Final Report

CoTS Control Program Independent Review

A Report for the Great Barrier Reef Foundation

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Abbreviations

AIMS	Australian Institute of Marine Science
AMPTO	Association of Marine Park Tourism Operators
CoTS	Crown-of-Thorns Starfish
CPUE	Catch per unit effort
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DSS	Decision Support System
EotH	Eye on the Reef
FMP	Field Monitoring Program (implemented by QPWS and GBRMP Rangers)
GBR	Great Barrier Reef
GBRMP	Great Barrier Reef Marine Park
GBRMPA	Great Barrier Reef Marine Park Authority
IPM	Integrated Pest Management
LTMP	Long Term Monitoring Plan
NESP	National Environmental Science Program
PLD	Pelagic Larval Duration
RHIS	Reef Health Impact Surveys
RRRC	Reef and Rainforest Research Centre
QPWS	Queensland Parks and Wildlife Service

1. Summary

This Report provides an independent assessment of the CoTS Control Program under the coordination of GBRMPA between 2012/13 – 2018/19, reporting against the Terms of Reference:

- Summary of manual CoTS control initiatives implemented since 2012 in terms of location, scale and timing.
- Assessment of key strengths and weaknesses of various iterations of the CoTS Control Program as identified by prior reviews or scientific assessments.
- Validity of surveillance and control data to assess effectiveness and support decision making and prioritisation activities.
- In depth scientific analysis of available data to assess the impact of manual COTS control initiatives implemented since 2012. The reference for this assessment will be in line with the current GBRMPA's COTS Control Program Objective of protection of coral at key sites.

  Performance measures and indicators will be informed by the draft COTS Component Monitoring and Evaluation Plan. At a workshop on 29-30 January 2019, representatives from GBRF, GBRMPA, CSIRO and Australian Government (DoEE) identified key performance measures as 1) reduced density of CoTS at priority reefs, and 2) a reduction of the average size of CoTS at priority reefs. The review may recommend additional relative measures of success as part of their analysis.

  NOTE that in-depth scientific analyses of the available data were undertaken by CSIRO as part of the NESP programme of activities. As a consequence, this element was changed to undertake a critical review of Westcott and Fletcher (2018) and Fletcher et al (2019).
- Review of the current site prioritisation and decision support processes (at the local and regional levels) and links to information/data needs.
- General findings and recommendations for potential improvements to CoTS control activities and associated monitoring, data management and decision support systems.

We find that the CoTS Control Program has undergone a suite of continuous and adaptive changes, resulting in three periods of activity: 2012/13-1014/15; 2015/16-2017/18; and 2018/19. These periods have resulted in refinements of objectives, locations, scales and timing of efforts driven by changes in strategy (eg site/reef selection; release of IPM strategy in 2016), application of best available scientific evidence (eg definition of outbreak threshold densities; determination of control targets; efficiency of surveillance and control methods), and increasing incorporation of data driven decision-making. Specifically we note that program objectives have shifted from a reactionary (tactical) response almost entirely focused on economic values to a more strategic response focused on core environmental values (ie protecting coral cover) that also deliver economic and social benefits.

The CoTS Control Program has had several scientific and stakeholder reviews and evaluations that have identified a variety of strengths and weaknesses. We reviewed 71 articles from both primary and grey literature and noted that with one exception, all articles focussed on early periods of the CoTS Control Program (prior to 2015) or provided generic

(not time specific) comment on strengths and weaknesses of CoTS manual control. Key strengths and weaknesses highlighted by the articles included Strategies (Surveillance and intelligence gathering; Site selection; Integrated Pest Management); Operational Logistics and Targets (Voyage planning and revisitation frequency; CPUE thresholds; CoTS size classes) and Data collection, curation and transparency. While several points of concern were identified, we found that changes in the CoTS Control Program, specifically the adoption of an IPM Strategy, has addressed most of these concerns or provides a mechanism for the suggested changes to be considered and incorporated.

We assessed two previous reviews of data to determine if the CoTS Control Program demonstrably reduced CoTS densities at priority reefs, and if there was a reduction of the average size of COTS at priority reefs. We found that the scientific assessments undertaken by both Westcott and Fletcher (2018) and Fletcher et al (2019) for the periods 2012/13-2017/18 and 2018/19, respectively, were of high quality. They both provided evidence that the CoTS Control Program, and specifically the Expanded Control Program (2018/19) was able to reduce CoTS densities at priority reefs, and reduce larger size classes of COTS at priority reefs, but that this was contingent on three key factors:

- Persistent effort to achieve a unified goal (eg a target of CPUE below ecological thresholds);
- Consistent application of and adherence to culling protocols, noting that the simplified decision trees underpinning the Expanded Control Program (presented by Fletcher et al 2019) support consistency;
- The fundamental value of appropriately collected and curated data to support and inform decision-making.

We also reviewed the current site prioritisation and decision-making processes in the Expanded Control Program. We found that the site prioritisation process implemented in the Expanded Control Program is appropriate and commensurate with the stated goals of mitigating CoTS impacts on hard coral cover by reducing CoTS densities to levels that decrease hard coral consumption below hard coral regeneration rates. Reef prioritisation continues to focus on key ecological (hard coral source reefs) and economic (tourism assets) and facilitate regional disruption of CoTS spread. The key shift has been recognition that reefs are the appropriate management unit and prioritised targeting of key ecological (hard coral source reefs) and economic (tourism assets) reefs, as well as reefs that facilitate regional disruption of CoTS spread.

The decision-making processes in the Expanded Control Program are currently mostly in development, however the underpinning assumptions and principles are sound.

We find that the current iteration of the CoTS Control Program under the guidance of the IPM Strategy provides a strategic and conservative approach to application of best available science and best practice.

2. Introduction

The Great Barrier Reef (GBR) is an iconic aspect of the Australian psyche and represents unique value to Australia and the global community as acknowledge in its World Heritage status (listed in 1981). The foundations of this unique reef ecosystem are reef building stony corals, stretching over an area of ~345,000km^2. Despite the relative isolation from large human population centres, the stony corals of the GBR have been under increasing threats associated with a changing natural environment including cyclone frequency, storm water runoff and oceanic heat waves, coupled with human-mediated impacts such as land-based runoff of nutrients and sediments, increased fishing pressures and tourism activities, shipping and recreational boating (e.g., Brodie and Waterhouse 2012; De'Ath et al. 2012). These pressures, and the synergies between them, are believed to have resulted in an ecosystem increasingly out of balance, leading to perturbations that are now having wider affects.

As the GBR condition has continued to deteriorate in the face of these multiple stressors, statutory authorities Great Barrier Reef Marine Park Authority (Australian Government; GBRMPA) and Queensland State Government have undertaken broad scale (regional) actions such as the rezoning of the Great Barrier Reef Marine Park (GBRMP) to manage adverse boating and fishing impacts (Day 2002; Fernandes et al. 2005) and significant management attempts to limit nutrient inputs into the reef system (see Brodie and Waterhouse 2012, and Westcott and Fletcher 2018). Despite continuing best efforts, coral cover has been documented as suffering major declines across the Great Barrier Reef with two stressors - tropical cyclones and coral predation by Crown-of-thorns Starfish (CoTS; *Acanthaster cf. solaris*) – each accounting for >40% of losses (De'Ath et al. 2012; Mellin et al 2019). Of these two pressures, CoTS impacts are most amenable to management action.

The native coral predator, the Crown-of-Thorns Starfish (CoTS), has exhibited cyclic population fluctuations over the last 60 years on the GBR and is now considered to be one of the major sources of coral mortality across the GBRMP, comparable in its wide reaching affects to cyclones and severe bleaching events (De'Ath et al. 2012; Mellin et al 2019). While some evidence of cyclic CoTS outbreaks have been documented in deep history (Dana 1970; Fabricius et al 2010), recent outbreaks have received significant attention by the public resulting in numerous efforts at mitigation response (reviewed in Moran 1986 and Pratchett et al. 2014).

CoTS outbreaks have some degree of predictability, particularly within the cycle of an outbreak, leading to opportunities for intervention to minimise or even prevent coral loss. When a new outbreak cycle was detected in 2010 (the fourth outbreak cycle since the 1960s; Vanhatalo et al 2017), several parties including tourism operators, reef managers and key members of the public lobbied for significant efforts to minimise the CoTS impact through manual control efforts at sites of strategic importance. In 2012 the Australian Government provided $21.7M in funding support to GBRMPA for manual CoTS control at key economic assets between 2012 and June 2018, and an additional $23.2M was provided to the GBRMPA for an expanded program between July 2018 to June 2020. Additionally under Component 3 of the Reef Trust Partnership, according to the Agreement, "the purpose of this Component is to expand efforts to control CoTS and to reduce coral mortality from CoTS predation in order to protect high ecological and economic value coral reefs in line with GBRMPA's CoTS Control Strategy" (to be released as GBRMPA's CoTS Management Strategy).

Given that manual control of CoTS remains the best currently understood and demonstrated option available to Reef managers to protect coral cover, and that the development of alternative direct and indirect control methods will take time, it will be important to support in-water manual control (including surveillance) at priority sites at a level that is consistent with the best scientific advice, the intensity of the current outbreak, and the funding envelope available. That said, a lack of confidence in the CoTS Control Program will pose a significant risk in terms of long-term financial and stakeholder support.

The Reef Trust Partnership in consultation with strategic advisory bodies has highlighted the need for an independent review of the CoTS control effort to date (since 2012). This review would provide a solid foundation for the development and refinement of the CoTS Control Program activities to be considered under the Reef Trust Partnership and to ensure that the Program meets its objectives.

3. Aims of this Review

The focus of this review is to provide a scientific assessment of the effectiveness and efficiency of the CoTS control program at protecting coral cover at key sites with the following Terms of Reference:

The review will build on the recent Westcott and Fletcher (2018) CSIRO report “How effective are management responses in controlling crown-of-thorns starfish and their impacts on the Great Barrier Reef?” and consider more recent data from the increased CoTS control effort and implementation of an integrated pest management strategy.

This Report covers the following elements:

• Summary of manual CoTS control initiatives implemented since 2012 in terms of location, scale and timing.

• Assessment of key strengths and weaknesses of various iterations of the CoTS Control Program as identified by prior reviews or scientific assessments.

• Validity of surveillance and control data to assess effectiveness and support decision making and prioritisation activities.

• In depth scientific analysis of available data to assess the impact of manual COTS control initiatives implemented since 2012. The reference for this assessment will be in line with the current GBRMPA’s COTS Control Program Objective of protection of coral at key sites.

Performance measures and indicators will be informed by the draft COTS Component Monitoring and Evaluation Plan. At a workshop on 29-30 January 2019, representatives from GBRF, GBRMPA, CSIRO and Australian Government (DoEE) identified key performance measures as 1) reduced density of COTS at priority reefs, and 2) a reduction of the average size of COTS at priority reefs. The review may recommend additional relative measures of success as part of their analysis.

NOTE that in-depth scientific analyses of the available data were undertaken by CSIRO as part of the NESP programme of activities. As a consequence, this element was changed to undertake a critical review of Westcott and Fletcher (2018) and Fletcher et al (2019).

• Review of the current site prioritisation and decision support processes (at the local and regional levels) and links to information/data needs.

• General findings and recommendations for potential improvements to COTS control activities and associated monitoring, data management and decision support systems.

Out of scope

For the purpose of clarifying the boundaries of this review, it is exclusively focused on in-water manual CoTS control activities and will not include:

• A due diligence of the current GBRMPA CoTS manual control program delivery across the value chain (program structure, management systems, governance, funding, stakeholder engagement and communication);

• A strategic assessment of the integrated pest management approach (result of a NESP collaborative research program which is widely accepted as the preferred approach);

• A strategic assessment of the balance between manual control and non-manual control activities;

• A strategic assessment of the role of R&D and innovation in supporting future improvements to the program, with the exception of recommendations related to the design of surveillance programs and to the acquisition and utilisation of surveillance data.

The findings of the review will be shared with GBRMPA and the NESP Integrated Pest Management Group to enhance the effectiveness and efficiency of the CoTS Control Program. The review outcomes will also be circulated with key stakeholders and promoted through the Partnership communication activities. The results will be used by the Partnership to guide Annual Work Plans and Monitoring and Evaluation of the CoTS Component.

4. Summary of manual CoTS control initiatives implemented since 2012 in terms of location, scale and timing

Significant Australian Government investments during the current CoTS outbreak cycle (outbreak cycle initiated 2008-2010; funding beginning in 2012) have resulted in a suite of initiatives under an adaptive management approach. Because of continuous and adaptive changes, we roughly report against three periods (in fiscal years) with roughly similar characteristics – 2012/13-2014/15, 2015/16-2017/18, and 2018/19.

4.1 2012/13 – 2014/15

This initial period was a transition from tourism operator led activity to coordination by GBRMPA. Program Objectives (program goals outlined in annual contracts) during this window were to protect 'key tourism sites' from coral damage and assist existing mitigation activities conducted by tourism operators. Control of CoTS at a broader scale was to assist research efforts to improve control efficiencies and to undertake CoTS control at sites to complement activity at key tourism sites, where resources allow.

GBRMPA contracted the Association of Marine Park Tourism Operators (AMPTO) to deliver response activity in the Cairns/Townsville region primarily focussed on "key tourism site" based protections with site response activity influenced by individual tourism operator requests for intervention. An increasing number of voyages occurred annually during this period by three vessels (2012/13 – 33; 2013/14 – 41; 2014/15 – 52; Figure 1). A shift in focus on 'priority' reefs occurred between 2012/13 to 2014/15 identified by the Site Selection Strategy (Figure 2). Initially (2012/13) only 30% of reefs visited were identified as priority (Figure 2a), however ~50% of operator culling actions were on 'priority' reefs. (Figure 2b). By 2014/15 this focus had shifted with >40% of reefs visits to priority locations (Figure 2a), and >80% of operator culling actions on 'priority' reefs. (Figure 2b).

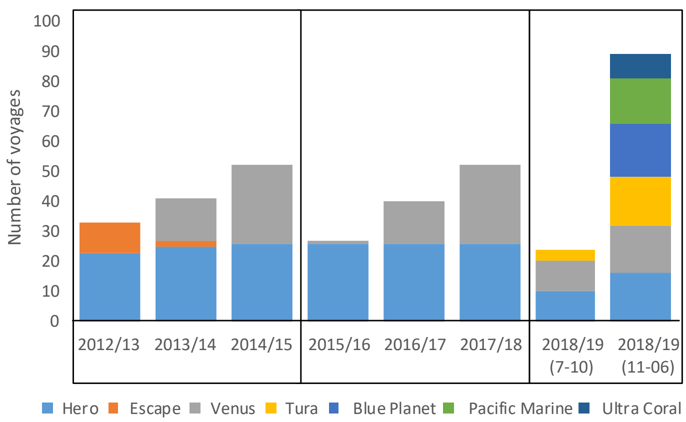

Figure 1: Number of Annual Voyages by individual Vessel in periods 2012/13 – 2014/15; 2015/16-2017/18; and 2018/19 (reported as July-October and November to June to represent the significant shift in vessel activity). Note some voyages crossed between fiscal years.

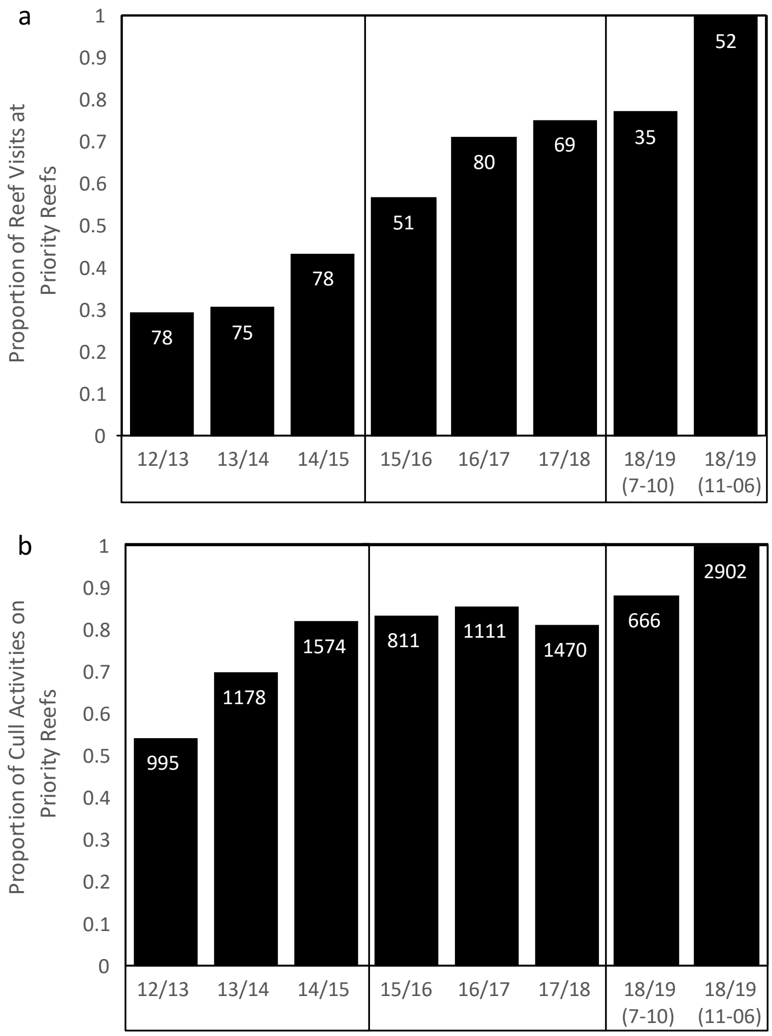

Figure 2: Focus on Prioritised Sites/Reefs: a) Proportion of Cull Activities on 'Priority' Reefs; b) Proportion of Cull Activities on 'Priority' Reefs. Note that Cull Activities represent multiple actions at a single site. Numbers in columns represent total number of activities/reefs.

During this period the site selection criteria shifted from a sole focus on key tourism sites on reefs to include the concept of key "spreader" reefs based on the understanding of regional reef connectivity, however as noted previously attention given to tourism operator requests diminished the strategic importance of site selection. It was noted that sites on reefs were targeted for culling action, rather than the whole reef being observed and treated.

Initially (2012/13) no site/reef revisitation targets were established however starting 2013/14 the discussion with AMPTO operators emphasising need for site revisitation was initiated and continued throughout this period.

There was no explicit decision-making when to initiate a cull. Culling efforts were initially focused on achieving a Catch per unit effort (CPUE) threshold of <0.1 CoTS /minute at culling sites however, in 2014/15 the program shifted to a CPUE threshold of 0.08 CoTS /minute at reefs with ≥40% hard coral cover and 0.04 CoTS /minute at reefs with <40% hard coral cover based on CSIRO report (Babcock et al 2014).

Surveillance data was collected from at least three replicate Reef Health Impact Surveys (RHIS) per cull site. The goal of RHIS evaluations is to consistently monitor coral reef health on reefs where culling occurs, however no permanent RHIS markers were initially established. In 2013/14 13 permanent RHIS sites were established, expanding to 36 permanent sites in 2014/15.

Additionally Manta Tow data collection included Counts of CoTS/tow, Counts of CoTS feeding scars/tow, and estimated percent of all live coral (hard and soft) with estimates of top species. CoTS outbreak status of sites was determined using De'Ath (2003) Manta Tow Thresholds:

>1 CoTS/2min manta tow represents a severe outbreak,

<0.22 - >0.11 CoTS/2min manta tow represents an established population, and

<0.11 CoTS/2min manta tow represents a natural density.

During this period, data collection and reporting for culling activity continued the pre-2012 APMTO reporting of the number of CoTS culled per site visit and the achieved CPUE.

Hard copy records are kept and maintained as logs and reported to managers after transfer to data sheets.

4.2 2015/16 – 2017/18

This second period shifted a focus in the Program Objectives (program goals outlined in annual contracts) from solely protecting 'key tourism sites', to include 'other high value or strategically important reefs in the GBR' as identified in the Site Selection Strategy which now incorporates connectivity data in decision making. A continued requirement to contribute to control of CoTS at a broader scale, by assisting research efforts to improve control efficiencies, was expanded to include a trial of the Integrated Pest Management (IPM) strategy in 2017/18 including; improving data collection and reporting to inform management actions.

GBRMPA contract Reef and Rainforest Research Centre (RRRC) for control actions, who subcontract AMPTO to continue to deliver response activity in the Cairns/Townsville region. Prioritisation of reefs continues to rely on the Site Selection Strategy but incorporating tourism data and best available information on reef connectivity to identify "super spreader" reefs for intervention. While remaining heavily focussed on "key tourism site" based protections, a decrease in non-priority site response activities are readily apparent. Two vessels delivered a similar number of voyages annually during this period (2015/16 – 27; 2016/17 – 40; 2017/18 – 52; Figure 1). The focus on priority reefs continued increasing from 57% of visited reefs prioritised to >75% (Figure 2a) and >80% of operator culling actions on 'priority' reefs in each year. (Figure 2b).

In 2017/18 57 high priority reefs were identified based on reef connectivity models, tourism visitation data, current coral cover and CoTS outbreak status (informed by regional surveillance from Field Management program and any previous experience at the site). With "Cull site polygons" (~ 10 hectares; 500m x 200m) mapped and established for a limited portion (2% - 6%) of high priority reefs. These pre-defined "cull site polygons" are established to increase consistency for both surveillance and response (cull action).

No explicit decision-making when to initiate a cull is apparent and cull sites are visited on an 'ad-hoc' basis. There is a continued target to achieve a CPUE threshold of 0.08 CoTS /minute at reefs with ≥40% hard coral cover and 0.04 CoTS /minute at reefs with <40% hard coral cover (Babcock et al 2014).

A target for 3 monthly revisits to ‘priority’ sites/reefs (note that culling activity continues to be site based, rather than whole of reef assessment and intervention) occurred in 2017/18 with the shift to the IPM strategy. Voyage scheduling sought to target areas with groups of priority reefs (though non-priority reefs were occasionally visited within the target area). Voyage schedules also sought to reinforce revisitation to target areas every 8 – 12 weeks.

Surveillance data was collected from at least three replicate Reef Health Impact Surveys (RHIS) per cull site with 53 sites having permanent RHIS markers in 2015/16. The goal of RHIS evaluations is to consistently monitor coral reef health on reefs where culling occurs.

Manta Tow data collection included Counts of CoTS/tow, Counts of CoTS feeding scars/tow, and estimated percent of all live coral (hard and soft) with records of top species. Manta Tows are used to identify large aggregations of CoTS but are undertaken in an ad-hoc fashion (rarely around entire reef perimeter). CoTS outbreak status of sites was determined using De’Ath (2003) Manta Tow Thresholds where >1.0 CoTS/2min manta tow represents a severe outbreak, <0.22 - >0.11 CoTS/2min manta tow represents an established population and <0.11 CoTS/2min manta tow represents a natural density.

Cull action reporting continued to include both the number of CoTS culled per site visit and the CPUE achieved but was expanded to include counts in four size classes (<15cm, 15-25cm, 25-40cm, >40cm) of CoTS culled per site visit.

Hard copy records are kept and maintained as logs and reported to managers after transfer to data sheets.

4.3 2018/19 – “Expanded Control Program”

The Expanded Control Program was implemented in November 2018 with additional funding from Commonwealth, resulting in an increased number of operating vessels contracted to undertake surveillance and control across a wider range of regions within the GBRMP (expanded to include areas outside of the Cairns/Townsville region).

GBRMPA establishes a Panel of Suppliers and expands contracts to fund six operating vessels (reduced to five vessels mid-2019 due to funding constraints) including: RRRC who subcontracts AMPTO for two vessels; Ultra Coral (1 vessel); Blue Planet Marine (1 vessel); Pacific Marine Group (1 vessel). The focus on priority reefs increased from 75% in early 2017/18 to 100% following full implementation of the IPM Strategy (Figure 2a); and from >85% of operator culling actions on ‘priority’ reefs in early 2017/18 to 100% (Figure 2b).

While the Objectives remain consistent with the previous period, the Expanded Control Program entailed a full implementation of the IPM Strategy and included a variety of operational shifts to support an increased number of operators across a broad scale. These included explicit direction to operators on areas of operation, frequency of visitation, explicit protocols for surveillance and decision-making rules for cull-action, as well as data collection and curation. In support of these changes an IPM-based decision process was developed by CSIRO researchers to aid data driven decision making in the field (note that at the time of this report an App based decision tool was in development to enhance consistency).

The key focus shifts to priority reefs, with pre-defined sites (“cull site polygons” 500m x 200m) around the entire perimeter, for both surveillance and response, to establish a whole of reef approach. Priority reefs are determined through connectivity models, tourism visitation data, current coral cover and CoTS outbreak status (informed by regional surveillance from Field Management program and any previous experience at the site).

Priority reefs are assigned “Intensive Control” or “Maintenance” modes by GBRMPA managers based on surveillance activities (eg FMP) and prior culling action. Reef Outbreak status is also defined by GBRMPA managers and determined as “No Outbreak”, “Potential”, “Established”, or “Severe” based on average COTS/tow and RHIS data intelligence.

Fletcher et al (2019) reported that in this period the CoTS Control Program visited 140 reefs across 10° of latitude (12° - 22° S) - 14 reefs were under Intensive Control; 33 reefs where transitioned from Intensive Control to Maintenance Mode; 66 reefs were placed in Maintenance Mode due to CoTS densities being below ecological thresholds; and 27 reefs were unable to be assessed due to weather or safety concerns (Fletcher et al 2019).

Voyage scheduling targets priority reefs (not areas) and responds to outbreak condition on reefs based on most current intelligence, however once culling action begins, continued effort until CPUE targets are achieved, has greater influence. Under the IPM Strategy and the associated operational strategy (Fletcher et al 2019) the revisitation frequency is targeted for ~ 2 weeks (approximately every 12 days).

Operationally the whole of reef approach meant targeted reefs were initially surveyed using Manta Tows in predefined “cull site polygons”. The presence of at least 1 CoTS and/or 1 CoTS feeding scar was sufficient to initiate culling action in that cull site polygon. Cull site polygons were prioritised based on CoTS or CoTS feeding scar densities. At least three RHIS are conducted at each cull site polygon prior to culling action to inform CPUE target, and repeated every three months, and after completion of culling action. Repeated culling at a cull site polygon occurred until the CPUE was below 0.08 CoTS /minute at reefs with ≥40% hard coral cover and 0.04 CoTS /minute at reefs with <40% hard coral cover. Additionally, Manta Tow surveys are conducted every six weeks around the entire perimeter of a targeted reef during culling, and then at the end of culling action once the reef is transferred to “maintenance” mode.

Surveillance data collected from Manta Tow was altered to align with the AIMS Long Term Monitoring program to facilitate comparisons. This included: Counts of CoTS /tow, CoTS feeding scars/tow recorded categorically (absent, present 1-10, common >10), and % live hard coral, % live soft coral, and % recently dead coral. CoTS outbreak status of sites was determined using Moran and De’Ath (1992) Manta Tow Thresholds where; >1 CoTS /2min manta tow represents a severe outbreak, <0.22 - >0.11 CoTS /2min manta tow represents an established population and <0.11 CoTS /2min manta tow represents a natural density.

RHIS surveys are now aligned to culling action rather than surveillance data collection. Note that GPS coordinates are now used instead of permanent markers.

Cull action data collection and reporting continued to report on both the number of CoTS culled per site visit (total and by four size classes: four size classes (<15cm, 15-25cm, 25-40cm, >40cm), and the achieved CPUE.

While hard copy records are kept and maintained as logs, the use of tablets and Apps to record data on CoTS surveillance, CoTS cull activity and RHIS (EotR Health and Impact Survey) is established to reduce handling and transposition errors and speed the transfer of data into decision-making.

4.4 Summary

Through discussion with key GBRMPA personnel, and examination of various reports, it is apparent that adaptive shifts have occurred between 2012 and 2019, often on an annual basis, resulting in continuous improvements through refinements to objectives, locations, scale and timing of efforts. These shifts have been driven by changes in strategy (eg site/reef selection; release of IPM strategy in 2016), application of best available scientific evidence (eg definition of outbreak threshold densities; determination of control targets; efficiency of surveillance and control methods) and increasing incorporation of data driven decision-making. We note that that while the program objectives remained similar throughout the period, the shift from a reactionary (tactical) response almost entirely focused on economic values to a more strategic response focused on core environmental values (ie protecting coral cover) that also delivers economic and social benefits is apparent.

Location - The CoTS Control Program initially focused in the Cairns/Townsville region for various reasons including fiscal constraints, stakeholder driven program objectives, demonstrable impacts of COTS in a region of high economic value, and the phase of the outbreak cycle. These constraints have shifted through time and as best available information has improved, allowing the release of additional resources to enable implementation of an Expanded Control Program that increases the breadth of focus to include a much wider engagement across the GBRMP. In the most recent period (2018/19) the CoTS Control Program visited 140 reefs across 10° of latitude (12° - 22° S).

Scale – The scale of activity has shifted from individual undefined sites on reefs where CoTS aggregations were either reported or detected, to a whole of reef approach whereby a formalised structure for assessing the reef in spatially explicit and consistent polygons informs prioritised locations (sites) on the reef to be culled.

Timing – frequency of revisitation was initially unclear, resulting in partial culling actions, but through time the requirement for revisitation at ~3 monthly intervals for priority sites has become well established and in the current Expanded Control Program (2018/19) has increased even further to ~ 2 weeks (approximately every 12 days) once culling action has begun.

5. Assessment of key strengths and weaknesses of various iterations of the CoTS Control Program as identified by prior reviews or scientific assessments

A key concern of various stakeholders has been the efficacy and appropriateness of management actions to control the Crown-of-Thorns Starfish (CoTS) in the current outbreak cycle (initiated 2010). Several critical reviews and scientific assessments have highlighted key strengths and weaknesses in the CoTS Control Program. The extent to which these critical analyses have been addressed by the adaptive management changes between 2012-2019 (as reviewed above) remains unclear. Here we assess the scientific literature and collated grey literature reviews and reports to determine the key findings and the relevance to the three periods of the 2012-2019 CoTS Control Program (2012/13- 2014/15; 2015/16-2017/18; 2018/19). We then examine whether the key findings are addressed within the subsequent iterations (periods) of the CoTS Control Program.

5.1 Methods

We undertook a systematic review of the primary scientific literature to identify commentary on the GBR CoTS Control Program between 2012-2019. We searched the literature using the bibliometric database *Scopus* between January 2012 and December 2019 for key word terms: "*Acanthaster*" OR "Crown-of-Thorns" OR "Crown of Thorns" OR "CoTS", AND "Great Barrier Reef". We included all literature (primary research articles, reviews, book chapters, books, communications and letters). Our search identified 68 unique articles from *Scopus*. Additionally, four specific review articles were identified through stakeholder interviews for inclusion in the assessment (Engelhardt 2015; Westcott and Fletcher 2018; Fletcher et al 2019; and Westcott et al submitted). We examined each of the 72 articles to determine if they had relevance to GBR CoTS Management using keyword searches of the entire article (Figure 3; see Appendix 1 for complete list of references) resulting in 47 articles.

These 47 articles were read in depth and evaluated to determine if direct or indirect comment was made on the GBRMPA CoTS Control Program, with a focus on the relevance to the 2012-2019 timeframe. This resulted in 19 articles of relevance (including the four identified from stakeholders). Six articles (Hock et al 2014, 2016; Babcock et al 2016; Vercelloni et al 2017; Keesing et al 2018; Pratchett et al 2019) did not explicitly focus on a CoTS Control Program time period but were included in the assessment given the commentary about strengths and weaknesses of CoTS control in general. Four articles focused explicitly on CoTS Control datasets prior to 2012 (Brodie and Waterhouse 2012; De'Ath et al 2012; Morello et al 2014; Pratchett et al 2014), however the commentary in the discussion was clearly focused on the 'current' CoTS Control Program (2012-2019). We then collated the comments on strengths or weaknesses and determined the CoTS Control Program period of relevance.

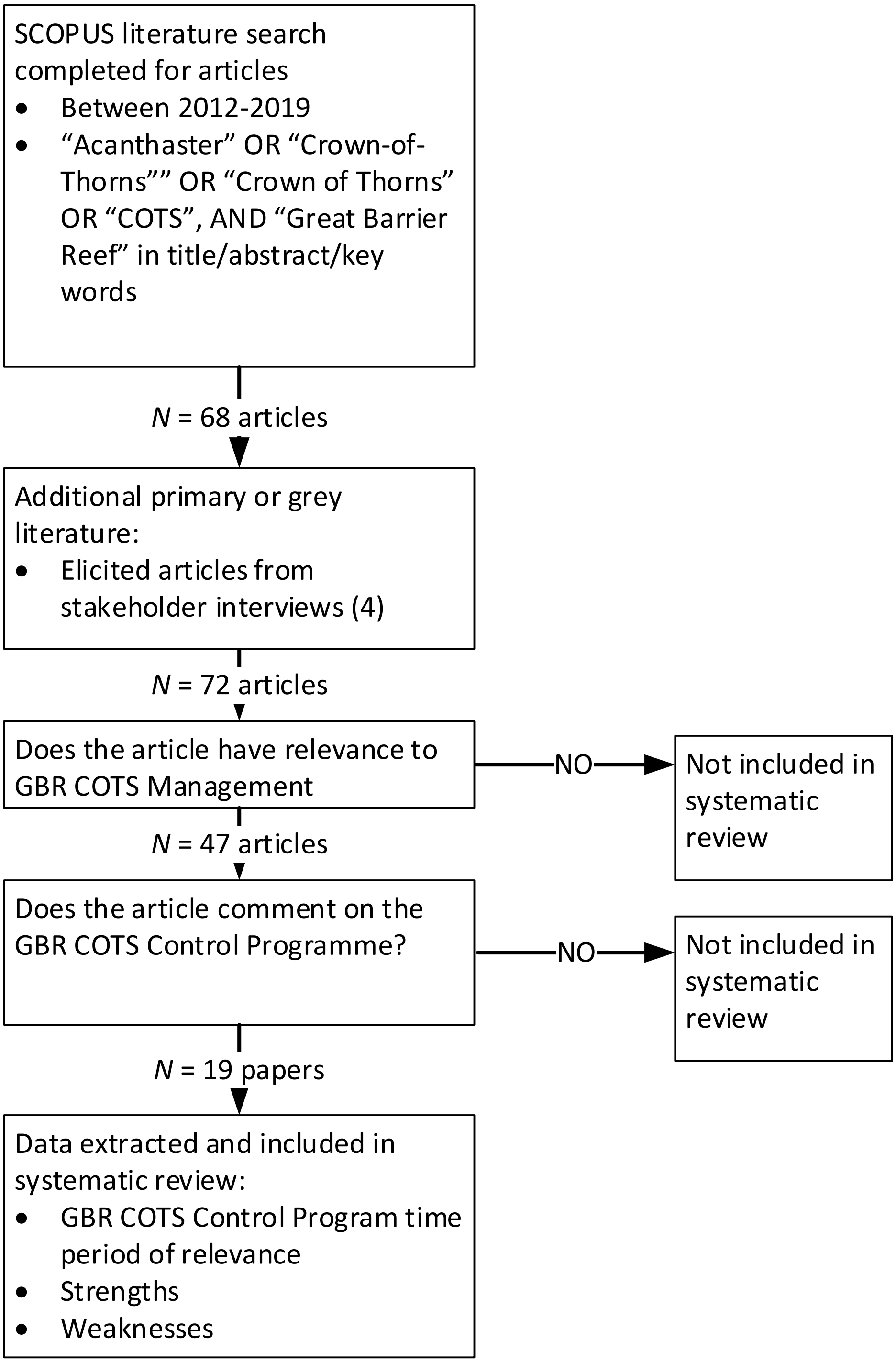

Figure 3: Schematic flowchart of the decision tree for the Systematic Review.

5.2 Results

Eight of the 19 articles commented on CoTS Control Program prior to 2015 (4 prior to 2012; 4 first time period – 2012/13-2014/15), only two articles (Westcott and Fletcher 2018; Westcott et al submitted)) examined data from the second time period (2015/16-2017/18) and one (Fletcher et al 2019) examined data from the third period (2018/19)(see Table 1).

Several articles noted that the primary objectives were to protect or enable recovery of hard coral cover, and that management actions had to acknowledge the variety of stressors and synergies between stressors impacting on coral cover and reef health. Specifically, several articles highlighted the benefits of no-take zones and water quality improvements, including the associated influence on CoTS densities (Brodie and Waterhouse 2012; De'Ath et al 2012; Pratchett et al 2014; Babcock et al 2016; Westcott and Fletcher 2018; Westcott et al submitted).

Thirteen articles provided general commentary on the likelihood of manual control programs succeeding in controlling CoTS outbreaks. Ten articles concluded that manual control (ie culling) via removal and /or injection was the most appropriate action (Brodie et al 2012; De'Ath et al 2012; Pratchett et al 2014, 2019; Engelhardt 2015; Hoey et al 2016; Vercelloni et al 2017; Westcott and Fletcher 2018; Fletcher et al 2019; Westcott et al submitted). However various authors were cautious as to the scale of likely control (at the individual reef scale rather than whole of GBRMP) and were concerned over the resource intensity of maintaining response efforts. In contrast, five articles stated that manual removal /injection control programs are fraught with failure (Hock et al 2014; Morello et al 2014; Uthicke et al 2015; Babcock et al 2016; MacNeil et al 2016). Most authors noted that management success was contingent on a variety of key actions, including: political and societal will in order to sustain longer term strategies (Hoey et al 2016; Vercelloni et al 2017); sustained surveillance and response efforts (and associated funding) during both outbreak and non-outbreak periods (Pratchett et al 2014, 2019; Hoey et al 2016; Westcott and Fletcher 2018; Westcott et al submitted); and better data quality (Pratchett et al 2014, 2019; MacNeil et al 2016; Westcott and Fletcher 2018; Fletcher et al 2019; Westcott et al submitted).

A number of articles were clearly focused on lessons to be learned for the next outbreak cycle, rather than the current outbreak. The need for enhanced surveillance and detection efforts (Morello et al 2014; Pratchett et al 2014, 2019; Uthicke et al 2015; Hoey et al 2016; Keesing et al 2018), including appropriate targeting of locations to enhance rapid response was highlighted (Hock et al 2014, 2016; Pratchett et al 2014, 2019; Hoey et al 2016; MacNeil et al 2016; Westcott and Fletcher 2018; Fletcher et al 2019; Westcott et al submitted). Additionally, several articles suggested that enhancing natural controls and resilience through greater understanding of system dynamics was the key to ultimately manage CoTS outbreaks (eg Morello et al 2014; Pratchett et al 2014, 2019; Babcock et al 2016).

Engelhardt (2015) provided the most critical commentary and made explicit calls for changes to the CoTS Control Program. As stated above, Engelhardt's analysis examined the 2012/13-2014/15 period, highlighting a number of areas of concern including: CoTS Strategy Development; Project Management; CoTS Control Procedures; and Field Operations / Logistics. In his evaluation the first two elements (CoTS Control Procedures, Field Operations / Logistics) were deemed to have been adequately addressed, however he stated that the CoTS Strategy Development and Project Management during the 2012/13-2014/15 period failed to deliver on key outcomes.

Table 1: Articles identified in the Systematic Review for detailed analysis.

Citation	Source	Period of comment
Babcock et al 2016a	SCOPUS	N/A
Bos et al 2013	SCOPUS	2009
Brodie and Waterhouse 2012	SCOPUS	<2012
De'Ath et al 2012	SCOPUS	<2012
Engelhardt 2015	Stakeholder	2012-2015
Fletcher et al 2019	Stakeholder	2018/19
Hall et al 2017	SCOPUS	1950-2016
Hock et al 2014	SCOPUS	N/A
Hock et al 2016	SCOPUS	N/A
Hoey et al 2016	SCOPUS	2012-2015
Keesing et al 2018	SCOPUS	N/A
MacNeil et al 2016	SCOPUS	2014
Morello et al 2014	SCOPUS	<2012
Pratchett et al 2014	SCOPUS	<2012
Pratchett et al 2019	SCOPUS	N/A
Uthicke et al 2015a	SCOPUS	2014
Vercelloni et al 2017	SCOPUS	N/A
Westcott and Fletcher 2018	Stakeholder	2012-2018
Westcott et al submitted	Stakeholder	2012-2018

5.3 Discussion

5.3.1 Strategies

A key focus in several articles was determining appropriate strategies for site selection including a call for appropriate surveillance across the GBRMP (Hock et al 2014, 2016; Pratchett et al 2014, 2019; Engelhardt 2015; Hoey et al 2016; MacNeil et al 2016) and the development of an Integrated Pest Management (IPM) framework to inform decision making.

5.3.1.1 Surveillance and Intelligence Gathering

Surveillance and intelligence gathering to inform site selection and prioritisation for management action was of concern for several participants (Hock et al 2014, 2017; Morello et al 2014; Pratchett et al 2014, 2019; Engelhardt 2015; Uthicke et al 2015; Hoey et al 2016; MacNeil et al 2016; Westcott and Fletcher 2018; Fletcher et al 2019; Westcott et al submitted). These criticisms were variously focused on previous response efforts prior to 2012 or the early period (2012/13-2014/15) where surveillance appears to have been an ad hoc process (MacNeil et al 2016; Pratchett et al 2019). Additionally, several calls were more generic and focused on early detection of the onset of an outbreak cycle in the initiation box (Pratchett et al 2014; Hoey et al 2016).

The changes to the CoTS Control Program during the second period (2015/16-2017/18) were implemented to shift from a reactive to a strategic culling program. Intelligence to prioritise sites for action was gathered from the previous fiscal year's culling program and the Field Monitoring Program (FMP) data on CoTS density and reef health (hard coral cover). These were used to identify reefs where culling intervention was more likely to have a greater impact, that is reefs with "outbreak" CoTS densities (or incipient outbreak densities) yet retaining coral cover >20%.

The implementation of the IPM Strategy in the third period (2018/19) has seen the use of data for prioritising and scheduling reefs for priority action become formally incorporated into the IPM Decision Support process. Manta Tow frequencies at Intensive Control reefs are recommended every 36 days, similar to the frequency used in prior Program periods (Fletcher et al 2019). Once a reef shifts into Maintenance Mode, Fletcher et al (2019) recommend that Manta Tow frequency shift to every three to six months as a means to manage the surveillance load on operators and to balance attention between Intensive Control and Maintenance Mode reefs.

A suite of authors have proposed additional methods to rapidly gather intelligence of CoTS density from reefs using eDNA (Uthicke et al 2015; Keesing et al 2018; Pratchett et al 2019).While these new methods show promise, they have yet to be incorporated into the IPM Strategy for reef intelligence. The use and application of eDNA for pest management remains in an early stage of development (Borell et al 2017; Grey et al 2018) and while it can provide quick information returns, must be accompanied by on-site validation (Goldberg et al 2016; Pochon et al 2017).

5.3.1.2 Site Selection Strategy

As previously mentioned, site selection was initially focused on protecting economic assets (as agreed in the funding arrangements) with key tourism sites identified in consultation with tourism operators (noting that response to tourism operator requests diminished the focus on 'priority' sites/reefs; Figure 2). However, as the CoTS Control Program developed, site selection increasingly shifted to strategic intervention by considering reef connectivity of both CoTS and coral larvae. The initial calls for a more appropriate (eg science informed) site selection strategy were initially addressed in the second period (2015/16-2017/18) using the best available evidence for the Cairns/Townsville region, and further developed in the third period (2018/19) with the full implementation of the IPM Strategy (at this point a shift to "whole of reef" management was made). These shifts were influenced by criticisms of the early period of the CoTS Control Program and participation in the continuous adaptations (Hock et al 2014, 2016, 2017; Pratchett et al 2014, 2019; Engelhardt 2015; Hoey et al 2016; MacNeil et al 2016; but see Westcott and Fletcher 2018; Fletcher et al 2019; Westcott et al submitted).

Site selection within the whole of reef approach implemented in 2018/19 should continue to prioritise the high-density CoTS aggregations using regular Manta Tow surveillance data in active control sites (Fletcher et al 2019).

The development of a reef connectivity model (Hock et al 2014, 2016, 2017) significantly informed the development of the Site Selection Strategy; however, several authors have expressed concerns over elements of the model including; the data underlying assignment of reef health, and the use of appropriate Pelagic Larval Durations (PLDs) for CoTS and for individual species of coral.

Engelhardt (2015) raised concerns that decisions to initiate a culling action were ad hoc and inconsistent. As indicated in Section 4, the decision to initiate a management (culling) action was shifted from the vessel operator (2012/13-2014/15) to a planned management decision through prioritisation of sites/reefs based on prior intelligence from various sources (2015/16-2017/18; 2018/19).

5.3.1.3 Integrated Pest Management (IPM) Strategy

Several authors explicitly made early calls for an Integrated Pest Management (IPM) strategy to support decision-making and the efficacy of management efforts (eg Engelhardt 2015; Hoey et al 2016). IPM reflects a developmental history drawn from invasion (pest) ecology and biosecurity management where significant data paucity, competing interests and limited funding create the need for clear decision frameworks. This call for application of IPM was provided both in response to the current outbreak cycle (eg Engelhardt 2015) and as a mechanism to manage across multiple cycles (eg Hoey et al 2016).

The continuing development of the CoTS Control Program and inputs from the scientific community resulted in the development of an IPM Strategy, released in 2016 (Westcott et al 2016) and implemented in the final assessed period (2018/19; Fletcher et al 2019). The IPM Strategy has been developed in concert with consultation and advice of stakeholders and addresses many of the concerns raised by authors. Specifically, the IPM Strategy provides a clear decision making framework informed by best available science that incorporates appropriate data collection to inform the efficacy of efforts in a consistent and commensurate fashion.

The IPM Strategy addresses a number of key concerns raised by stakeholders and the scientific community including Site Selection, evidence-based Decision Making, and a strategic approach to managing for coral reef resilience at a wider (GBR) scale. Of utmost importance was the need to design a program that demonstrated the ability to create a lasting decrease in CoTS abundance and have an increase in hard coral cover.

5.3.2 Operational Logistics and Targets

5.3.2.1 Voyage Planning and Site Revisitation Frequency

A number of authors highlighted the need to have repeated manual control at a site in order to ensure cryptic individuals were detected and managed (Bos et al 2013; MacNeil et al 2016) with control actions undertaken at size classes and timing prior to reproduction (Bos et al 2013; Morello et al 2014; Hock et al 2014). As indicated in Section 4, the initial period of the CoTS Control Program (2012/13-2014/15) exhibited a continuation of site-based controls largely responding to high densities with less focus on repeat visits and complete culls of individual sites on reefs. Response to tourism operator requests remained high leading to criticisms of ad hoc control efforts (Engelhardt 2015; MacNeil et al 2016). As the program has matured, there has been a greater focus on voyage planning using priority areas (identified areas with priority reefs) during the second period (2015/16-2017/18) and explicit voyage planning targeting priority reefs in the final period (2018/19).

The need to repeat visits to individual cull sites was acknowledged and recognised in 2013/14, however a target of at least once every three months was only contractually established in the second period (2015/16-2017/18) and explicit decision-rules through application of the IPM Strategy in the final period (2018/19). In this final period control action at a priority reef continues until the reef achieves the targeted CPUE threshold at the whole of reef scale. It is worth noting that Westcott and Fletcher (2018) found that multiple voyages were required to consistently bring the population abundance below the target CPUE threshold. The added benefit of repeat visits to limit the likelihood of reproduction was also noted (Bos et al 2013; Hock et al 2014; Engelhardt 2015).

Under the IPM Strategy and the associated operational strategy (Fletcher et al 2019) the revisitation frequency is targeted for ~ 2 weeks (approximately every 12 days). This period is considered to be sufficient for CoTS populations at individual culling sites to replenish (ie cryptic CoTS individuals to emerge) and previously injected CoTS to disintegrate in order to optimise culling activity.

5.3.2.2 CPUE Thresholds

Culling targets initially were a continuation of the pre-2012 targets, however as additional scientific evidence was developed (Babcock et al 2014) CPUE thresholds were adjusted to also consider the hard coral cover at a site to inform the target CPUE. These thresholds were considered conservative estimates of the carrying capacity of a site to allow hard coral recovery.

In assessing the first period (2012/13-2014/15), Engelhardt (2015) highlighted the need for CPUE targets to be set against available coral cover, however this was addressed in 2014/15 with the Babcock et al (2014) CSIRO report which established CPUE thresholds of 0.08 CoTS /minute at reefs with ≥40% hard coral cover and 0.04 CoTS /minute at reefs with <40% hard coral cover.

Both Engelhardt (2015) and MacNeil et al (2016) expressed concern that CPUE is a flawed metric for estimating CoTS abundance and control efficacy. Engelhardt (2015) highlighted factors that can affect CPUE estimates including natural CoTS declines in abundance and detection limits (eg visibility, diver fatigue, site rugosity). Both articles acknowledge consistency in methodology and diver training to reduce the variability in these estimates, however CPUE is also subject to biases based on the population dispersion of the target organism. As discussed by MacNeil et al (2016) using independent estimates of true abundance, the AMPTO CPUE estimates were “hyperstable” (CPUE estimates of abundance are higher than true abundance). This means that the AMPTO CPUE estimates increasingly provide a conservatively biased measure of abundance at lower CPUE (see Figure 3a in MacNeil et al 2016), potentially resulting in a greater reduction in true population than the target CPUE suggests. Westcott and Fletcher (2018) analysed manual control efforts from 2012/13 to 2016/17and discerned evidence that manual control using CPUE targets was “effective in reducing CoTS numbers at a site”.

Engelhardt (2015) also suggested that possible ecological risks associated with inadequate CoTS controls would lead to “enhanced” CoTS impact as was observed in Okinawa, Japan (Yamaguchi 1986; Nakamura et al 2014). Engelhardt’s conclusion was that:

“If you can’t allocate sufficient control effort to <u>completely eradicate</u> the active CoTS population with an intensive, relatively short-term control effort then it may be more beneficial to not intervene at all” (underline from the original).

CoTS is a native corallivorous predator and attains outbreak densities at some localities that lead to significant impacts, particularly when added to other stressors contributing to coral decline. The focus of the CoTS Control program has been to <u>reduce</u> CoTS populations to levels below ecological impact thresholds that allow coral recovery, not to <u>completely eradicate</u> the species even from target locations (Pratchett et al. 2019). This is repeatedly highlighted and agreed as a key underlying principle of the CoTS Control Program.

It should be noted that Fletcher et al (2019) recommend that the current CPUE Targets (Babcock et al 2014) should remain in place, noting the trade-off between ecological outcomes and logistic (cost) constraints. Fletcher et al (2019) do recommend that refinements to the CPUE ecological thresholds should increasingly consider CoTS size class distributions and potentially consider a range of hard coral covers.

5.3.2.3 CoTS Size Classes

Several authors raised concerns that restricting the COTS Control Program to control adults alone would likely result in failure of the program or create an ongoing need for control (Morello et al 2014; Engelhardt 2015; Uthicke et al 2015; Babcock et al 2016; MacNeil et al 2016; Pratchett et al 2019). While not explicitly reported, there was no contractual requirement to only cull 'adult' individuals (presumably >25cm) during any period of the CoTS Control Program (2012/13 – 2018/19). In the second period (2015/16-2017/18) an explicit requirement was made for cull data reporting to include culled CoTS individuals by size classes. Westcott and Fletcher (2018) undertook an analysis of cull efficacy across four size classes (<15cm, 15-25cm, 25-40cm, >40cm) as a function of repeat visits (voyages to sites) between 2013/14 and 2016/17. They determined that the three largest size classes decline in number following consistent culling efforts, whereas the smallest size class shows a reduction but remains at "relatively high numbers" thereafter. They highlighted that this is beneficial due to larger individuals exhibiting the greatest predation pressure (Keesing 1990), and are the most fertile (Kettle and Lucas 1987).

Several authors highlight the need to expand control to earlier life history stages (Pratchett et al 2014, 2019; Uthicke et al 2015; MacNeil et al 2016). MacNeil and others stated, "Without the ability to detect and kill juvenile CoTS, adult control operations will only remove the threat to corals for a single year, after which juvenile CoTS will mature and emerge from the reef substrate to feed. Fletcher et al (2019) suggest that a future refinement of CPUE targets could examine CoTS size class specific CPUE thresholds.

It is likely only through early detection of larvae (Uthicke et al., 2015), juvenile, and pre-spawn adult CoTS that candidate control methods could hope to arrest initial outbreaks. To this end, exploration of attractants and baits have been suggested as a means to enhance efficacy of the program and extend culling to smaller size classes (Pratchett et al 2019).

5.3.3 Data Collection, Curation and Transparency

5.3.3.1 Data Collection and Compatibilities

A number of authors highlighted concerns with inconsistently collected data, poor reporting or lack of compatibility between data collection programs (Hock et al 2014, 2016, 2017; Engelhardt 2015; MacNeil et al 2016). Specific concerns were identified by Engelhardt (2015) that coral cover estimates during the first period (2012/13-2014/15) were inconsistent and erroneous, however he acknowledged "these were addressed" with the installation of permanent RHIS markers.

Despite long-term focus on the GBR, there have been a number of issues with data compatibility (and trustworthiness) between various programs. These include the CoTS Control Program relationships and compatibilities with the Field Monitoring Program (Queensland Parks and Wildlife Service and GBRMP Rangers), AIMS LTMP, Tourism operators and citizen science inputs (Eye on the Reef). Many of these issues have been or are being resolved –

- FMP data is considered to be of high quality with excellent curation; design of program is consistent, well structured, with systematic effort across reefs and regions. In IPM Strategy now informing site prioritisation for culling activity and voyage scheduling
- AIMS LTMP data is of high quality and consistent and well structured, but limited overlap with CoTS Control Program prioritised reefs. Initially Manta Tow data collection in the two programs was not aligned, however in 2017/18 the CoTS Control Program realigned Manta Tow data collection to mirror AIMS LTMP specifically to ensure cross-comparability.
- Tourism operators and citizen scientists provide inputs that can be ad hoc with limited validation and curation. Information on sightings can help inform areas where additional effort might be needed, but a “lack of sightings” has no value and cannot infer low COTS densities.

5.3.3.2 Data Curation

Data Curation has shifted from hard copy reports alone to direct submission through both Surveillance and Control Apps with direct inputs via tablets that allow immediate application to decision-rules while at the site. This provides immediate and consistent feedback to operators demonstrating the utility of data collection.

5.3.3.3 Data Transparency

A number of interviewed stakeholders signalled significant concern that the COTS Control Program had insufficient communications and transparency in developing robust scientific assessments of control efficacy, particularly on hard coral recovery. The lack of information flow often meant the ability for program objectives aligned to facilitating research were compromised. Similarly, there was concern that the scientific rigour of the program, particularly during earlier periods, was questionable (eg Engelhardt 2015). Changes to the program, such as the development of the IPM Strategy and the NESP IPM program bringing researchers together has addressed most of these objections.

Most stakeholders acknowledged that this was a management control program, with the intent to demonstrate capability to control COTS at small scales in the first instance. There was consistent and resounding support that this has been demonstrated.

5.4 Summary

An examination of primary and grey literature, including prior reviews and scientific assessments of the COTS Control Program 2012-2019 identified 71 articles, of which 18 articles provided direct comment on the Control Program strengths and weaknesses. With one exception, all articles focussed on early periods of the COTS Control Program (prior to 2015) or provided generic (not time specific) comment on strengths and weaknesses of COTS manual control. Half of the articles provided some endorsement of COTS manual control as an appropriate mechanism for management action and half cautioned that manual control alone was unlikely to manage COTS at the GBR scale. It should be noted that eight articles explicitly identified key learnings necessary for detecting and managing a new outbreak cycle.

Key strengths and weaknesses highlighted by the articles included Strategies (Surveillance and intelligence gathering; Site selection; Integrated Pest Management); Operational Logistics and Targets (Voyage planning and revisitation frequency; CPUE thresholds; CoTS size classes) and Data collection, curation and transparency. While several points of concern were identified, we found that changes in the CoTS Control Program, specifically the adoption of an IPM Strategy, has addressed most of these concerns or provides a mechanism for the suggested changes to be considered and incorporated.

6. Validity of surveillance and control data to assess effectiveness and support decision making and prioritisation activities

The extent to which the data from surveillance and control activities has been sufficient or appropriate to aid prioritisation activities, support decision-making, and measure the effectiveness of the control program have been raised (see Section 5). Significant changes to the CoTS control program have occurred over the three identified time periods (2012/13-2014/15; 2015/16-17/18; 2018/19). A critical shift from tactical protection of economic assets (key tourism sites) where CoTS impacts on hard coral cover might negatively influence tourist behaviours resulting in economic loss and reputational damage, to strategic protection of key environmental values that would have economic and social benefits has been the most salient demonstration of strategic change in the CoTS Control Program. These include refinements to what data is collected, how data is collected and reported, as well as how that data is used, such as influence on decision-making highlighting “where to cull”, “when to cull”, and “how much to cull”. Here we assess the current “Expanded Control Program” (2018/19) data collections.

6.1 Surveillance data

Surveillance data provides forward intelligence for targeted planning and informs strategic allocation of resources, as well as providing immediate intelligence to inform local response (eg, identifying sites on reefs requiring CoTS culling action; identifying CPUE targets based on coral cover estimates). Additionally, surveillance data is critical to inform Program efficacy against the key objective – are hard corals recovering? Development of the CoTS Control Program has seen refinements to the methods used to collect surveillance data resulting in greater levels of consistency.

6.1.1 Coral cover

Coral cover estimates have been collected from both RHIS and Manta Tow surveys, however concerns with consistency of RHIS locations at sites (resulting in highly variable coral cover estimates between visits) was previously highlighted. Beginning in 2013/14 permanently marked RHIS sites increased to 53 sites and have now been replaced with high accuracy GPS coordinates to inform coral cover estimates.

The appropriateness of the RHIS methodology has previously been questioned – whether it is fit for purpose to accurately assess and track coral cover. The use of more refined and scientifically valid point-intersect transects, photograph stations or video transects has been proposed (aligned to AIMS LTMP), however time and resource limitations have been highlighted as challenges. Additionally, previous studies have shown the RHIS method to provide a robust measure of coral cover and coral health (Hock et al 2014).

In addition to RHIS, Manta Tows provide estimates of coral cover, CoTS density and evidence of CoTS presence (based on feeding scars). Manta Tow data collection refinements have improved information for both site based response and forward planning as well as becoming more closely aligned to the AIMS LTMP methodology. This increasing alignment with AIMS LTMP has had the added benefit of access to other data sources to enhance cross-compatibility and allow GBR wide comparisons.

6.2 Control data

Effort based Control data relates to the Number of CoTS killed per site visit in total by size classes (<15cm, 15-25cm, 25-40cm, >40cm), and the CPUE achieved during the site visit. At least three replicate RHIS are conducted at each cull site polygon prior to culling action to inform the CPUE target, and replicate RHIS are repeated every three months during active culling, and after completion of culling action. This alignment of RHIS evaluations with control action dynamically informs decision making (potentially adjusts the CPUE target as coral cover is reduced) and is used as a baseline for evaluation of hard coral recovery.

6.3 Evaluation of sufficiency

The key question to be addressed is whether the current "Expanded Control Program" (2018/19) data collection, that is post implementation of the IPM Strategy, provides sufficient information to inform Site Prioritisation, Decision-making and Control Program Efficacy. Fletcher et al (2019) provide an evaluation of the Expanded Control Program (2018/2019) after the first eight months (November 2018 – June 2019), specifically focused on performance of the IPM Decision Criteria, but also include assessments of program performance.

6.3.1 Site prioritisation

In the current period (2018/19) under the IPM Strategy, a whole of reef approach has been established for management action. Data collection from both RHIS and Manta Tow Surveys provide sufficient information to inform tactical site prioritisation within a reef and as inputs to strategic reef prioritisation for annual voyage planning.

Tactical culling response site prioritisation on a reef uses the data collected from comprehensive Manta Tows conducted within predefined polygons covering the entire reef circumference. These Manta Tows provide information on coral cover and CoTS presence based on abundance estimates or detection of feeding scars. Sites are conservatively prioritised based on a two-step process: whether a site is to be culled based on a binary assessment (presence of either CoTS or CoTS feeding scars) and second which site is to be culled first based on greatest density of CoTS observed in the Manta Tows.

Strategic reef prioritisation is based on a number of factors including previous year's culling activity and whether a reef remains under active control. This shift enforces the IPM Strategy and ensures that culling actions achieve target CPUE thresholds.

6.3.2 CoTS density and feeding scar prevalence

CoTS density estimates (including prevalence based on feeding scars) are primarily derived from Manta Tow evaluations, either undertaken prior to a culling action or as part of the FMP Surveillance data collection. As indicated above, the data collected from Manta Tows have now been aligned to AIMS LTMP, particularly with relevance to feeding scar prevalence (absent, present 0-10, common >10).

FMP Manta Tow data has demonstrably been shown to provide an accurate representation of true CoTS population densities with a consistent bias based on detectability (Figure 3 in MacNeil et al 2016). There is no similar analysis of accuracy for CoTS feeding scars/tow, however these are used in a binary fashion for site prioritisation and culling response decision making (see below) therefore the required level of accuracy is sufficient.

6.3.3 Decision-making

As stated above, individual sites on a reef are conservatively prioritised based on a two step process: whether a site is to be culled based on a binary assessment (presence of either CoTS or CoTS feeding scars) and second which site is to be culled first based on greatest density of CoTS observed in the Manta Tows.

CPUE targets are determined by coral cover and determined dynamically based on a minimum of three replicate RHIS surveys in the culling polygon, and applied to the Babcock et al (2014) CPUE thresholds (0.08 CoTS /minute at reefs with ≥40% hard coral cover and 0.04 CoTS /minute at reefs with <40% hard coral cover). The level of accuracy and precision provided by RHIS estimates of hard coral cover are sufficient to inform decision-making rules based on binary thresholds of hard coral cover (<40%:>40%). Under the Expanded Control Program (2018/19) these thresholds continue and are informed by re-assessment every 36 weeks (Fletcher et al 2019), with the potential to dynamically alter the CPUE target as active culling proceeds.

As stated previously, replicate RHIS are conducted at each cull site polygon prior to culling action to inform CPUE target, repeated every three months, and after completion of culling action. This may inform an adjusted CPUE target should coral cover fall below key coral cover thresholds (Babcock et al 2014).

Both the surveillance and control data inform decision making for continuing management action and directly inform the transition of a reef from active management to maintenance mode.

6.3.4 Effectiveness of CoTS Control Program

Previous reviews (Engelhardt 2015; Westcott and Fletcher 2018) have explicitly evaluated surveillance and control data in relation to their ability to address the effectiveness of the CoTS Control Program, and their criticisms were reported in Section 5. Both evaluations explicitly focused on early periods (2012/13-2014/15 and 2015/16-2017/19, respectively).

6.3.4.1 Increase in Hard Coral Cover

The ultimate objective of the CoTS Control Program has been to protect live hard coral cover, by reducing CoTS predation through culling CoTS densities to levels below ecological thresholds (Babcock et al 2014). As the program has developed, these objectives have shifted to “maintain or improve coral cover”. In order to determine whether the CoTS Control Program has protected (or improved) coral cover we need to be able to determine the contribution CoTS removal provides.

A significant criticism of the CoTS Control Program by various authors and stakeholders has been the lack of explicit control reefs with and without CoTS (eg above and below ecological thresholds). A formal Before/After Control/Impact (BACI) paired reef design would allow for much more detailed assessment of the contribution that CoTS removal makes to hard coral cover recovery, given the multiplicity of factors that affect coral cover at a site (De’Ath et al 2012; Mellin et al 2019). We note that paired cull/no cull sites were established in the Cairns/Townsville region to be annually evaluated by the FMP (2018-2020), however a significant and widespread bleaching event in January 2019 may affect the evaluation.

Despite this lack of formalised control reefs, before/after culling comparisons of reef condition, that use culling frequency (site visits) as a predictive factor, can be used to evaluate effects on coral cover as demonstrated by the analyses of Westcott and Fletcher (2018) and Westcott et al (submitted).

The current iteration of the program undertakes before/after evaluations of reef health using RHIS and Manta Tow data to estimate coral cover. As previously noted, the RHIS and Manta Tow data for CoTS densities have been assessed for accuracy (MacNeil et al 2016) but a similar comparison for coral cover does not appear to be available. This assessment would provide a clear understanding of the biases and sensitivities to measurement of performance. Similarly, an understanding of the sensitivity of surveys to detect coral recovery by regrowth versus recruitment, and for specific coral functional groups, would be useful. Given that these survey methods have been employed for some years and by various groups, these biases may already be known.

Previous assessments of the CoTS Control Program data by Westcott and Fletcher (2018) and Westcott et al (submitted) indicated that the levels of accuracy and precision provided by RHIS data are sufficient for assessing coral recovery following CoTS control action.

6.3.4.2 Reduction in CoTS Density at Priority Reefs

CoTS density is measured through Manta Tow surveys (Number of CoTS/tow), RHIS evaluations (Number of CoTS/400m^2), as well as during the culling activity (CPUE). Manta Tow and RHIS surveys provide an accurate estimate of true abundance biased by detectability of CoTS (MacNeil et al 2016).

As previously discussed, CPUE provides a biased measure of true CoTS population density. We have highlighted that the findings of MacNeil et al (2016) indicate that the AMPTO CPUE estimates were “hyperstable” (CPUE estimates of abundance are higher than true abundance) relative to the independently (more accurately) assessed true abundance. This suggests that the CPUE target threshold will provide a conservatively biased target (see Figure 3a in MacNeil et al 2016), potentially resulting in a greater reduction in the true CoTS population density than the target CPUE suggests.

Previous analyses by Westcott and Fletcher (2018), Westcott et al (submitted), and Fletcher et al (2019) used CPUE as the response metric and determined that both in the previous periods (2012/13-2014/15; 2015/16-2017/18) and the current period (2018/19) persistent culling effort at a site resulted in a decline in the density of CoTS encountered.

6.3.4.3 Reduction in Average Size of CoTS at Priority Reefs

The collection of data on CoTS CPUE based on individual size classes is relatively recent (2015/16). We note that MacNeil et al (2016) evaluated AMPTO CPUE data collected in 2014 and did not evaluate the biases associated with detection and estimation of population density for specific size classes.

Westcott and Fletcher (2018), Westcott et al (submitted), used CPUE as the response metric and detected a persistent reduction in CoTS densities for all size classes (<15cm, 15-25cm, 25-40cm, >40cm), and below CPUE targets for the three larger size classes, as a function of repeat visits (voyages to sites) between 2013/14 and 2016/17. Fletcher et al (2019) similarly detected a persistent decline at John Brewer Reef with repeat culling activities. We find the use of CPUE data by size classes to be sufficient to determine a reduction in average size of CoTS at priority reefs.

6.4 Recommendations

The CoTS Control Program in the current Expanded Control Program phase is a robust, evidence based framework that provides clear mechanisms for adaptive improvements. Fletcher et al (2019) make clear recommendations for additional changes. Here we provide recommendations for key data needs to inform and improve the program. We note that many of these changes have already been identified and mooted within the IPM framework.

A persistent criticism of the CoTS Control Program has been the lack of control reefs to assess the effect of CoTS culling relative to other stressors to hard coral cover. The current IPM Strategy and prioritisation of reefs based on connectivity and reef health suggests that control reefs are no longer feasible without compromising the integrity of the Program (ie leaving uncontrolled reefs embedded within the highly connected network). Instead, the assessment of the underlying connectivity model assumptions becomes critical.

The sensitivity of reef connectivity outcomes against larval Pelagic Larval Durations (PLDs) for different coral species and CoTS is critical. Similarly, self-recruiting coral and CoTS populations on individual reefs as an input is critical.

As indicated, the underlying data for reef health is required for a wider network of reefs. The cross validation of hard coral cover estimates based on RHIS and Manta Tow Surveys to determine biases in data, similar to that conducted by MacNeil et al (2016) for CPUE and Manta Tow estimates of CoTS density, would inform the sensitivity of coral cover data to accurately determine recovery. This might include determining the sensitivity of RHIS and Manta Tow hard coral cover estimates to detect regrowth versus coral recruitment.

Current assessments of reef health (and prioritisation) are based on hard coral cover and do not differentiate between types of coral, despite known relative differences in CoTS feeding preference and effect on CoTS reproductive energetics.

Sites shifted into Maintenance Mode should be assessed using more scientifically robust survey techniques to establish baselines against which hard coral recovery rates can accurately be determined.

Additional work on CoTS detectability will aid in improving understanding of target CPUE, particularly with respect to size classes.

Additionally, understanding the CoTS ‘replenishment’ following a culling activity will aid determination of optimal revisitation, noting that ‘replenishment’ may vary by CoTS size classes.

7. Review the in-depth scientific analysis of available data to assess the impact of manual CoTS control initiatives implemented since 2012

The initial Terms of Reference for the Independent Review requested an “In depth scientific analysis of available data to assess the impact of manual CoTS control initiatives implemented since 2012. The reference for this assessment will be in line with the current GBRMPA’s CoTS Control Program Objective of protection of coral at key sites.” The contracting of the Independent Review was superseded by ongoing efforts of the NESP Program of Work that included in depth scientific analyses of the available data by CSIRO (Westcott and Fletcher 2018; Fletcher et al 2019) for the periods, 2015/16-2017/19, and 2018/19. As a consequence, this element of the Terms of Reference was adjusted to critically review the scientific analyses found in Westcott and Fletcher (2018), and Fletcher et al (2019). The key performance measures for assessment were identified at a workshop on 29-30 January 2019, with representatives from GBRF, GBRMPA, CSIRO and Australian Government (DoEE): 1) reduced density of CoTS at priority reefs, and 2) a reduction of the average size of COTS at priority reefs.

7.1 Westcott and Fletcher (2018)

Westcott and Fletcher (2018) undertook an evaluation of the relative efficacy of three management intervention strategies in reducing CoTS numbers on targeted reefs: i) water quality improvement efforts, ii) zoning, and iii) manual control. All three management interventions have been in effect during (or before) the current outbreak at some scale (manual control at a limited number of reef sites). They used CoTS abundance data from the CoTS control program to determine if the three intervention strategies were effective in reducing and maintaining CoTS densities below the ecological threshold determined by Babcock et al (2014). Additionally, they evaluated whether the three intervention strategies successfully resulted in a (positive) response in hard coral cover using coral cover estimates from GBRMPA’s reef health monitoring program.

For manual control, they evaluated CoTS control program data from 2012/13-2017/18 (representing the first and second periods of the Control Program; Sections 4.1 and 4.2), assessing number of CoTS killed ha-1 as the dependent variable against the number of voyages to a site. Fifty-three (53) sites at 21 Priority Reefs determined that CoTS densities decline as a function of the number of voyage visits until the 11th voyage and then fluctuate at low densities (see Figure 1 in Westcott and Fletcher 2018).

Similarly, they evaluated the impact of number of voyages to a site on the number of CoTS killed ha-1 in four individual size classes (>40cm; 25-40cm; 15-25cm; <15cm) in the same fashion. They found a significant decline in the three larger size classes (>40cm; 25-40cm; 15-25cm), however the smallest size class showed a long term reduction, but relatively high numbers (see Figure 2 in Westcott and Fletcher 2018).

They concluded that manual control efforts were effective at reducing CoTS densities at control sites and reducing the numbers of CoTS in larger size classes (>15cm equivalent to >year 2 cohorts) but only after several culling visits. Sites that were visited infrequently did not achieve a desired reduction in CPUE, often CPUE levels remained close to pre-culling. They noted that at least five voyages were required to bring 75% of sites below the ecological threshold, and that only after 11 voyage visits was the decline in CoTS densities halted. The interpretation was that successive visits were required to expose cryptic CoTS to culling activity, and that an optimum site visit frequency might be calculated based on the minimum time for cryptic individuals to move into the open, balanced against the costs of site visitation.

Size class findings suggest that an initial intensive effort at a site is required to suppress the density of larger (>year 2 cohorts) CoTS, however once suppression has been achieved, that a “maintenance” of smaller size class removal can be enacted less frequently.

We find the Westcott and Fletcher (2018) analysis of the 2012/13 – 2017/18 dataset to be of high quality and note that it provides a critical, and in-depth assessment of the data sufficient to address the two key performance measures in the Terms of Reference. They determined that manual control suppressed overall CoTS densities and specifically removed larger size classes resulting in a skewed age-class distribution in the population. They concluded that this suggests that CoTS detected in later voyages represent individuals missed from previous voyages rather than immigrants. They note that preferential removal of larger size classes represents a desired outcome as larger individuals consume more hard coral per capita, and represent a greater reproductive potential.

We note that the comparison of size class removal was against ecological thresholds for CoTS outbreaks for the population (defined by Babcock et al 2014). Babcock et al (2014) developed and evaluated a model using CoTS and coral data reported in Pratchett (2005, 2010) which “refer to CoTS individuals mostly larger than 15 cm, corresponding to our 2+ age class”. While this estimate of CPUE thresholds is applied to population levels, its application to individual size classes (particularly the smallest size class <15cm) is indicative and not appropriate.

Additionally, Babcock et al (2014) and Morello et al (2014) explored the influence of removal efficiency for the smallest (<15cm) size class on CoTS population reduction and hard coral recovery. They found a differential effect of preferentially targeting the smallest size class (age class) in determining the success of removals. Consequently, there remains a critical need to investigate the true extent of size class crypsis and determine more efficient methods of detection and removal.

7.2 Fletcher et al (2019)

Fletcher et al (2019) outlines an “ecologically-informed framework for the management of day-to-day operations of the Expanded Crown-of-Thorns Starfish…Control Program on the Great Barrier Reef.” As a component of the report they evaluated the first eight months of data from mid 2018 representing the Expanded Control Program (Section 4.3). They undertook an assessment to determine if the Expanded Control Program Decision Trees were effective in reducing CoTS densities to below ecological thresholds at culling sites using both the number of CoTS observed per Manta Tow, and the number of CoTS culled ha^{-1}.

They report that between October 2018 and May 2019 the Expanded Control Program had undertaken culling activities at 41 reefs, with varying numbers of voyages per reef (30 reefs with 1 voyage; 4 reefs with 2 voyages; 1 reef with 3 voyages; 2 reefs with 4; 2 reefs with 7 voyages; 1 reef with 8 voyages; and 1 reef with 10 voyages). Figures 4 through 6 (therein) represent three reefs (John Brewer, Farquharson Reef, Eddy Reef) where multiple culling voyages demonstrate a reduction of CoTS observed per Manta Tow and the number of CoTS culled ha^{-1} (CPUE) with effort.

They surmise that multiple voyages to a single location successfully reduces CoTS densities, reinforcing the findings from Westcott and Fletcher (2018). Additionally, the reduced time interval between Voyages (10 -15 days in the Expanded Control Program) is sufficient to allow CoTS to emerge from cryptic habitats or immigrate from adjacent locations, and lastly the declines in CoTS densities at a reef appear to periodically increase as a consequence of additional sites within a reef being included in culling effort.

They also evaluated the reduction of CoTS densities in four size classes (>40cm; 25-40cm; 15-25cm; 10-15cm) and conclude that size class declines in CoTS density occur most rapidly in larger size classes, however as individuals emerge from cryptic habitats or migrate from adjacent sites within the reef, or as additional sites are added to culling action, there are occasional increases in larger size class densities. They conclude that this highlights the need for ongoing surveillance and action once a reef is placed into “Maintenance mode”.

We find the analysis of the 2018/19 dataset to sufficiently demonstrate a reduction in CoTS densities, and a reduction in individual CoTS size class densities, at the evaluated sites. While the focus of the Fletcher et al (2019) report was not to provide an in-depth analysis, recognising that the Expanded Control Program had only been in operation for eight months, their analysis of new data reinforces the findings from Westcott and Fletcher (2018).

7.3 Summary and Recommendations

The analyses presented by Westcott and Fletcher (2018) and Fletcher et al (2019) demonstrate that the CoTS Control Program has successfully reduced CoTS densities when sufficient and consistent effort is made at individual sites and reefs. This overall reduction is primarily due to the reduction of CoTS densities in larger (>15cm) size classes, representing a reduction in the average size of CoTS at control locations. As previously discussed, the adaptive management approach has resulted in significant changes to the CoTS Control Program, based on lessons from previous iterations. The key factors in creating success include:

- Persistent effort to achieve a unified goal (eg a target of CPUE below ecological thresholds);
- Consistent application of and adherence to culling protocols, noting that the simplified decision trees underpinning the Expanded Control Program (presented by Fletcher et al 2019) support consistency;
- The fundamental value of appropriately collected and curated data to support and inform decision-making.

We note that both evaluations assessed the efficacy of manual control of CoTS on hard coral recovery – the ultimate goal of the program. While not an explicit key performance measure for assessment as identified at the 2019 workshop with representatives from GBRF, GBRMPA, CSIRO and Australian Government (DoEE), this is acknowledged as the purpose for imposing CoTS control. We endorse this metric as a third key performance measure going forward and recommend that it be formally incorporated in future assessments.

8. Review of the current site prioritisation and decision support processes

The current site prioritisation and decision processes have been established under the Expanded Control Program in mid-2018 and have been described and evaluated in Fletcher et al (2019).

8.1 Site prioritisation

We have previously reviewed the site selection and site prioritisation criteria across all periods of the CoTS Control Program (2012/13 – 2018/19) in Sections 5 and 6. In reviewing the previous criticisms of the CoTS Control Program we noted several points of concern specifically pertaining to the methods for site selection and prioritisation, including challenges to the appropriateness and quality of data collected to inform outcomes. We found that changes in the CoTS Control Program, specifically the adoption of an IPM Strategy, has addressed most of these concerns or provides a mechanism for the suggested changes to be considered and incorporated.

The current reef and site prioritisation rely explicitly on data inputs to create ecologically-informed management actions. Prioritising and scheduling reefs for action under the IPM Decision Support process fundamentally support protection of key ecological (hard coral source reefs) and economic (tourism assets) reefs, and facilitate regional disruption of CoTS spread. These management priorities are identified on a global scale and reefs are prioritised for control action based on prior information (surveillance data collected in previous seasons, or from the annual reef health surveys).

At a local reef scale, data collection from both RHIS and Manta Tow Surveys provide sufficient information to inform tactical site prioritisation within a reef. However, a key strategy was to cull entire reefs once prioritised. In doing so, this requires action at a reef to persist until all sites have been appropriately managed to ecological thresholds. Only after the reef remains below ecological thresholds for several visits will the reef shift into Maintenance Mode.

Once a reef shifts into Maintenance Mode, Fletcher et al (2019) have recommended that Manta Tow frequency shift to every three to six months as a means to manage the surveillance load on operators and to balance attention between Intensive Control and Maintenance Mode reefs.

We have found that the site prioritisation process implemented in the Expanded Control Program is appropriate and commensurate with the stated goals of mitigating CoTS impacts on hard coral cover by reducing CoTS densities to levels that decrease hard coral consumption below hard coral regeneration rates. Reef prioritisation continues to focus on key ecological (hard coral source reefs) and economic (tourism assets) sites, and facilitate regional disruption of CoTS spread. The key shift has been recognition that reefs are the appropriate management unit and prioritised targeting of key ecological (hard coral source reefs) and economic (tourism assets) reefs, as well as reefs that facilitate regional disruption of CoTS spread.

8.2 Decision support processes

At the core of the Integrated Pest Management program is a principle of ecologically informed decision-making, using as close to real-time data as is feasible, in order to make decision-making robust and to highlight the relevance and critical nature of quality assured collection of data to vessel operators. The key principles were developed in consultation with reef managers in 2018 and represent adaptive management in developing the Expanded Control Program.

Fletcher et al (2019) presented three decision trees – two to inform operational decision-making during on-water control actions, and one to inform strategic decisions by managers to prioritise and plan voyage actions.

8.2.1 Decision Tree 1: a simplified on-water decision tree for manual implementation

The first decision tree was developed and implemented at the start of the Expanded Control Program (mid 2018) as a simplified decision tree to inform day-to-day on-water decisions without requiring detailed analysis. This decision tree was intended for manual use (ie not requiring specialty software). It uses the ecological status of the reef, data from previous voyages and information collected from the surveillance component of the current voyage to inform an action plan including establishing within the reef, the priority site for culling action.

Fletcher et al (2019) undertook an assessment of data from the initial 8 months of the Expanded Control Program to assess the efficacy of the decision tree in addressing key aspects:

- detecting reefs that require control;
- reducing CoTS densities at reefs requiring control to below ecological thresholds; and
- keeping CoTS densities at those reefs low (eg below ecological thresholds).

They determined that the program is operating effectively across all three aspects.

8.2.1.1 Detecting reefs that require control

Fletcher et al (2019) assessed the rate of false negatives (reefs incorrectly deemed to have low CoTS densities and therefore not requiring management) from initial Manta Tow observations, particularly where the initial Manta Tow observations were low. They report that out of 120 reefs where 0 CoTS (not including CoTS feeding scars) were observed in Manta Tows, 17 reefs were found to have CoTS present, but only two (1.7%) were found at densities above the ecological threshold. They conclude that Manta Tow observations of CoTS (not feeding scars) correctly identified reefs that do not require control, 94% of the time. In contrast, Manta Tow observations of CoTS feeding scars *alone* accurately identified 100% of reefs above the ecological threshold. This clearly suggests that including both CoTS and CoTS feeding scars provides a highly conservative assessment, demonstrating that the decision tree conservatively detects reefs that require control.

8.2.1.2 Reducing COTS densities at reefs requiring control to below ecological thresholds

In the previous Section, we assessed the ability of the Expanded Control Program to effectively reduce CoTS densities below the ecological threshold (Section 7.2). We found that the analysis of the 2018/19 dataset sufficiently demonstrated a reduction in CoTS densities where a decision to undertake a control action was made. We deem this as also evaluating the efficiency of the decision tree.

8.2.1.3 Keeping COTS densities at those reefs low

As with the previous Section (8.2.1.2), we consider the analysis of the 2018/19 dataset sufficiently demonstrated not only a reduction in CoTS densities at reefs where control action was made, but was also indicative of the ability to maintain CoTS densities at low levels (ie below ecological thresholds). We noted that Fletcher et al (2019) highlighted the periodic increases in CoTS densities at a reef when additional sites were added to the culling action, creating an apparent increase in CPUE. We accepted that this interpretation was accurate and consider that this also demonstrates the efficacy of the decision tree.

8.2.2 Decision Tree 2: An advanced on-water decision tree leveraging data analysis and adaptive management

The second decision tree (referred to as a Decision Support System - DSS) is under development and being delivered as part of the CoTS Control Centre under the NESP CoTS IPM Research Program (Westcott and Fletcher 2019, referenced in Fletcher et al 2019). This decision tree improves on the first, which simplified ecological decisions and therefore may be overly conservative in assessments. The intent is that the DSS will incorporate locally collected data to create efficiencies for local scale management, feeding into a larger scale (regional) action across multiple vessels. We note that the intent is to undertake more advanced analyses to ensure that various processes are optimised including: 1) optimum amount of time between Manta Tows on Maintenance Mode Reefs; 2) optimum amount of time between Manta Tows on Intensive Control Reefs; and 3) the optimum time between culling dives at Intensive Control Reef sites.

We note that this DSS will provide ecological and management intelligence on prior reef status, and estimate future status including estimates of CoTS densities based on a predictive model. This estimated state will directly influence reef and site workplans during a single voyage.

8.2.3 Decision Tree 3: An advanced Voyage Plan decision tree leveraging adaptive management to structure voyages within a region

The third decision tree (Voyage Plan decision tree) is currently under development and will provide a mechanism to balance operational (logistic) constraints in creating a priority list of reefs for individual voyages. Fletcher et al (2019) highlight that three “rules-of-thumb” for the order of reef visitation: 1) Maintenance Mode reefs requiring Manta Tow surveillance; 2) Intensive Control Reefs where control actions have already begun; and 3) Intensive Control Reefs where control actions have yet to begin. Reefs evaluated for priority sequence are determined against the GBRMPA Priority Reef list within the operating region of individual vessels. While this decision tree has yet to be implemented, the underpinning rules-of-thumb coupled with vessel and region specific operational constraints, appear to be well considered and address the need to apply a strategic planning element that balances short-term culling needs with long-term surveillance requirements.

We note that this decision tree is specifically designed for managers in developing forward plans however, the on-water operators can override the Voyage Plan based on expert opinion. This expert opinion however, is constrained to accessibility to reefs given prevailing weather conditions and other operational concerns and constraints.

Summary

We have found that the site prioritisation process implemented in the Expanded Control Program is appropriate and commensurate with the stated goals of mitigating CoTS impacts on hard coral cover by reducing CoTS densities to levels that decrease hard coral consumption below hard coral regeneration rates. The key shift through time has been the recognition that reefs are the appropriate management unit, and that prioritised targeting of key ecological (hard coral source reefs) and economic (tourism assets) reefs coupled with targeting reefs that facilitate regional disruption of CoTS spread, remains a critical strategy for success at regional scales.

We note that three decision trees are presented by Fletcher et al (2019), however only the first has been implemented in manual form and data collected to enable assessment of its efficacy in operation. We have found this first decision tree to provide a conservative, and therefore protective, response in operation.

The second decision tree is under development and will replace the first, manual decision tree with a more sophisticated, software driven Decision Support System to exploit efficiencies based on model predictions. The third decision tree is primarily for reef managers to develop Voyage Plans that prioritise reefs for individual voyages, and within a region. Neither the second nor the third decision trees have been implemented and their efficacy cannot be currently evaluated, however the underpinning assumptions and the logic flow for decisions are commensurate with program objectives.

9. Conclusions

Our independent assessment of the CoTS Control Program under the coordination of GBRMPA between 2012/13 – 2018/19 has evaluated the elements under the Terms of Reference:

9.1 Summary of manual CoTS control initiatives implemented since 2012 in terms of location, scale and timing.

We find that the Program has undergone a suite of continuous and adaptive changes, resulting in three periods of activity: 2012/13-1014/15; 2015/16-2017/18; and 2018/19. These periods have resulted in refinements of objectives, locations, scales and timing of efforts driven by changes in strategy, application of best available scientific evidence, and increasing incorporation of data driven decision-making. Specifically, we note that program objectives have shifted from a reactionary (tactical) response almost entirely focused on economic values to a more strategic response focused on core environmental values (ie protecting coral cover) that also deliver economic and social benefits.

Location - The CoTS Control Program initially focused in the Cairns/Townsville region for various reasons including fiscal constraints, stakeholder driven program objectives, demonstrable impacts of COTS in a region of high economic value, and the phase of the outbreak cycle. These constraints have shifted through time and as best available information has improved, allowing the release of additional resources to enable implementation of an Expanded Control Program that increases the breadth of focus to include a much wider engagement across the GBRMP. In the most recent period (2018/19) the CoTS Control Program visited 140 reefs across 10° of latitude (12° - 22° S).

Scale – The scale of activity has shifted from individual undefined sites on reefs where CoTS aggregations were either reported or detected, to a whole of reef approach whereby a formalised structure for assessing the reef in spatially explicit and consistent polygons informs prioritised locations (sites) on the reef to be culled.

Timing – frequency of revisitation was initially unclear, resulting in partial culling actions, but through time the requirement for revisitation at ~3 monthly intervals for priority sites has become well established and in the current Expanded Control Program (2018/19) has increased even further to ~ 2 weeks (approximately every 12 days) once culling action has begun.

9.2 Assessment of key strengths and weaknesses of various iterations of the CoTS Control Program as identified by prior reviews or scientific assessments.

The CoTS Control Program has had several scientific and stakeholder reviews and evaluations that have identified a variety of strengths and weaknesses. We reviewed 71 articles from both primary and grey literature and noted that with one exception, all articles focussed on early periods of the COTS Control Program (prior to 2015) or provided generic (not time specific) comment on strengths and weaknesses of COTS manual control. Key strengths and weaknesses highlighted by the articles included Strategies (Surveillance and intelligence gathering; Site selection; Integrated Pest Management); Operational Logistics and Targets (Voyage planning and revisitation frequency; CPUE thresholds; CoTS size classes) and Data collection, curation and transparency. While several points of concern were identified, we found that changes in the CoTS Control Program, specifically the adoption of an IPM Strategy, has addressed most of these concerns or provides a mechanism for the suggested changes to be considered and incorporated.

9.3 Validity of surveillance and control data to assess effectiveness and support decision making and prioritisation activities.

We find that the surveillance and control data collections in the current “Expanded Control Program” (2018/19) are sufficient to assess the effectiveness of the Program, and to support decision making and prioritisation activities. The Program is a robust, evidence based framework that provides clear mechanisms for adaptive improvements. We make recommendations for data improvements, in many cases reiterating previously identified data needs. These are primarily focused on validating and improving reef connectivity models and estimates for assessing hard coral cover.

9.4 Undertake a critical review of the scientific analyses of available data found in Westcott and Fletcher (2018) and Fletcher et al (2019) to assess the impact of manual COTS control initiatives implemented since 2012.

We find that the analyses presented by Westcott and Fletcher (2018) and Fletcher et al (2019) demonstrate that the CoTS Control Program has successfully reduced CoTS densities, and reduced the densities of larger size classes of CoTS, when sufficient and consistent effort is made at individual sites and reefs. The adaptive management approach has resulted in a robust application of Integrated Pest Management and represents a data driven approach to achieve critical success. The key factors in creating success include:

- Persistent effort to achieve a unified goal (eg a target of CPUE below ecological thresholds);
- Consistent application of and adherence to culling protocols, noting that the simplified decision trees underpinning the Expanded Control Program (presented by Fletcher et al 2019) support consistency;
- The fundamental value of appropriately collected and curated data to support and inform decision-making.

We endorse the addition of hard coral recovery (relative to initial state) as a key performance measure by both Westcott and Fletcher (2018) and Fletcher et al (2019) and recommend that this be formally adopted in future assessments.

9.5 Review of the current site prioritisation and decision support processes (at the local and regional levels) and links to information/data needs.

We have found that the site prioritisation process implemented in the Expanded Control Program is appropriate and commensurate with the stated goals of mitigating CoTS impacts on hard coral cover by reducing CoTS densities to levels that decrease hard coral consumption below hard coral regeneration rates. The key shift through time has been the recognition that reefs are the appropriate management unit, and that prioritised targeting of key ecological (hard coral source reefs) and economic (tourism assets) reefs coupled with targeting reefs that facilitate regional disruption of CoTS spread, remains a critical strategy for success at regional scales.

We note that three decision trees are presented by Fletcher et al (2019), however only the first has been implemented in manual form and data collected to enable assessment of its efficacy in operation. We have found this first decision tree to provide a conservative, and therefore protective, response in operation.

The second decision tree is under development and will replace the first, manual decision tree with a more sophisticated, software driven Decision Support System to exploit efficiencies based on model predictions. The third decision tree is primarily for reef managers to develop Voyage Plans that prioritise reefs for individual voyages, and within a region. Neither the second nor the third decision trees have been implemented and their efficacy cannot be currently evaluated, however the underpinning assumptions and the logic flow for decisions are commensurate with program objectives.

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12. Appendix 1

Table A1: Literature identified in the Systematic Review with assessment of Relevance to GBR CoTS Management and whether the article makes comment on the GBR CoTS Control Program.

Citation	Source	Relevance to GBR CoTS Management	Comment on GBR CoTS Control Program
Adjeroud et al 2018	SCOPUS	N	N
Babcock et al 2016a	SCOPUS	Y	Y
Babcock et al 2016b	SCOPUS	Y	N
Bell et al 2014	SCOPUS	Y	N
Bos et al 2013	SCOPUS	Y	Y
Brodie and Waterhouse 2012	SCOPUS	Y	Y
Carrier et al 2018	SCOPUS	N	N
Chazottes et al 2017	SCOPUS	N	N
Chen et al 2017	SCOPUS	Y	N
Condie et al 2018	SCOPUS	Y	N
Dayoub et al 2015	SCOPUS	N	N
Deane et al 2018	SCOPUS	N	N
De'Ath et al 2012	SCOPUS	Y	Y
Doyle et al 2017	SCOPUS	Y	N
Emslie et al 2017	SCOPUS	N	N
Engelhardt 2015	Stakeholder	Y	Y
Fabricius et al 2016	SCOPUS	N	N
Fletcher et al 2019	Stakeholder	Y	Y
Fraser et al 2017	SCOPUS	N	N
Graham et al 2014	SCOPUS	Y	N
Hairsine et al 2017	SCOPUS	N	N
Hall et al 2017	SCOPUS	Y	Y
Harrison et al 2015	SCOPUS	N	N
Harrison et al 2017	SCOPUS	Y	N
Hock et al 2014	SCOPUS	Y	Y
Hock et al 2016	SCOPUS	Y	Y
Hock et al 2017	SCOPUS	Y	N
Hoey et al 2016	SCOPUS	Y	Y
Keesing et al 2018	SCOPUS	Y	Y
Lam et al 2018	SCOPUS	Y	N
MacNeil et al 2016	SCOPUS	Y	Y
MacNeil et al 2019	SCOPUS	N	N
Matthews et al 2019	SCOPUS	Y	N
Maynard et al 2016	SCOPUS	N	N
Medina et al 2017	SCOPUS	Y	N

Mellin et al 2016	SCOPUS	N	N
Mellin et al 2017	SCOPUS	N	N
Mellin et al 2019	SCOPUS	Y	N
Messmer et al 2017	SCOPUS	Y	N
Miller et al 2015	SCOPUS	Y	N
Morello et al 2014	SCOPUS	Y	Y
Nim et al 2016	SCOPUS	N	N
Ortiz et al 2018	SCOPUS	Y	N
Pisapia et al 2016	SCOPUS	N	N
Pratchett et al 2014	SCOPUS	Y	Y
Pratchett et al 2015	SCOPUS	Y	N
Pratchett et al 2017	SCOPUS	Y	N
Pratchett et al 2019	SCOPUS	Y	Y
Riginos et al 2019	SCOPUS	Y	N
Rivera-Posada et al 2014	SCOPUS	Y	N
Roberts et al 2018	SCOPUS	N	N
Smith et al 2017	SCOPUS	N	N
Smith et al 2018	SCOPUS	N	N
Smith et al 2019	SCOPUS	N	N
Sparks et al 2017	SCOPUS	N	N
Tan et al 2018	SCOPUS	Y	N
Uthicke et al 2013	SCOPUS	Y	N
Uthicke et al 2015a	SCOPUS	Y	Y
Uthicke et al 2015b	SCOPUS	Y	N
Uthicke et al 2018	SCOPUS	Y	N
Uthicke et al 2019	SCOPUS	N	N
Vanhatalo et al 2017	SCOPUS	Y	N
Vercelloni et al 2017	SCOPUS	Y	Y
Westcott and Fletcher 2018	Stakeholder	Y	Y
Westcott et al submitted	Stakeholder	Y	Y
Wilmes et al 2017	SCOPUS	Y	N
Wilmes et al 2019	SCOPUS	N	N
Wolfe et al 2015	SCOPUS	N	N
Wolff et al 2018	SCOPUS	Y	N
Wooldridge et al 2014	SCOPUS	Y	N
Wooldridge et al 2015	SCOPUS	Y	N
Yuasa et al 2017	SCOPUS	N	N

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