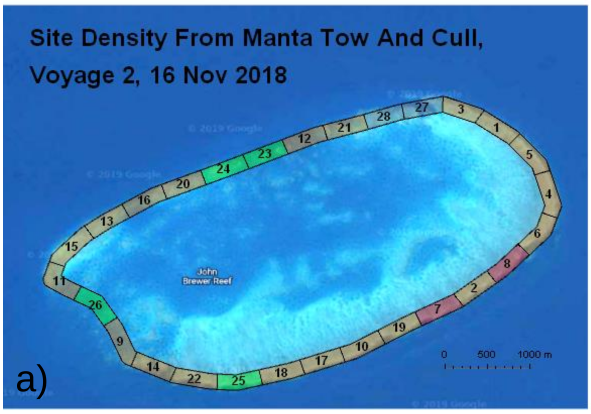
On the second Voyage, the on-water decision tree directed control program staff to begin culling without performing a new manta tow (Table 6, empty 'Manta tow' column). Instead, the decision tree directed control program staff to prioritise Sites for cull starting with:

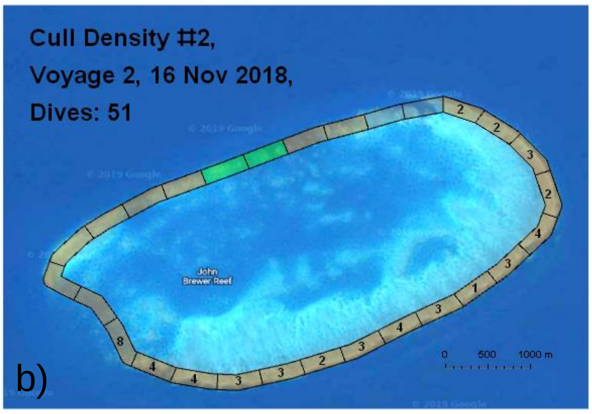
1) previously culled Sites with CPUEs above the Ecological Threshold, in order from highest CPUE to lowest; and
2) previously unculled Sites based on the most recent manta tow density, from highest to lowest (Table 6 'Rank Before' column and Figure 13a, numbers inside Site polygons).

Again, at this point the on-water decision tree then instructed staff to begin cull actions at the highest ranked Sites first, diving repeatedly at a Site until it had been comprehensively covered from one end to the other. On-water staff accordingly began control actions at the highest ranked Sites, as illustrated in Figure 13 and Table 6 ('Cull' columns). Because no manta tow was required at the beginning of the Voyage, and because the Sites culled generally took fewer Dives to cover comprehensively than those in Voyage 1, far more Sites were culled during Voyage 2. An interesting exception was Site 16, which required 10 Dives to cover comprehensively, for a total CPUE over those Dives of 0.44 COTS per minute bottom time.

After completing 69 Dives, the Vessel headed back to port. With the exception of Sites 2 and 3, both of which were culled during Voyage 1, the CPUEs achieved at the culled Sites were significantly higher than the Ecological Threshold.

Figure 13 and Table 6: Voyage 2





Site	Manta tow			Cull						
	COTS Count	Scar Category	Above Threshold?	Rank From	Rank Before	Number of Dives	CPUE	Above Threshold?	Rank After	Rank From
1				C	3	2	0.13	Y	15	C
2				C	1	3	0.05	N	17	C
3				C	5	4	0.09	Y	16	C
4				C	4	3	0.17	Y	13	C
5				C	6	5	0.33	Y	11	C
6				M	8	5	0.42	Y	8	C
7				C	2	2	0.15	Y	14	C
8				M	7	3	0.34	Y	10	C
9				M	19	6	0.53	Y	6	C
10				M	10	4	0.63	Y	4	C
11				M	17	3	0.76	Y	1	C
12				M	18	4	0.65	Y	3	C
13				M	25	4	0.59	Y	5	C
14				M	22	5	0.65	Y	2	C
15				M	14	5	0.36	Y	9	C
16				M	9	10	0.44	Y	7	C
17				M	26	1	0.20	Y	12	C
18				M	11				18	M
19				M	15				21	M
20				M	13				20	M
21				M	16				22	M
22				M	20				23	M
23				M	24				26	M
24				M	23				25	M
25				M	12				19	M
26				M	21				24	M
27				M	28				28	M
28				M	27				27	M

Voyage 3

On the third Voyage, the on-water decision tree directed control program staff to begin culling without performing a new manta tow. However, control program staff did manta tow at the beginning of Voyage 3 (Figure 14a, solid lines and Table 7, ‘Manta tow’ column). Having completed a manta tow, the simplified decision tree directed control program staff to rerank all Sites based on the estimated density from the new manta tow. On-water this was done by-eye from observation of manta tow results, and as a result, on-water operators focussed cull activities during Voyage 3 across Sites 14 – 18. With the benefit of hindsight and advanced analysis, we can calculate the precise rank of each Site (Table 7, ‘Rank Before’ column). Again, the precise analysis shows broad agreement with the Sites selected on-water, with three of the four highest ranked Sites controlled.

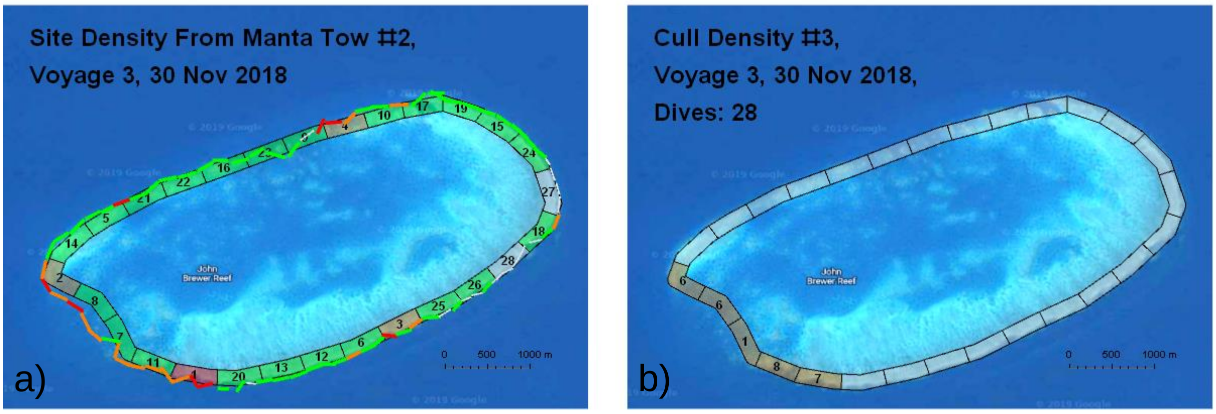
At this point, the on-water decision tree instructed staff to begin cull actions at the highest ranked Sites first, diving repeatedly at each Site until it had been comprehensively covered from one end to the other. On-water staff accordingly began control actions at the highest ranked Sites, as illustrated in Figure 14 and Table 7 (‘Cull’ columns). In total, five Sites were covered during Voyage 3, using 37 Dives.

After completing the comprehensive manta tow and cull Dives, the Vessel headed back to port. The CPUEs achieved at the culled Sites were all significantly higher than the Ecological Threshold.

Voyages 4 - 15

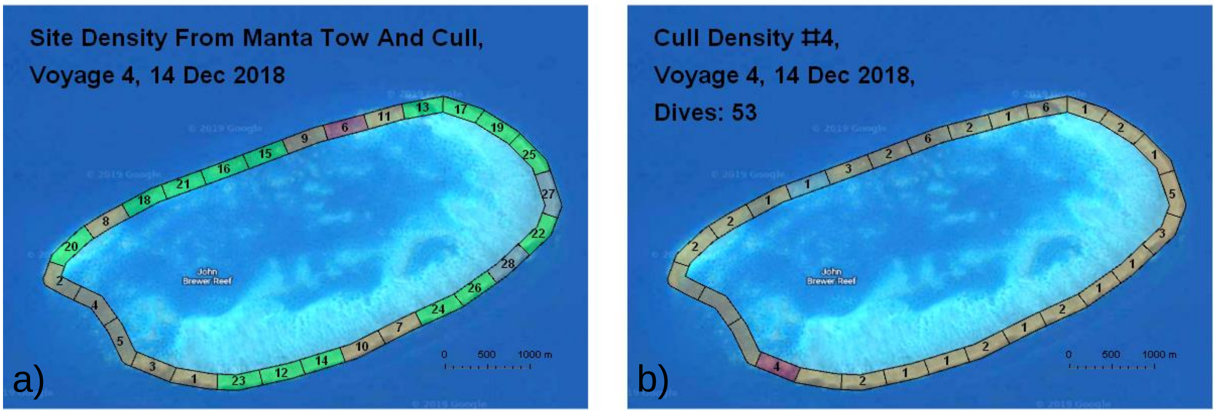
The same process was then followed for the subsequent twelve Voyages. The corresponding Figures and Tables are presented below.

Figure 14 and Table 7: Voyage 3



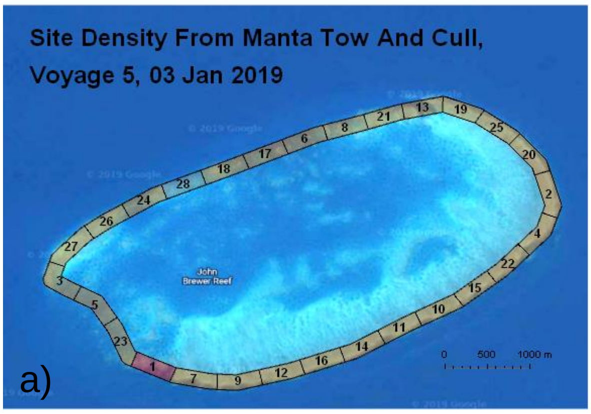
Site	Manta tow			Cull						
	COTS Count	Scar Category	Above Threshold?	Rank From	Rank Before	Number of Dives	CPUE	Above Threshold?	Rank After	Rank From
1	0, 0	p, p	Y	M	21				21	M
2	0, 0, 0	p, p, p	Y	M	17				17	M
3	0, 0, 0	a, p, p	Y	M	24				24	M
4	0, 0, 0	a, a, a	N	M	28				28	M
5	0, 0, 2	a, p, p	Y	M	22				22	M
6	0, 0, 0, 0	a, a, a, a	N	M	27				27	M
7	0, 0, 0	a, a, p	Y	M	26				26	M
8	0, 0, 0	p, a, p	Y	M	23				23	M
9	1, 0, 0	c, p, c	Y	M	5				7	M
10	0, 0, 0	c, p, p	Y	M	9				11	M
11	0, 0, 0	p, p, p	Y	M	20				20	M
12	0, 0, 0	p, p, p	Y	M	19				19	M
13	0, 0, 0	p, a, p	Y	M	25				25	M
14	1, 0, 4	c, c, c	Y	M	1	11	0.59	Y	1	C
15	3, 1, 1	p, p, p	Y	M	10	13	0.35	Y	3	C
16	1, 2, 0, 1	p, p, p, p	Y	M	11	1	0.06	N	5	C
17	2, 1	p, c	Y	M	4	6	0.29	Y	4	C
18	1, 10, 2	p, c, p	Y	M	3	6	0.50	Y	2	C
19	0, 0, 0	p, p, p	Y	M	18				18	M
20	0, 0, 1	p, p, c	Y	M	6				8	M
21	0, 0	p, p	Y	M	16				16	M
22	0, 0	p, p	Y	M	15				15	M
23	0, 0, 0	p, p, p	Y	M	14				14	M
24	0, 0	p, p	Y	M	13				13	M
25	0, 0, 3	p, a, c	Y	M	8				10	M
26	2, 0	c, c	Y	M	2				6	M
27	0, 0, 0	p, p, c	Y	M	7				9	M
28	0, 0, 0	p, p, p	Y	M	12				12	M

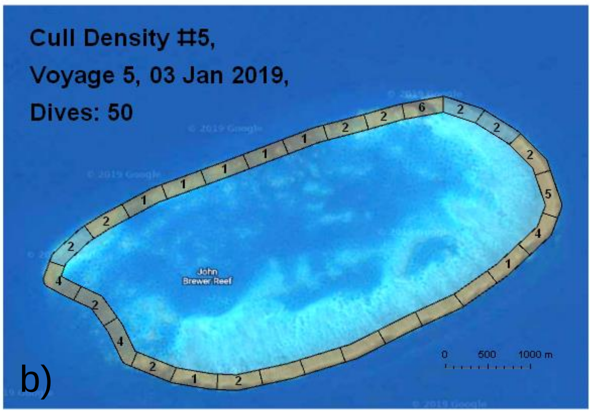
Figure 15 and Table 8: Voyage 4



Site	Manta tow			Cull						
	COTS Count	Scar Category	Above Threshold?	Rank From	Rank Before	Number of Dives	CPUE	Above Threshold?	Rank After	Rank From
1				M	17	2	0.09	Y	19	C
2				M	19	4	0.06	N	25	C
3				M	25	1	0.09	Y	20	C
4				M	27	6	0.51	Y	2	C
5				M	22	4	0.33	Y	4	C
6				M	28	2	0.07	N	22	C
7				M	26	2	0.14	Y	15	C
8				M	24	4	0.21	Y	10	C
9				M	7	2	0.20	Y	11	C
10				M	10	3	0.14	Y	14	C
11				M	14	1	0.12	Y	16	C
12				M	12	1	0.17	Y	12	C
13				M	23	3	0.21	Y	9	C
14				C	1	1	0.25	Y	7	C
15				C	3	4	1.30	Y	1	C
16				C	5				23	C
17				C	4				5	C
18				C	2				3	C
19				M	20	3	0.05	N	27	C
20				M	8	3	0.06	N	26	C
21				M	18	2	0.06	N	24	C
22				M	21	2	0.04	N	28	C
23				M	16	3	0.09	Y	18	C
24				M	15	2	0.10	Y	17	C
25				M	9	7	0.28	Y	6	C
26				M	6	3	0.22	Y	8	C
27				M	11	1	0.08	N	21	C
28				M	13	7	0.15	Y	13	C

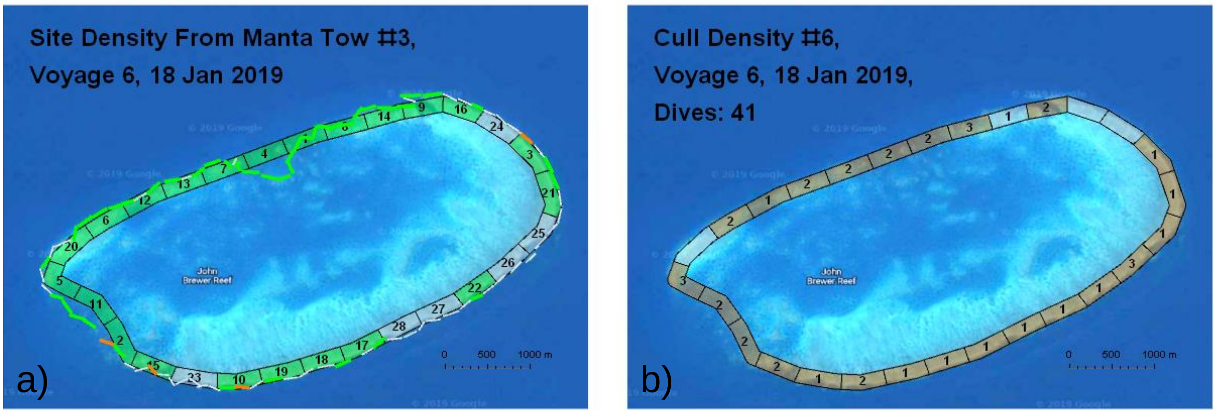
Figure 16 and Table 9: Voyage 5





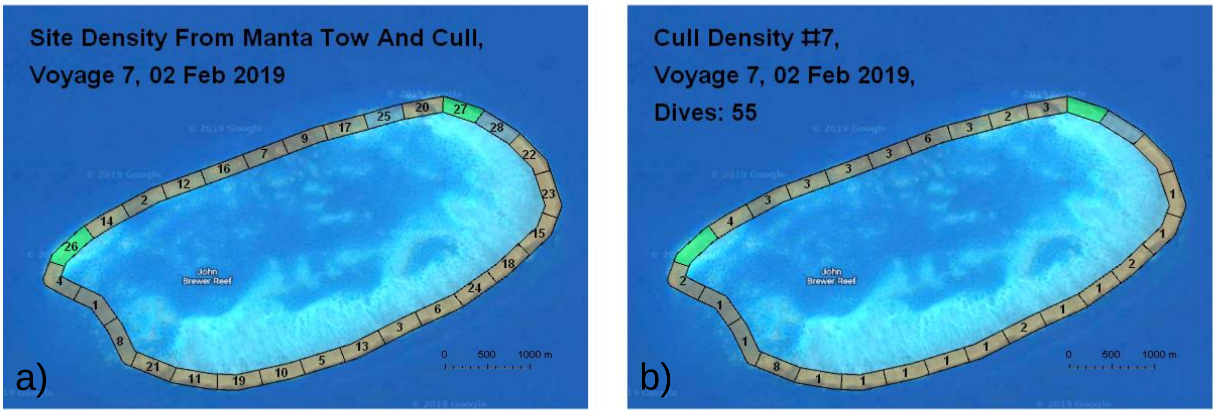
Site	Manta tow			Cull						
	COTS Count	Scar Category	Above Threshold?	Rank From	Rank Before	Number of Dives	CPUE	Above Threshold?	Rank After	Rank From
1				C	19	3	0.03	N	28	C
2				C	25	3	0.03	N	27	C
3				C	20	3	0.07	N	24	C
4				C	2	7	0.18	Y	9	C
5				C	4	5	0.10	Y	20	C
6				C	22	1	0.10	Y	18	C
7				C	15				14	C
8				C	10				6	C
9				C	11				7	C
10				C	14				13	C
11				C	16				17	C
12				C	12				11	C
13				C	9	3	0.17	Y	10	C
14				C	7	2	0.10	Y	19	C
15				C	1	3	0.18	Y	8	C
16				C	23	6	0.23	Y	4	C
17				C	5	3	0.36	Y	2	C
18				C	3	6	0.21	Y	5	C
19				C	27	3	0.03	N	26	C
20				C	26	2	0.26	Y	3	C
21				C	24	3	0.58	Y	1	C
22				C	28	2	0.12	Y	16	C
23				C	18	2	0.09	Y	21	C
24				C	17	2	0.08	Y	22	C
25				C	6	2	0.15	Y	12	C
26				C	8	4	0.13	Y	15	C
27				C	21	3	0.07	N	25	C
28				C	13	8	0.08	N	23	C

Figure 17 and Table 10: Voyage 6



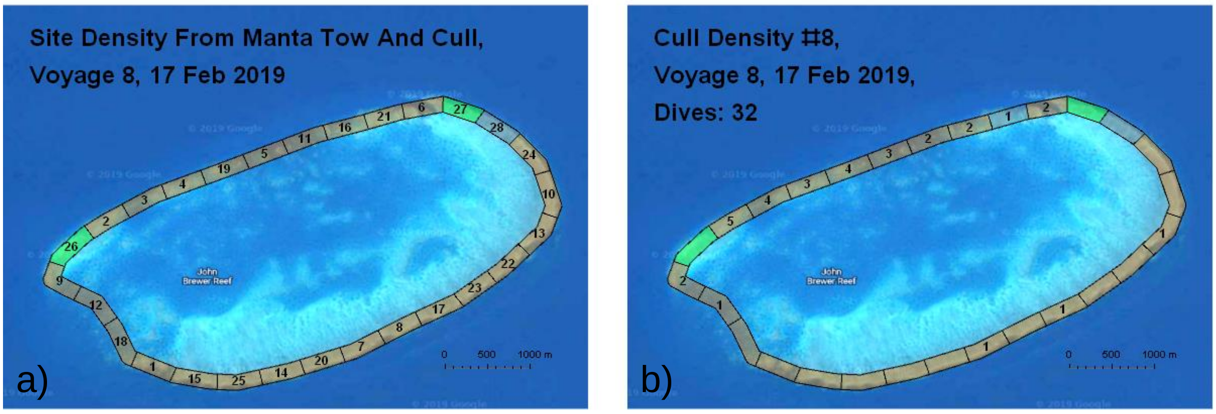
Site	Manta tow			Cull						
	COTS Count	Scar Category	Above Threshold?	Rank From	Rank Before	Number of Dives	CPUE	Above Threshold?	Rank After	Rank From
1	0, 0, 0	p, a, a	Y	M	22				27	M
2	0, 0, 0, 0	a, a, a, a	N	M	28				28	M
3	0, 0, 0	p, a, c	Y	M	2	1	0.05	N	22	C
4	0, 0, 0	a, a, p	Y	M	19	2	0.04	N	23	C
5	0, 0	a, a	N	M	26	2	0.11	Y	15	C
6	0, 0, 0	a, a, a	N	M	27	5	0.07	N	18	C
7	0, 0, 0	a, p, a	Y	M	20	2	0.04	N	24	C
8	0, 0	a, a	N	M	24	2	0.18	Y	6	C
9	0, 0, 0	a, a, a	N	M	23	2	0.24	Y	3	C
10	0, 0	a, p	Y	M	16	2	0.12	Y	13	C
11	0, 0, 0	p, a, a	Y	M	18	1	0.21	Y	5	C
12	0, 0	p, a	Y	M	15	1	0.14	Y	10	C
13	0, 2, 0	p, p, a	Y	M	9	2	0.06	N	19	C
14	0, 0, 0, 0, 0, 0	a, a, a, a, a, a	N	M	25	2	0.13	Y	11	C
15	0, 1, 0	a, p, a	Y	M	17	3	0.06	N	21	C
16	0, 0, 0	a, p, c	Y	M	1	3	0.15	Y	8	C
17	0, 0	p, p	Y	M	3	4	0.38	Y	1	C
18	0, 0, 0, 0, 0	p, p, a, a, p	Y	M	14	4	0.23	Y	4	C
19	0, 0, 0	a, a, p	Y	M	21				26	M
20	0, 0, 0	p, p, p	Y	M	6	2	0.12	Y	14	C
21	0, 0, 0	p, a, p	Y	M	12	3	0.26	Y	2	C
22	0, 0, 0	p, a, p	Y	M	13	3	0.13	Y	12	C
23	0, 0, 0, 0	p, p, p, a	Y	M	10	2	0.11	Y	16	C
24	0, 0, 0, 0	p, p, p, p	Y	M	4	2	0.16	Y	7	C
25	0, 0, 0, 0, 0	p, p, p, p, p	Y	M	5	2	0.14	Y	9	C
26	0, 0, 0	p, p, p	Y	M	7	3	0.11	Y	17	C
27	0, 0	p, p	Y	M	8	2	0.04	N	25	C
28	0, 0, 0, 0	p, a, p, p	Y	M	11	3	0.06	N	20	C

Figure 18 and Table 11: Voyage 7



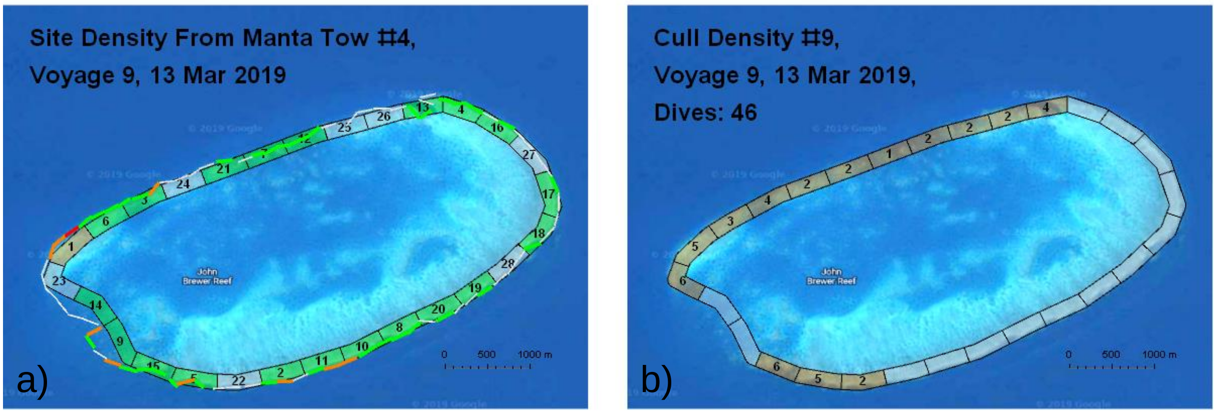
Site	Manta tow			Cull						
	COTS Count	Scar Category	Above Threshold?	Rank From	Rank Before	Number of Dives	CPUE	Above Threshold?	Rank After	Rank From
1				M	27				27	M
2				M	28				28	M
3				C	22				24	C
4				C	23	2	0.12	Y	10	C
5				C	15	2	0.11	Y	13	C
6				C	18	3	0.06	N	22	C
7				C	24	3	0.05	N	23	C
8				C	6	2	0.09	Y	17	C
9				C	3	3	0.14	Y	8	C
10				C	13	3	0.14	Y	7	C
11				C	5	2	0.08	N	20	C
12				C	10	2	0.10	Y	14	C
13				C	19	3	0.05	N	25	C
14				C	11	2	0.10	Y	15	C
15				C	21	7	0.39	Y	1	C
16				C	8	2	0.09	Y	18	C
17				C	1	1	0.11	Y	12	C
18				C	4	2	0.12	Y	9	C
19				M	26				26	M
20				C	14	5	0.39	Y	2	C
21				C	2	4	0.29	Y	3	C
22				C	12	4	0.18	Y	4	C
23				C	16	4	0.08	N	19	C
24				C	7	5	0.14	Y	5	C
25				C	9	8	0.12	Y	11	C
26				C	17	3	0.09	Y	16	C
27				C	25	3	0.06	N	21	C
28				C	20	4	0.14	Y	6	C

Figure 19 and Table 12: Voyage 8



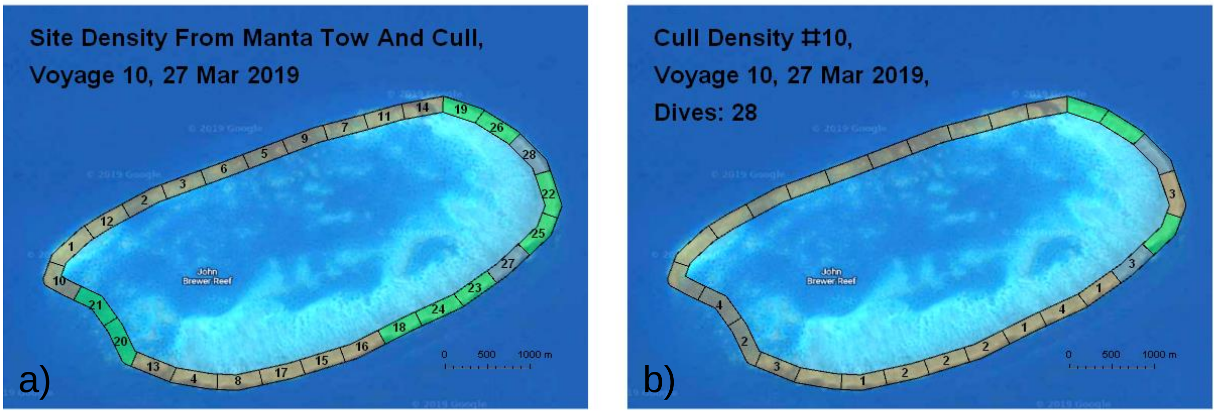
Site	Manta tow			Cull						
	COTS Count	Scar Category	Above Threshold?	Rank From	Rank Before	Number of Dives	CPUE	Above Threshold?	Rank After	Rank From
1				M	27				27	M
2				M	28				28	M
3				C	24				22	C
4				C	10				5	C
5				C	13	1	0.10	Y	10	C
6				C	22				20	C
7				C	23				21	C
8				C	17	2	0.08	N	15	C
9				C	8	1	0.13	Y	4	C
10				C	7	2	0.05	N	23	C
11				C	20	1	0.21	Y	2	C
12				C	14				8	C
13				C	25				24	C
14				C	15				9	C
15				C	1				1	C
16				C	18	1	0.06	N	18	C
17				C	12	2	0.08	N	14	C
18				C	9	2	0.08	Y	11	C
19				M	26				26	M
20				C	2	6	0.08	Y	12	C
21				C	3	5	0.08	Y	13	C
22				C	4	4	0.11	Y	6	C
23				C	19	5	0.07	N	17	C
24				C	5	4	0.11	Y	7	C
25				C	11	3	0.07	N	16	C
26				C	16	3	0.06	N	19	C
27				C	21	2	0.03	N	25	C
28				C	6	3	0.15	Y	3	C

Figure 20 and Table 13: Voyage 9



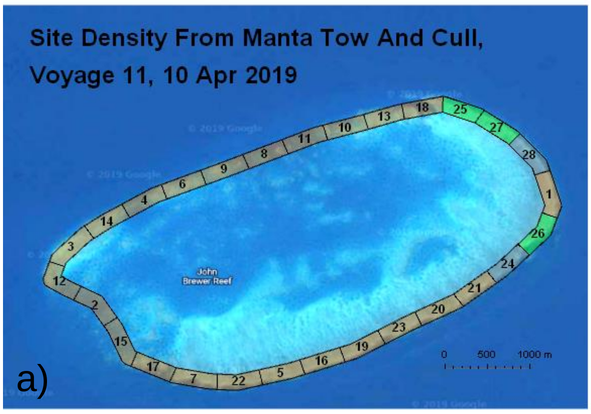
Site	Manta tow			Cull						
	COTS Count	Scar Category	Above Threshold?	Rank From	Rank Before	Number of Dives	CPUE	Above Threshold?	Rank After	Rank From
1	0, 0, 0	p, p, p	Y	M	10				19	M
2	0, 0, 0	a, p, a	Y	M	20				26	M
3	0, 0, 0	a, a, a	N	M	28				28	M
4	0, 0	a, p	Y	M	17				23	M
5	0, 0, 0	p, a, a	Y	M	19				25	M
6	0, 0, 0	a, a, a	N	M	27				27	M
7	0, 0	a, p	Y	M	16				22	M
8	0, 0, 0	a, p, a	Y	M	18				24	M
9	0, 0, 0	p, p, p	Y	M	9				18	M
10	1, 0	p, p	Y	M	3				16	M
11	0, 1	p, p	Y	M	2				15	M
12	0, 4, 0	p, p, a	Y	M	5				17	M
13	0, 0, 0	a, a, a	N	M	24	3	0.07	N	8	C
14	2, 2, 2	a, a, p	Y	M	6	8	0.09	Y	4	C
15	0, 1	p, a	Y	M	12	8	0.06	N	13	C
16	0, 1, 0, 1	p, p, a, a	Y	M	13				20	M
17	2, 0, 0	p, a, a	Y	M	14				21	M
18	0, 0, 0, 0	a, a, a, a	N	M	25	8	0.06	N	10	C
19	2, 4, 3	p, p, c	Y	M	1	7	0.15	Y	1	C
20	0, 0, 0	p, p, p	Y	M	8	4	0.06	N	12	C
21	0, 0, 1	p, p, p	Y	M	4	6	0.14	Y	2	C
22	0, 0, 0	a, a, a	N	M	22	4	0.10	Y	3	C
23	0, 1	a, a	Y	M	21	3	0.08	N	6	C
24	0, 0, 0, 0	a, p, p, p	Y	M	11	2	0.08	Y	5	C
25	0, 0	p, p	Y	M	7	3	0.07	N	9	C
26	0, 0	a, a	N	M	23	3	0.08	N	7	C
27	0, 0, 0	a, a, a	N	M	26	3	0.06	N	11	C
28	0, 0, 0, 0	p, p, a, a	Y	M	15	6	0.05	N	14	C

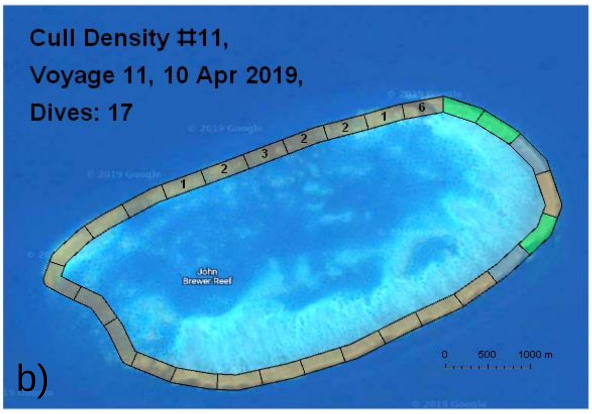
Figure 21 and Table 14: Voyage 10



Site	Manta tow			Cull						
	COTS Count	Scar Category	Above Threshold?	Rank From	Rank Before	Number of Dives	CPUE	Above Threshold?	Rank After	Rank From
1				M	19				25	M
2				M	26				27	M
3				M	28				28	M
4				M	22	4	0.25	Y	1	C
5				M	25				26	M
6				M	27	4	0.04	N	24	C
7				M	23	4	0.05	N	21	C
8				M	24	6	0.05	N	20	C
9				M	18	3	0.04	N	23	C
10				M	16	4	0.05	N	19	C
11				M	15	4	0.06	N	16	C
12				M	17	4	0.10	Y	5	C
13				C	8	2	0.05	N	22	C
14				C	4				7	C
15				C	13	4	0.05	N	17	C
16				M	20	3	0.06	N	15	C
17				M	21	5	0.15	Y	2	C
18				C	10				12	C
19				C	1				3	C
20				C	12				14	C
21				C	2				4	C
22				C	3				6	C
23				C	6				9	C
24				C	5				8	C
25				C	9				11	C
26				C	7				10	C
27				C	11				13	C
28				C	14				18	C

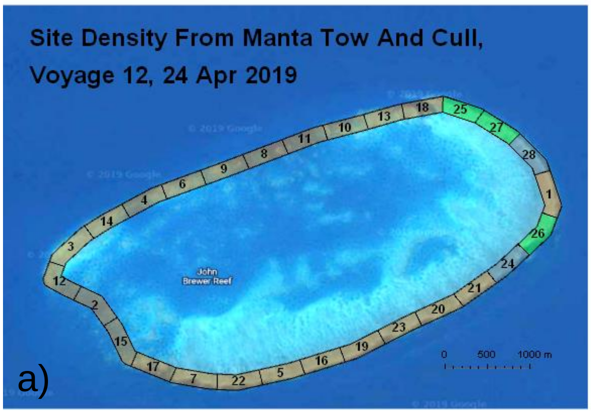
Figure 22 and Table 15: Voyage 11

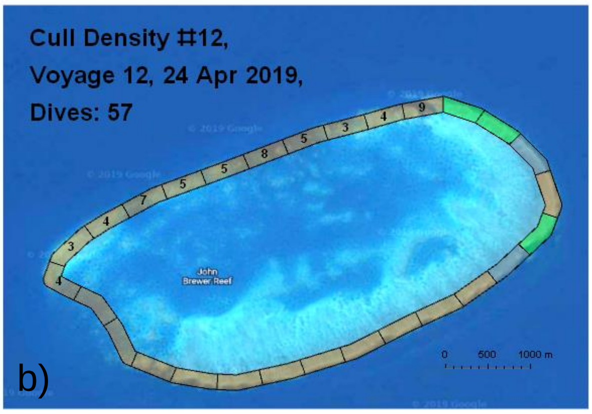




Site	Manta tow			Cull						
	COTS Count	Scar Category	Above Threshold?	Rank From	Rank Before	Number of Dives	CPUE	Above Threshold?	Rank After	Rank From
1				M	25				25	M
2				M	27				27	M
3				M	28				28	M
4				C	1				1	C
5				M	26				26	M
6				C	24				24	C
7				C	21				21	C
8				C	20				20	C
9				C	23				23	C
10				C	19				19	C
11				C	16				17	C
12				C	5				11	C
13				C	22				22	C
14				C	7				12	C
15				C	17				18	C
16				C	15				16	C
17				C	2				6	C
18				C	12				14	C
19				C	3				7	C
20				C	14				15	C
21				C	4				10	C
22				C	6	2	0.16	Y	4	C
23				C	9	5	0.20	Y	2	C
24				C	8	6	0.17	Y	3	C
25				C	11	4	0.15	Y	5	C
26				C	10	5	0.15	Y	9	C
27				C	13	2	0.15	Y	8	C
28				C	18	8	0.08	Y	13	C

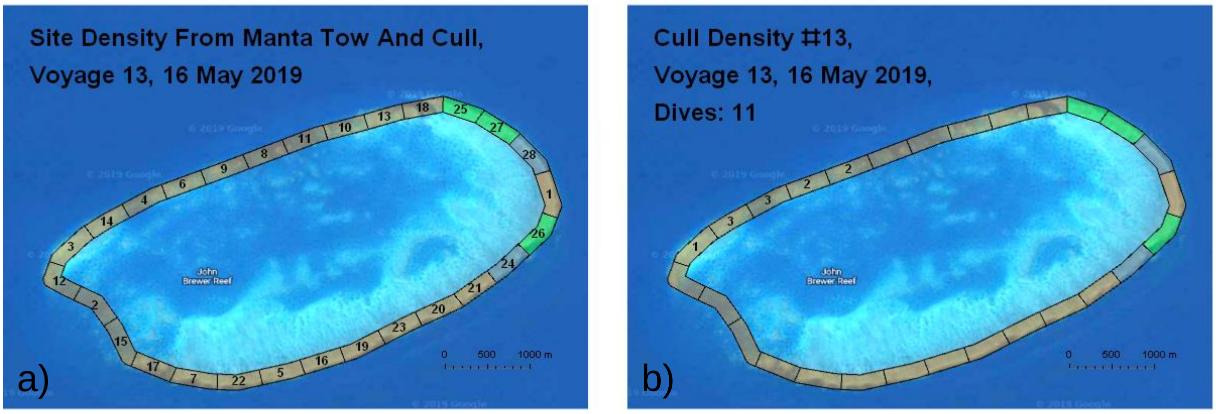
Figure 23 and Table 16: Voyage 12





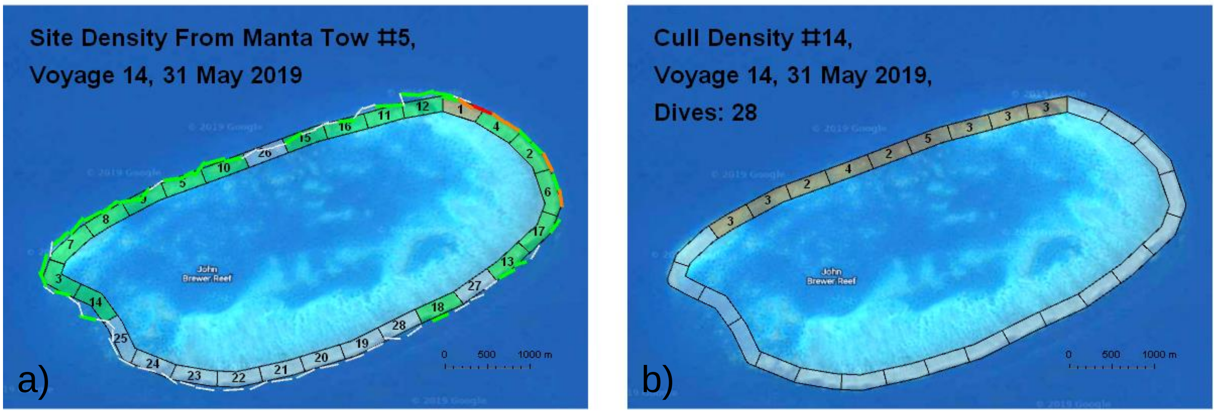
Site	Manta tow			Cull						
	COTS Count	Scar Category	Above Threshold?	Rank From	Rank Before	Number of Dives	CPUE	Above Threshold?	Rank After	Rank From
1				M	25				25	M
2				M	27				27	M
3				M	28				28	M
4				C	1				1	C
5				M	26				26	M
6				C	24				24	C
7				C	21				21	C
8				C	20				20	C
9				C	23				23	C
10				C	19				19	C
11				C	16				17	C
12				C	5				11	C
13				C	22				22	C
14				C	7				12	C
15				C	17				18	C
16				C	15				16	C
17				C	2				6	C
18				C	12	4	0.11	Y	14	C
19				C	3	4	0.39	Y	7	C
20				C	14	7	0.22	Y	15	C
21				C	4	11	0.24	Y	10	C
22				C	6	8	0.11	Y	4	C
23				C	9	8	0.11	Y	2	C
24				C	8	12	0.16	Y	3	C
25				C	11	8	0.09	Y	5	C
26				C	10	8	0.06	N	9	C
27				C	13	8	0.05	N	8	C
28				C	18	12	0.06	N	13	C

Figure 24 and Table 17: Voyage 13



Site	Manta tow			Cull						
	COTS Count	Scar Category	Above Threshold?	Rank From	Rank Before	Number of Dives	CPUE	Above Threshold?	Rank After	Rank From
1				M	25				25	M
2				M	27				27	M
3				M	28				28	M
4				C	1				1	C
5				M	26				26	M
6				C	24				24	C
7				C	21				21	C
8				C	20				20	C
9				C	23				23	C
10				C	19				19	C
11				C	16				17	C
12				C	5				11	C
13				C	22				22	C
14				C	7				12	C
15				C	17				18	C
16				C	15				16	C
17				C	2				6	C
18				C	12				14	C
19				C	3	1	0.20	Y	7	C
20				C	14	4	0.19	Y	15	C
21				C	4	4	0.15	Y	10	C
22				C	6	3	0.11	Y	4	C
23				C	9	2	0.17	Y	2	C
24				C	8				3	C
25				C	11				5	C
26				C	10				9	C
27				C	13				8	C
28				C	18				13	C

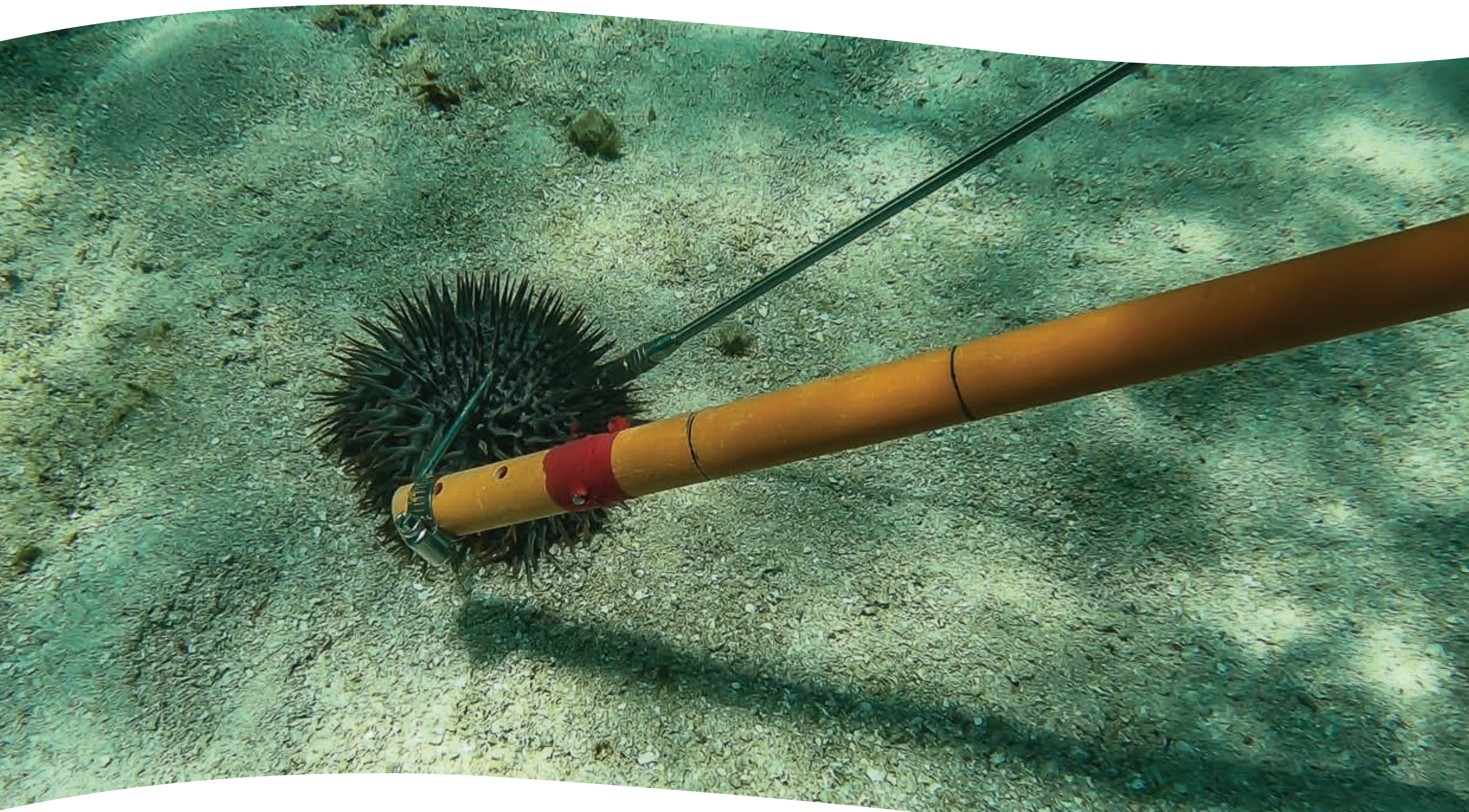
Figure 25 and Table 18: Voyage 14



Site	Manta tow			Cull						
	COTS Count	Scar Category	Above Threshold?	Rank From	Rank Before	Number of Dives	CPUE	Above Threshold?	Rank After	Rank From
1	5, 0, 3, 0, 0	c, a, p, p, p	Y	M	1				10	M
2	1, 2	p, p	Y	M	2				11	M
3	1, 0, 0	p, p, p	Y	M	4				13	M
4	1, 0	p, p	Y	M	3				12	M
5	0, 0	a, p	Y	M	15				18	M
6	1, 0	a, p	Y	M	12				15	M
7	0, 0	a, a	N	M	21				21	M
8	0, 0	p, a	Y	M	14				17	M
9	0, 0	a, a	N	M	20				20	M
10	0, 0	a, a	N	M	28				28	M
11	0	a	N	M	27				27	M
12	0, 0	a, a	N	M	26				26	M
13	0, 0	a, a	N	M	25				25	M
14	0, 0	a, a	N	M	24				24	M
15	0, 0	a, a	N	M	23				23	M
16	0, 0, 0, 0	a, a, a, a	N	M	22				22	M
17	0, 0, 0, 0	a, p, a, a	Y	M	18				19	M
18	0, 0, 0, 0	p, a, p, p	Y	M	8				14	M
19	0, 0, 0	a, p, p	Y	M	13				16	M
20	0, 0	p, p	Y	M	7	4	0.17	Y	5	C
21	0, 0, 0	p, p, a	Y	M	9	4	0.15	Y	6	C
22	0, 0, 0	p, p, p	Y	M	5	3	0.24	Y	1	C
23	0, 0	p, p	Y	M	6	6	0.23	Y	2	C
24	0, 0, 0	a, a, a	N	M	19	4	0.10	Y	8	C
25	0, 0, 0	p, a, a	Y	M	17	10	0.19	Y	4	C
26	0, 0, 0	a, p, a	Y	M	16	4	0.20	Y	3	C
27	0, 0, 0	p, a, p	Y	M	10	4	0.13	Y	7	C
28	0, 0, 0	p, a, p	Y	M	11	5	0.05	N	9	C

Figure 26 and Table 19: Voyage 15

Site	Manta tow			Cull						
	COTS Count	Scar Category	Above Threshold?	Rank From	Rank Before	Number of Dives	CPUE	Above Threshold?	Rank After	Rank From
1				M	10	6	0.13	Y	9	C
2				M	11	4	0.07	N	16	C
3				M	13	4	0.09	Y	13	C
4				M	12	6	0.08	Y	14	C
5				M	18				28	M
6				M	16	4	0.03	N	23	C
7				M	25	4	0.03	N	22	C
8				M	17	4	0.02	N	24	C
9				M	28	4	0.02	N	27	C
10				M	26	2	0.02	N	25	C
11				M	21	2	0.04	N	18	C
12				M	23	4	0.03	N	20	C
13				M	24	4	0.03	N	21	C
14				M	27	4	0.02	N	26	C
15				M	22	2	0.04	N	19	C
16				M	20	3	0.08	N	15	C
17				M	19	2	0.10	Y	11	C
18				M	14	2	0.16	Y	8	C
19				M	15	8	0.73	Y	1	C
20				C	5	6	0.63	Y	2	C
21				C	6	7	0.32	Y	4	C
22				C	1	4	0.38	Y	3	C
23				C	2	2	0.28	Y	5	C
24				C	8				12	C
25				C	4				7	C
26				C	3				6	C
27				C	7				10	C
28				C	9				17	C



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