

Integrated Pest Management Crown-of-Thorns Starfish Control Program on the Great Barrier Reef: Current Performance and Future Potential

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Cover photographs: (front) COTS feeding on a plate Acropora coral. White coral is freshly consumed, light brown very recently consumed with algae just taking hold, green coral is recently consumed with algae established. Image: David Westcott. (back) COTs feeding on coral on the Central GBR. Image: David Westcott.

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ACRONYMS

AMPTO	Association of Marine Park Tourism Operators
COTS	Crown-of-Thorns Starfish
GBR	Great Barrier Reef
GBRMPA	Great Barrier Reef Marine Park Authority
IPM	Integrated Pest Management
NESP	National Environmental Science Program
Pre-IPM	Pre-Integrated Pest Management
RRRC	Reef and Rainforest Research Centre Limited
SD	Standard Deviation
TWQ	Tropical Water Quality

ABBREVIATIONS

ha⁻¹	hectares
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This report reviews the performance of the Integrated Pest Management (IPM) Crown-of-thorns Starfish (COTS) Control Strategy in its first years of implementation. Ultimately, the implementation of that Program was dependent on the good will, enthusiasm and professionalism of the COTS Control Teams and Operators. We acknowledge their efforts and thank them. We thank Great Barrier Reef Marine Park Authority (GBRMPA) staff (past and present) for working with us on the implementation and for preparing and providing data for these analyses. In particular we thank Mary Bonin for her contributions to turning the strategy into action. We thank Sheriden Morris who planted the seed that became the current IPM control program and Reef and Rainforest Research Centre (RRRC) staff who have supported us over the years.

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EXECUTIVE SUMMARY

Crown-of-Thorns Starfish (COTS; *Acanthaster* spp.) are voracious coral predators and the cause of significant coral loss on Australia's Great Barrier Reef (GBR). Managing the impacts of COTS outbreaks is a major objective of management strategies and investment on the GBR. The IPM Crown-of-Thorns Starfish Control Program is the product of a 5-year and on-going collaboration between GBR managers, researchers and on-water control operators conducted under the auspices of the National Environmental Science Program's Tropical Water Quality Hub. After several years of research and development, the IPM COTS Control Program was implemented in late 2018. In this report, we assess the program's performance through to mid-2020 and consider what this suggests about the strategy for the program, and its potential performance, in meeting the challenge of future COTS outbreaks.

Specifically, we use data from the COTS IPM Control Program and previous programs to:

- i) describe the performance of the IPM COTS Control Program over the first 20 months of its operations;
- ii) assess the performance of the IPM program in the light of the Control Program's objectives;
- iii) compare this against the performance of the Pre-IPM program to assess the benefits gained through the adoption of the IPM approach; and
- iv) use these assessments to consider how the methods applied in the IPM program could scale to the challenge of managing the 'next' COTS outbreak, and what this means for the design of the Control Program into the future.

IPM Program Performance

During the period 3rd November 2018 to 30th July 2020, the IPM COTS Control Program conducted management activities at 202 reefs between latitudes 12.9°S and 24.1°S. At each of these reefs: 1) surveillance manta tows were conducted around the entire reef perimeter; and 2) control operations were conducted where this initial surveillance indicated it was necessary based on the decision rules of the control program. Of these 202 reefs, surveillance indicated that cull dives were not required at 81. At 18 reefs, surveillance had been conducted but control had not begun by 30 July 2020, while at the remaining 103 reefs, cull dives were conducted at 884 sites where COTS or feeding scars were detected. By 30 July 2020, control activities had successfully achieved the management objective along the entire perimeter of 92 (89%) of these 103 reefs, with COTS densities being reduced to below the conservative threshold density of 3 COTS ha⁻¹.

While assessing the performance of control in meeting objectives at particular locations is an important component of assessing overall program performance, so too is the assessment of the individual decision rules used in guiding control. The most important of these in the current control program is the criterion used to decide whether culling is required at a site or not based on manta tow surveillance around the reef. The consequences of erroneously deciding that a site or reef does not need to be culled when COTS densities there are actually above the threshold are serious, with coral continuing to be lost to COTS predation and COTS from that reef continuing to contribute to the spread of the outbreak. We assessed the reliability of the decision criteria at 33 reefs where no COTS or COTS feeding scars were detected during manta tows but at which cull dives were conducted nevertheless. This analysis indicated that

the chance of not diving a reef that required culling was 3% while the chance of diving a reef that did not require culling was 68%. This is deemed a reasonable balance of errors given the high ecological cost of not conducting cull dives when they are required as opposed to the very low cost of diving when it is not required.

Comparison with the Pre-IPM Control Program

The transition from the operations of the COTS control program that preceded the IPM COTS Control Program has required significant modification to how the control fleet is deployed and operates and has been supported by additional oversight and research input. What has been gained through this investment? We compared the performance of both programs to explore how benefits of the IPM approach accrue in terms of its objectives.

We found that the Pre-IPM control program was highly effective in targeting sites with high densities of COTS and, as a result, of achieving a high cull count. However, it was far less efficient at achieving meaningful COTS control objectives, particularly at the scale of entire reefs. The IPM COTS Control Program was twice as likely to reduce a site requiring control to below the three COTS ha⁻¹ threshold and did so in 63% of the time of the Pre-IPM program. If time and coral consumption are linearly related this means that 63% less coral was lost at control sites during management. The final mean density at an IPM site was one sixth that of a Pre-IPM site meaning that lower on-going rates of coral loss and contribution to downstream recruitment would be expected. Critically, the IPM Control Program achieved its management objectives at a reef scale at 89% of the 103 reefs it targeted, while the Pre-IPM program achieved this objective at 0% of 102 reefs.

These results indicate that the IPM COTS Control Program has turned an effective culling method developed in the Pre-IPM program into a potent tool for achieving COTS control objectives and protecting coral at the scales of sites, reefs, and hundreds of reefs.

IPM Program Potential in future outbreaks

While the IPM COTS Control Program is reliably achieving COTS control objectives of suppressing COTS densities and protecting coral at scales not previously achieved nor considered possible, it doesn't directly inform us about how it might perform in suppressing an establishing, new outbreak. This is because the program was implemented 8 years after the start of the current outbreak and during this period the outbreak spread across much of the GBR, spanning many hundreds of reefs over a large geographic range. The scale and extent of the current outbreak is now much larger than the number of reefs successfully managed during the first 20 months of the IPM Control Program. However, this mismatch in scales might not have occurred if the current IPM Control Program had been implemented right at the outset of the outbreak, when the number and geographic spread of outbreaking reefs was limited. In order to assess the program's potential for stopping or suppressing the progress of the next outbreak we assessed when and in which region of the GBR control would be most effective. We then compared the program's capacity relative to the scale of the task in the identified region.

We identified the region between 13°S and 18°S as the region where control to stop or suppress an outbreak stands the greatest chance of success. This is a function of the fact that the region is: i) hypothesised as the area in which outbreaks begin; ii) where the number of individual reefs is lowest; iii) where the area of reefs is lowest; and iv) closest to major

operational ports from which the control program can be coordinated. Essentially this is the region where the scale of control resources is most advantageously matched to the problem. We then assessed the capacity of the IPM COTS Control Program to comprehensively manage reefs in this region. We assumed that the next outbreak would have similar characteristics to the current outbreak, that the control program would be similarly resourced and that it would use similar methods. Under these assumptions, we could expect that each year the IPM COTS Control Program would be capable of managing 26% of the reefs and 87% of the reef area in the combined Dispersal and Initiation Boxes. In addition, it would be capable of manta towing 114% of the reef perimeters. Given that the outbreak residency period in this region during the current outbreak is estimated to have been at least 4 years, this suggests that near comprehensive management of reefs in this region could be possible. This level of coverage may allow us to prevent the spread of the outbreak from the initiation box entirely or, more likely, moderate its magnitude and spread and greatly reduce both the extent of its impact and the amount of coral lost. Such an outcome would be a valuable contribution to enhancing reef resilience going forward.

Summary

On the basis of the work reported in this and companion reports from the program, we make the following recommendations as priorities for the program going forward:

- 1) A standing COTS control fleet must be maintained through all outbreak phases to ensure a timely and adequate control response can be mounted at the time and place where a successful outcome is most likely. This will require long-term and sustainable funding throughout the entire COTS outbreak cycle.
- 2) A COTS control specific monitoring program must be implemented as an integral component of the IPM COTS Control Program to ensure detection of initiating outbreaks and to enable a targeted, effective and efficient management response
- 3) New monitoring technologies must be developed to improve the scope and sensitivity of the monitoring data informing the program and to improve geographic coverage of monitoring. This is vital for informed and timely decision making.
- 4) COTS control must operate under an ecologically informed and adaptive strategy such as the IPM COTS Control Program and that program should maintain a focus on refinement and improvement
- 5) The prioritization process on which reefs are selected must continue to evolve in response to improved monitoring data and program capabilities and needs.
- 6) COTS control will inevitably be a long-term investment and consequently alternative and improved control technologies must be investigated and deployed where feasible.

Overall, we conclude that the current IPM COTS Control Program is an effective and efficient tool for achieving COTS control objectives and protecting coral on the GBR. It has the potential to play a foundational role in efforts to enhance coral cover and reef condition and resilience into the coming decades. Given the escalating pressures currently impacting the economic and biodiversity values of the Marine Park, manual control of COTS populations is one of the few currently available, effective, scalable and targetable management tools for reducing coral loss on high-value priority reefs. It can only achieve this outcome with reliable and sustained investment.

1.0 INTRODUCTION

Tropical coral reefs around the world face pervasive and increasing anthropogenic threats and are in crisis (Bellwood et al. 2004, Mora 2008, Hughes et al. 2010, Hughes et al. 2017, Claar et al. 2018, Bellwood et al. 2019). Many of these threats impact on reefs indirectly, by altering physical and biological processes within coral reefs themselves but, critically, some also act indirectly through broader ecosystem processes at regional and global scales (Bellwood et al. 2019, Hughes et al. 2019). Because these broader processes operate at scales greater than the reef system itself, they can render traditional conservation protection approaches at the reef scale ineffective. An effective management response to promote coral reef resilience must, therefore, simultaneously treat symptoms and direct threats at the reef scale, to maintain and promote the health of today's coral ecosystems, while seeking action at higher levels to address issues at larger scales (Great Barrier Reef Marine Park Authority 2019, Anthony et al. 2020). As a result, on the Great Barrier Reef, managers are increasingly focusing on direct interventions that can sustain reefs while larger scale solutions are developed (Queensland Department of Environment and Science 2019).

Crown-of-Thorns Starfish (COTS; *Acanthaster* spp.) are a common and voracious coral predator found throughout the Indo-Pacific (Pratchett et al. 2014). COTS populations can experience dramatic irruptions (hereafter called 'outbreaks') (Campbell and Ormond 1970, Endean 1971, Endean 1982, Birkeland and Lucas 1990, Moran and De'ath 1992), which are thought to be driven by some combination of inherent life history traits, environmental conditions and anthropogenic impacts, including water quality and climate change (Pratchett et al. 2014, Pratchett et al. 2017). COTS outbreaks have been recorded from across the region since the 1950s and 1960s, with reports of coral loss as high as 90% (Endean 1969, Walsh et al. 1971, Moran 1986). It has been suggested that both their frequency and their magnitude have been exacerbated by human activities (Birkeland and Lucas 1990, Doherty 2012, Pratchett et al. 2014). On the Great Barrier Reef as a whole, as much as c. 42% of multi-decadal coral loss has been attributed to COTS (De'ath et al. 2012). As a consequence of their extreme impact on coral reefs, tens of millions of dollars have been invested globally in direct and indirect management actions intended to control or limit COTS populations, and tens of millions of COTS have been culled (Pratchett et al. 2014, Pratchett and Cumming 2019, Westcott et al. 2020).

The majority of COTS management effort has involved manual control at small (sub-reef) scales, either in the form of the physical removal of the COTS onto land or by lethal injection (Pratchett and Cumming 2019). Until the recent development of single-shot lethal injections (Rivera-Posada et al. 2013, Moutardier et al. 2015, Boström-Einarsson and Rivera-Posada 2016) these methods were labour intensive, time consuming and, consequently, spatially constrained. As a consequence, and despite the huge investment, past COTS control has had limited success. Reviews of manual control have typically concluded that control programs are only effective under very constrained circumstances, including where outbreaks were small in terms of population numbers, where outbreaks were accessible, and where there were large resources invested (Moran 1986, Yamaguchi 1986, Nakamura et al. 2016, Pratchett and Cumming 2019). While most of the examples of COTS control have occurred at small spatial scales, the first attempt to manage COTS at an entire reef scale and over a period of two decades occurred in Japan from the late 1960s through to the 1980s. This program is

considered a failure due to its operation as a bounty program with a focus on numbers culled rather than the number of starfish remaining after culling, as well as delays in the initiation of culling after detection of outbreaks (Yamaguchi 1986). Given this experience, most authors have argued that there is little chance of control programs being successful (Lassig 1991, 1993, Pratchett et al. 2014, Nakamura et al. 2016, Anthony et al. 2019, Pratchett and Cumming 2019).

For most of its history, COTS control in Australia has focused on protecting individual sites of tourism importance. This focus emerged from early control attempts at Green Island in 1962 and at a number of locations during the subsequent two outbreaks, and was reinforced by reviews of the management response to early outbreaks, which concluded that manual control would only be effective at the site scale (Walsh et al. 1971, Lassig 1991). Changes during the current outbreak, however, have revolutionized the way COTS control is conducted and opened a broader perspective on what might be achieved. The first of these changes, in 2013, was the establishment of a program based on dedicated control vessels staffed by trained divers (hereafter referred to as the Pre-IPM Control Program, where IPM refers to “Integrated Pest Management”). This coordinated effort was enhanced by the introduction of single-shot injections for culling (Rivera-Posada et al. 2013, Moutardier et al. 2015, Boström-Einarsson and Rivera-Posada 2016), which dramatically reduced the time and effort required to kill each starfish, vastly improving the efficiency of individual divers and the program as a whole. The third change was the development and phased implementation of a structured IPM approach to COTS control (Westcott et al. 2016, Fletcher et al. 2020) (hereafter referred to as the IPM Control Program). This approach integrated an understanding of the underlying processes driving the spatial and temporal dynamics of COTS populations with control operations to support the program’s strategy and decision-making processes. Fourth, and key to the development of this IPM strategy, has been a close collaboration with reef managers, control vessel operators and researchers, along with developments in our understanding of the key processes and thresholds in population dynamics and control operations (Westcott et al. 2016). These developments have included: incorporation of surveillance to target control actions (Fletcher and Westcott 2016); the application of connectivity to prioritise reefs for control (Hock et al. 2017); the implementation of repeated visits on short timeframes (Fletcher et al. 2020); and the use of ecological and reproductive thresholds (Rogers et al. 2017, Plagányi et al. 2020) to gauge stopping points and performance (Fletcher et al. 2020).

The net result of these developments has been the demonstration that we can manage COTS populations and their impacts at site scales (Westcott et al. 2020) and the subsequent development of a strategy for managing at entire reef scales (Fletcher et al. 2020). These developments, and the encouraging results stemming from the implementation of the COTS IPM Control Program, contributed to the Australian Government’s decision to invest \$58M in the COTS Control Program over a five-year period, and led to a scaling up of the program from two vessels operating in the Cairns region to five vessels operating across the full extent of the GBR Marine Park (Price 2018, Fletcher et al. 2020). While the demonstrated success of the program at site and reef scales, and the support of funders for a coordinated control program both represent positive progress, several questions remain: how effective is the program’s performance at scale?; how far can the program be scaled up?, and; what is the outcome of this scaling up likely to be? These considerations all point to the underlying question of whether the IPM COTS Control Program can generate ecologically relevant outcomes at the GBR scale of sufficient magnitude to warrant the investment. This is an important consideration

because manual control is an intensive process and the resources required and constraints in its application increase with the spatial scale of the program (Morello et al. 2014, Pratchett et al. 2019).

In this report we address these issues using data from the COTS IPM Control Program to:

- i) describe the performance of the IPM COTS Control Program over the first 20 months of its operations;
- ii) assess the performance of the IPM program in light of the Control Program objectives;
- iii) compare this against the performance of the Pre-IPM program to assess the benefits gained through the adoption of the IPM approach; and
- iv) use these assessments to consider how the capacity of the IPM program scales to the challenge of managing the 'next' COTS outbreak, and what this means for the design of the Control Program into the future.

2.0 CONTROL OPERATIONS IN THE DIFFERENT PHASES

2.1 Pre-IPM Control Program

During the Pre-IPM Control Program, control activities were conducted by two dedicated control vessels crewed by trained and experienced COTS control staff. The program was funded by the Australian Government through the Great Barrier Reef Marine Park Authority (GBRMPA) and on water operations were conducted by the Association of Marine Park Tourism Operators (AMPTO). Over the first five years of the program (2013-2017), control efforts were nominally focused on 56 sites at 21 'high value' reefs in the Cairns region. These were considered high value because they were economically important tourism sites or because they were considered ecologically important due to their location or attributes.

Pre-IPM COTS control boats operated on the basis of 10-day voyages, with each voyage visiting a preselected set of reefs and specific sites on those reefs. This selection was made as much as 12 months in advance of a voyage and updated when high densities were identified. Each site where control was conducted was mapped as geolocated polygons. During a voyage, each polygon was searched and COTS culled until no more COTS were available to cull. Depending on the size of the polygon and the density of COTS encountered, reducing COTS to this level sometimes required multiple dives over a period of days by a team of divers. Site revisitation in subsequent voyages was somewhat *ad hoc*. Some sites, particularly tourism sites, were culled on a regular basis. Elsewhere, revisitation was influenced, but only sometimes determined, by the estimated remaining density of COTS present at the site based on the culling.

While the Pre-IPM Control Program's intention was to maintain a focus on the 56 sites at the 21 Priority Reefs, it ultimately evolved into a largely reactive program that shifted its investment to locations with high COTS densities as these were reported. This resulted in culling being conducted at a total of 314 sites at 102 reefs. Despite this expansion in the scope of the program's operations, its implicit objectives remained constant. At the scale of the site, the program's objective was to prevent coral loss by reducing COTS densities to close to zero as possible and, at all sites, to below the COTS density at which coral growth could outpace COTS damage based on the estimates of Babcock et al. (2014). At larger spatial scales, the objective was to protect sites by controlling as much reef around them as was possible. This resulted in control sites being widely variable in size, with a mean area of c. 23.3ha (± 27.6 SD).

2.2 IPM Control Program

The IPM COTS Control Program is funded by the Australian Government and was administered by the Great Barrier Reef Marine Park Authority and more recently by the Great Barrier Reef Foundation.

While the strategic underpinnings of the IPM Control Program (Fletcher et al. 2020) are fundamentally different to those of the Pre-IPM program, the Pre-IPM program provided the operational foundation on which the IPM program was developed. The move to the IPM COTS Control Program strategy involved a transition phase, the period of 2016 to mid-2018, during which elements of the IPM approach were trialled or implemented on some or all vessels. The

transition to the IPM COTS Control Program was completed in November 2018 with five vessels operating along the full length of the GBR according to the IPM decision rules described in Fletcher et al. (2020) since that time.

At the scale of an individual cull dive the IPM program uses the same methods for culling as were used in the Pre-IPM program. Furthermore, the objective in the IPM control program is the same as was the case for the Pre-IPM program, to manage COTS densities down to below ecological thresholds. In the IPM Control Program the relevant ecological threshold is the 'ecological' threshold defined as the density of COTS that could be sustained by without loss of coral cover (4-5 COTS ha⁻¹, Babcock et al. 2014, Plagányi et al. 2020). In the context of this assessment, however, we use the 'reproductive' threshold, defined as the density of COTS above which proximity results in enhanced fertilization success (3 COTS ha⁻¹, Rogers et al. 2017). We use this threshold as our metric of success because it is the more stringent measure and importantly because it addresses both the impact of COTS on coral but also the processes that drive outbreak initiation and spread.

A key difference between the two programs is that in the IPM COTS Control Program sites are not managed in isolation. Rather, in the IPM COTS Control Program the goal is to manage entire reefs because they represent discrete management and population units. As a consequence, geo-located and standardised 500x200m (10 ha) sites are established to encompass the entire perimeter of each reef. Where surveillance indicates the need, cull sites are also established at other accessible locations on each reef. All sites at a reef are managed to below the desired threshold density before culling is diverted to a new reef.

With insufficient resources available to manage all reefs, the IPM program must identify a suite of Priority Reefs at which culling will be invested. In total, between November 2018 – late 2020 289 reefs distributed across the GBR were identified as Priority Reefs and targeted for COTS control. Priority Reefs are identified on the basis of attributes (measured or modelled) that indicated high ecological and economic value. Ecological value is based on an estimation of coral condition and the reef's capacity to contribute to coral population dynamics and resilience through their role as a source of coral larvae, and their connectivity to other reefs. Economic value is based on a reef's value as a tourism destination. These values are updated when new information becomes available. Approximately 48% of priority reefs are identified as such because of their ecological values alone, 20% for their economic values, and 32% for both ecological and economic values.

3.0 PERFORMANCE DURING THE DIFFERENT PHASES OF THE CONTROL PROGRAM

3.1 Pre-IPM Control Program Performance

The Pre-IPM COTS Control Program began on-water operations in July of 2013 and operated one or two vessels over the subsequent 2.4 years before the IPM Strategy was developed (December 2015) and began influencing on-water decision making. During this initial period two vessels conducted culling operations on 850 days at 314 sites at 103 reefs distributed between latitudes 14.7 and 18.8°S. These sites had an average area of 23.3 ha and at most of these reefs the managed sites encompassed <5% of the total reef area. A total of 3,415 'cull dives' were conducted, resulting in 14,737 hours of bottom time distributed over 22,106 individual dives. During these dives 304,221 COTS were injected, a mean of 2,870 COTS (range 0 to 67,515) per reef and 968 (range 0-12,850) COTS per site.

Ninety-six sites were visited just once. Thirty-seven of these had COTS densities above the 3 COTS ha⁻¹ reproductive threshold and 59 had densities below that threshold.

Of the 218 sites that were visited on more than one voyage, 40 were found to have had maximum densities below 3 COTS ha⁻¹ (mean 1.2, standard deviation (SD), ±0.88) while 178 had maximum COTS densities above this threshold. Culling at these 178 sites reduced COTS densities by an average of 52% (± 42 SD) from a mean maximum density of 56.8 (± 79.7 SD) COTS ha⁻¹ to a mean final density of 17.8 (± 33.2 SD) COTS ha⁻¹. At the end of this period COTS densities were reduced to below the ecological threshold of 3 COTS ha⁻¹ at 68 (38%) of the 178 above threshold sites. This was achieved over an average of 6.2 (± 3.8 SD) voyages and 536 (± 219 SD) days. No reef's perimeter was controlled in its entirety.

3.2 IPM Control Program Performance

The Control Program fleet adopted the full suite of IPM decision rules on voyages that began on the 3rd November 2018, and the data presented in these analyses comprises the voyages conducted from then until 30th July 2020. This represents a period of 635 days or 1.75 years and a total of 1,190 operational days across the vessels.

Over this period, 202 reefs from the GBRMPA Priority Reef list located between 12.9°S and 24.1°S were visited and surveillance manta tows were conducted around their entire perimeter. In all, 41,852 manta tows, equating to a total tow distance of 8,374km, were conducted. Eighty-one of these 202 manta towed reefs were identified as not requiring cull dives on the basis that no COTS or scars were recorded during the manta tows. At 103 reefs one or more COTS or scars were observed which triggered the commencement of cull dives. A further 18 reefs qualified for culling which had yet to begin at the commencement of this analysis.

A total of 6,494 'cull dives' were conducted at the 103 reefs identified as requiring culling. This resulted in 21,973 hours of bottom time distributed over 32,959 dives by individual divers. During these dives 192,285 COTS were removed, with a mean of 1,865 COTS (range 0–51,206) removed per reef. At these reefs, cull dives were conducted at a total of 884 cull sites with an average of 218 (range 0–6,058) COTS being removed per site. These cull dives

resulted in COTS densities at 92 (89%) of these reefs being reduced to below the ecological threshold along the entire reef perimeter. At the time of this analysis, the 11 remaining reefs were still subject to culling, but the densities present on these reefs had been reduced in all cases.

Fifty-five (53%) of the 103 reefs where cull dives commenced were dived during just one voyage with those dives confirming that COTS densities were below 3 COTS ha⁻¹. Forty-eight reefs were visited on more than one voyage with the mean number of voyages to these reefs being 11.8 (range 2–39; Figure 1, lower panel) and the mean number of voyages to bring a reef from >3 to <3 COTS ha⁻¹ being 14.4 (range 2–27).

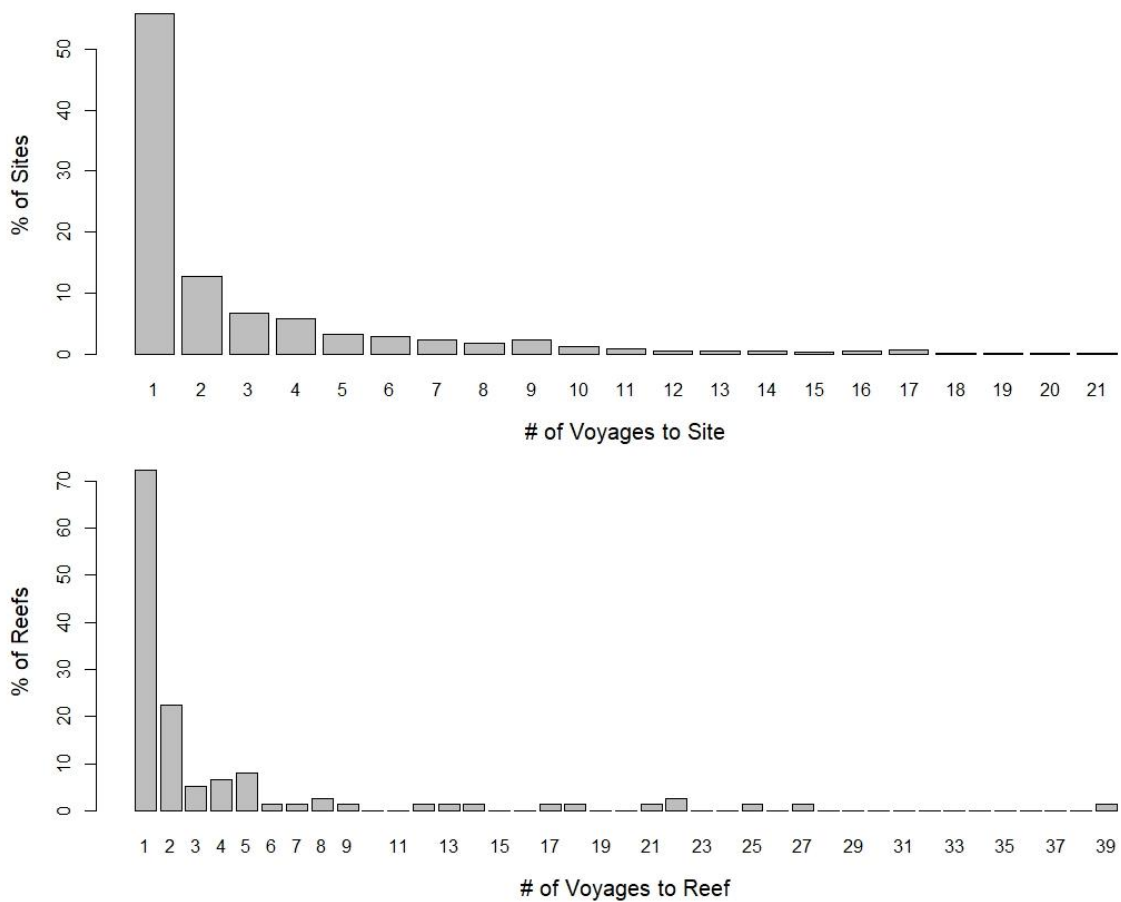


Figure 1: Frequency distribution of the number of voyages during which cull dives were conducted at 884 sites (upper panel) and 103 reefs (lower panel).

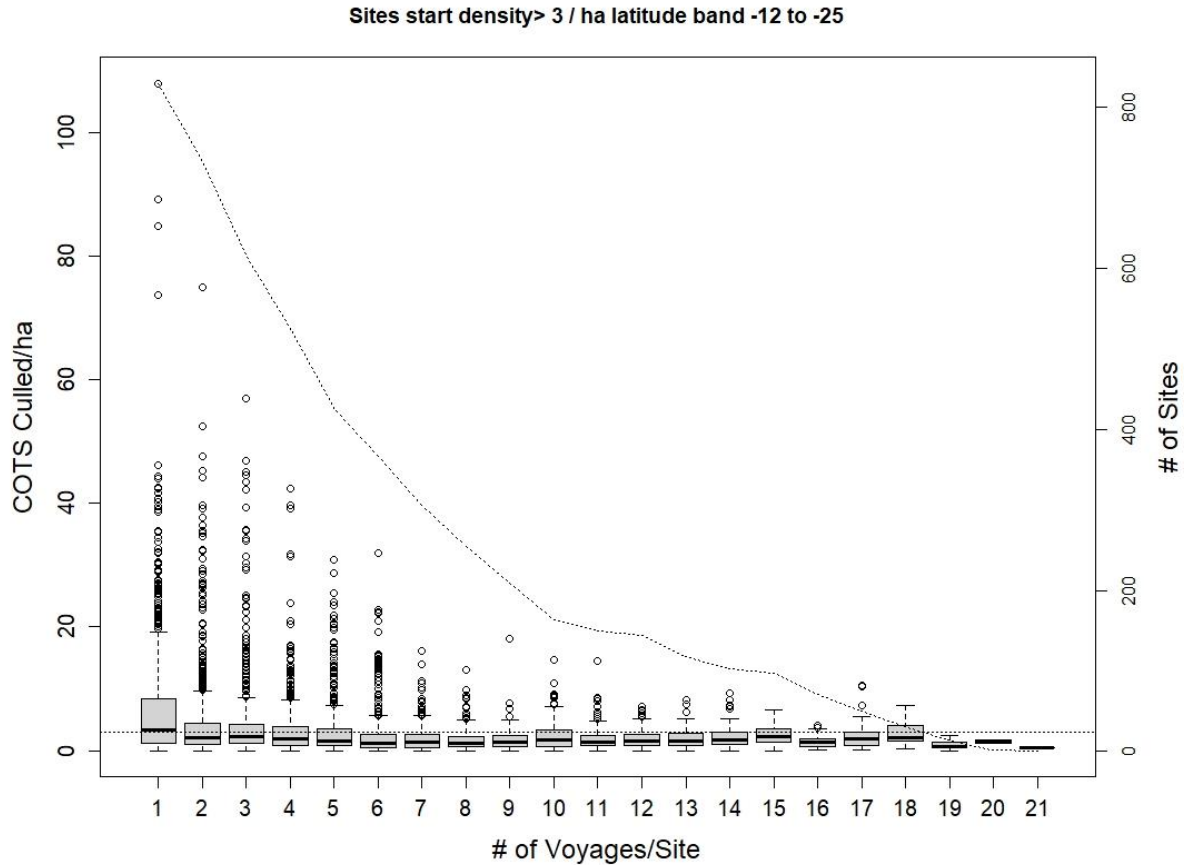


Figure 2: Density of COTS (box and whisker plot, left y-axis) at sites as a function of the number of voyages to a site at that point and the number of sites that had received that number of voyages (line, right y-axis). Each boxplot or voyage comprises only sites that were identified as being above the culling threshold (for the first voyage) or to still have COTS present at the end of the previous voyage (voyages 2 and above). Sites at which no COTS are culled during a voyage are not revisited and so drop out of the analysis. The number of sites is shown by the dotted line and the right-hand y-axis.

A total of 884 cull sites were established across the 103 reefs where culling occurred. Four hundred and ninety-four of these sites (55%) were dived during just a single voyage and at 475 (96%) of these, COTS densities were found to be below 3 COTS ha⁻¹ (Figure 1 upper panel).

Three hundred and ninety sites were culled on >1 voyage. At 130 (33%) of these COTS densities were <3 COTS ha⁻¹ while at the remaining 260 (67%), COTS densities were >3 COTS ha⁻¹. The IPM Control Program's operations resulted in a 76% (± 29 SD) decline in COTS density at the 260 sites with >3 COTS ha⁻¹, from a mean maximum density of 31.2 COTS ha⁻¹ (± 38 SD) to a mean of 5.3 COTS ha⁻¹ (± 10.9 SD). These sites were visited 6.6 (± 4.3 SD) voyages on average over a mean of 197 (± 151 SD) days.

Of the 260 sites with initial densities of >3 COTS ha⁻¹, 169 (65%) were successfully reduced through control actions to <3 COTS ha⁻¹ at the time this analysis was completed. At these 169 sites where control was "completed", there was a decline of 90% (± 12 SD) from a maximum density of 26.9 (± 33.51) COTS ha⁻¹ to a mean density of 1.0 (± 0.74 SD) COTS ha⁻¹. These sites were visited on average on 6.7 (± 3.9 SD) voyages over a mean of 198 (± 125 SD) days.

Ninety-one (35%) of these 260 sites were still above the threshold when last visited. Culling reduced COTS densities at these sites by 50% (± 34 SD) from a mean maximum density of 39.2 COTS ha⁻¹ (± 45 SD) to 13.4 COTS ha⁻¹ (± 15.4 SD) over an average of 6.3 (± 4.8 SD) voyages over an average period of 196 (± 188 SD) days. Control was on-going at these sites. No COTS were found at 283 sites, while a further 203 sites had densities below the threshold (mean density = 0.45 ha⁻¹, ± 0.51 SD) and consequently were only visited once. At 19 sites that were visited just once, the COTS densities there were measured to be above the threshold (mean density = 10.25 ha⁻¹, ± 6.4 SD), and control was on-going.

3.3 Performance of IPM Decision Criteria and Tools

Under the IPM decision rules (Fletcher et al. 2020), the decision to begin dives at the 103 reefs is based on the detection of 1 or more COTS or COTS feeding scars being seen during the surveillance manta tows around a reef's circumference. This is a critical decision and one that is ultimately central to the Control Program's success. Two types of errors are possible here. The first, and arguably less critical, error is that a decision is made to dive a site when there are insufficient COTS to warrant a cull, i.e. a Type I error. The second and more consequential error would be to decide not to dive a site when COTS are present at densities that require culling, i.e. a Type II error. In the IPM program making a Type I error incurs the cost of unnecessary dives, usually just one dive is required to recognize the mistake, and so the cost of making this error is relatively low. Making a Type II error, however, fundamentally undermines the performance of the Control Program in achieving its objectives in that it allows above-threshold densities of COTS to continue consuming coral and spreading larvae downstream, driving the ongoing spread of the outbreak. Consequently, in balancing the probability of making these two types of error we should accept the risk of making a Type I error, and therefore dive in some circumstances when subsequent dives reveal it would not have been necessary, in order to minimise the possibility of making a Type II error and failing to dive when it is needed. Assessing the adequacy of this decision rule can be done by estimating the probability of making these errors based on data from the field.

Such an assessment is possible because, for a variety of operational and other reasons, cull dives were conducted at 33 reefs despite zero feeding scars being observed during surveillance manta tows. At a further 67 reefs, dives were conducted despite no COTS being observed (Table 1). Of the reefs where no COTS were observed, subsequent dives indicate that 16% would have failed to receive a cull when one was required. Of the reefs where no scars were observed or where neither COTS nor feeding scars were observed, just 3% had COTS densities above the 3 COTS ha⁻¹ threshold. Of the reefs where one COTS or feeding scar was recorded, 10 and 13% respectively, had average COTS densities above the threshold. Of the reefs where more than one COTS, feeding scar or both were observed, 52, 35, and 36% respectively had average densities greater than 3 COTS ha⁻¹. These results suggest that the decision criteria of 'dive if one or more COTS or scars are seen' is a reliable criterion with a low, but non-zero, probability of making an error. It comes with a high chance of committing a type I error, 68% of sites dived did not record maximum densities over 3 COTS ha⁻¹. The cost of this, however, is relatively low given that divers are already at the reef and a single dive is generally sufficient to determine if further investment is required; if sites dived just once are excluded the estimate drops to 28%.

A second critical decision is the decision of when to stop culling at a site. The decision to cease cull dives at a site is in theory, triggered when the population is assessed to have dropped below the (ecological) threshold at which coral growth can outpace COTS damage, generally at 5 COTS ha⁻¹. In practice, however, on a given voyage, dives at a site continued until divers assessed the site as having no further COTS available to cull. If the density of COTS removed was below 5 COTS ha⁻¹, the site was declared closed for subsequent voyages. In practice, this sequence of decisions had the effect of continuing cull dives beyond the voyage on which both the ecological and the more conservative reproductive threshold (3 COTS ha⁻¹) was reached. Combined with the start cull decision rule of dive sites when one or more COTS are detected, this also meant that some sites were dived on one or more voyages (n=390) despite not having COTS densities above even the more stringent reproductive threshold. On average, a mean of 2.28 (± 2.61 SD) dives more than required to reach the reproductive threshold were made at each site where COTS had been detected.

While these extra dives impose a cost burden on the program, this cost was not without benefits. First, the maximum density of COTS was not always detected on the first voyage to a site. At 317 of 782 sites where cull dives were made on more than one voyage, maximum densities were detected on the second, third or fourth voyage. At 84 sites densities above the ecological threshold were first detected on the second, third or fourth voyage, not on the first voyage to the site. In these cases, adjacent sites had densities above the threshold. In addition to demonstrating a benefit of committing a Type I error in this context, this also highlights the benefit of treating reefs as a whole, providing multiple points of reference for the COTS density across sites at a reef. Furthermore, continuing to dive while COTS were present ensured that densities remained low and provided a 'margin of error' that reduced the probability that densities would bounce back above the threshold in the short term.

Table 1: The number of reefs at which 0, 1, or more COTS, Feeding Scars, or COTS and/or Feeding Scars were observed during Manta Tows categorized by the maximum density of COTS culled at any site at each reef in the first two cull voyages. The Probability of making a Type I error (diving when it is unnecessary) and a Type II error (deciding not to dive when it was necessary) based on the criterion of conducting a cull dive if one or more COTS, Scars or Both are seen during a reef circumference manta tow.

# Observed	Maximum COTS Density	Scars	COTS	COTS & Scars
0	0	15	25	15
	<3/ha	17	32	17
	>3 ha	1	11	1
	Total	33	67	33
	T I dive not need	0.97	0.84	0.97
	T II not dived when needed	0.03	0.16	0.03
1	0	4	4	3
	<3/ha	5	9	3
	>3 ha	1	2	0
	Total	10	15	6
	T I dive not need	0.90	0.87	1.00
	T II not dived when needed	0.10	0.13	0.00
>1	0	13	3	14
	<3/ha	26	7	27
	>3 ha	21	11	23
	Total	60	21	64
	T I dive not need	0.65	0.48	0.64
	T II not dived when needed	0.35	0.52	0.36
Grand Total		103	103	103

3.4 Comparison the Performance of the Pre-IPM and IPM Programs?

The switch from the operations of the Pre-IPM Control Program to the IPM Control Program has required significant modification of how the control fleet is deployed and operates and was supported by additional oversight and research input. What has been gained through this investment? Comparing their performance allows us to explore how the benefits of the IPM approach accrue in terms of its objectives.

The Pre-IPM program was focused on protecting a set of economically or ecologically important sites at 21 reefs. A large number of additional sites and reefs were incorporated into the program in response to reports of high COTS numbers and the directives of the GBRMPA. During the Pre-IPM only sites at reefs were managed, not reefs themselves. As a result, individual control efforts tended to be focused on areas with high COTS densities at which high CPUEs were achieved. Gauging program performance purely on CPUE casts the pre-IPM performance in a positive light. There was, however, little consistency in approach across whole reefs or through time, which means that objectives related to site and reef-level protection were much less likely to be achieved.

In contrast, during the IPM phase, reefs were selected for inclusion into the program based on a priority ranking of their ecological and economic attributes (known or estimated) and

managed in order of their ranking, not the COTS densities present. The entire reef perimeter, and where possible other accessible areas, was managed and the sequence of sites at a reef was determined by COTS density, with higher density sites managed first. Importantly, control continued at reefs until densities at all sites were below the 3 COTS ha⁻¹ threshold. As a result, COTS were controlled consistently across reefs and over time, and to much lower densities and CPUEs than during the pre-IPM phase. This allowed reef-level objectives to be reliably achieved, but also averaged lower CPUEs over the period of management analysed.

In Table 2: Comparison of performance metrics of the Pre-IPM (P) and the IPM (I) Control Programs. Units are defined in the first column and given \pm standard deviation where appropriate. We compare a range of key performance measures for the two phases of COTS control. In doing so we recognise that the two phases were of differing durations and involved different numbers of vessels. As a consequence, wherever possible we use metrics that are not confounded by these differences.

Unsurprisingly, the focus on high density sites in the Pre-IPM phase is reflected in the higher mean densities at sites where culls were conducted and the higher cull numbers and rates. However, there were only minor differences in the total area controlled. More interestingly, despite the higher CPUEs achieved, the overall density reduction was only similar to that achieved in the IPM program. This suggests that although over 100,000 more COTS were removed in the Pre-IPM phase, the meaningful reduction in COTS density over time resulting from those culls was similar to that achieved by the IPM phase. The data also suggests that the dive teams themselves performed similarly across the two phases and that the differences in cull totals were primarily a function of how sites were selected for control, not diver performance.

Meaningful differences begin to appear when we consider the outcomes achieved at a site instead of simply the number of animals killed. While there was no significant difference in the number of voyages required to bring a site below the threshold, the IPM reduced the number of days required to achieve this by 63%. This difference translates into significant gains in terms of the coral not consumed by COTS before they were culled and if there is a 1:1 relationship that gain would be 63% less coral lost. Not only did the IPM reduce densities to below the thresholds much sooner but it did so much more reliably. Under the Pre-IPM program the probability that a site above the 3 COTS ha⁻¹ threshold would be brought below the threshold was half that of the IPM program while the probability that a site above the threshold would be visited just once, and hence not adequately controlled, was 2.4 times that of the IPM program. Across all sites the average final density of COTS under the Pre-IPM was four times the 3 COTS ha⁻¹ threshold and c. 6 times higher than the densities achieved by the IPM program. Eighty-eight percent of the IPM sites were below the threshold at the end of the study period compared with just 53% in the Pre-IPM phase.

While the site level differences between the programs are stark, the differences at the reef scale are even more pronounced. At the end of the Pre-IPM phase 0% of 102 reefs where culling occurred had their entire perimeter controlled to below the threshold, compared with 89% of 103 reefs during the IPM phase.

In summary, while the Pre-IPM phase of the program achieved a greater body count, this did not reliably translate into meaningful long-term outcomes at the site scale, and completely

failed to achieve reef scale objectives. In contrast, the strategy employed during the IPM phase ensured that culling investment achieved that program's objectives at site and reef scales, as well as at regional scales across the Priority Reefs. Furthermore, this improved performance included a greater probability of success at the scale of the site and the reef and achieved that success on a shorter timescale meaning that less coral was lost to COTS before they were culled. Indeed, across all sites, the IPM approach resulted in a reduction in mean COTS densities to below the critical thresholds. Significantly, the Pre-IPM program did not achieve reef-scale control at any reef (the IPM program achieved it at 89% of reefs) and was half as likely to achieve this threshold even at the site scale as the IPM program.

Table 2: Comparison of performance metrics of the Pre-IPM (P) and the IPM (I) Control Programs. Units are defined in the first column and given \pm standard deviation where appropriate. In the column 'Best' the method with the score that indicates a better outcome is identified – this does not necessarily imply a statistically significant difference between the methods. Scale refers to the operational scale of the objective being measure: C = cull, S= site, R = reef

Performance Metric	Pre-IPM	IPM	Best	Scale
Cull Performance				
Mean COTS/ha at a site	33.3 \pm 67	9.7 \pm 25	P	C
COTS Culled	304,221	192,285	P	C
COTS/Operational Day	359	162	P	C
Area managed/operational day (ha)	8.6	7.1	P	C
Area reduced from >3 COTS ha ⁻¹ to <3 COTS ha ⁻¹ /op day	1.8	1.4	P	C
Density reduction at sites reduced to <3 COTS ha ⁻¹	92 \pm 12	90 \pm 12	P	C
Site Performance				
Voyages to reduce below threshold	6.1 \pm 3.8	6.7 \pm 3.9	P	S
Days to reduce a site to below threshold	536 \pm 218	198 \pm 126	I	S
Probability site with >3 COTS ha ⁻¹ is visited just once	0.17	0.07	I	S
Probability (site with >3 COTS ha ⁻¹ reduced <3 COTS ha ⁻¹)	0.32	0.61	I	S
Mean density reduction at sites >3 COTS ha ⁻¹ (%)	50 \pm 42	76 \pm 29	I	S
Mean final density all sites	11.7 \pm 28	1.98 \pm 7	I	S
% sites below threshold at end	53	88	I	S
Reef Performance				
# reefs where culling took place	102	103	I	R
# reefs managed to completion (i.e. entire perimeter)	0	92	I	R
Total # sites	314	884		

4.0 IPM CONTROL PROGRAM POTENTIAL

Our analysis thus far has focused on the performance of control operations during the current outbreak. What do the results to date tell us about the program's future potential in controlling a new outbreak and the likely strategies that will be required for success? While we have identified the IPM Control Program to be effective at achieving its objectives at the site and reef scales across 103 Priority reefs, this does not necessarily mean that it can be scaled up sufficiently to stop outbreak establishment or even to reduce the magnitude of the next outbreak. While this is partly a question of the program's capacity relative to the spatial distribution of the outbreak, it is also critically dependent on the effectiveness of the particular deployment strategy.

Success in achieving any larger scale objective demands that resources be deployed in a manner that is not only effective in achieving outcomes at the site and reef scale but also that resources are deployed at times and in places that take advantage of i) the dynamics of COTS population processes; ii) the distribution of COTS spread; and iii) the environmental constraints on those processes. In the following analysis, we use the current outbreak and the performance of the IPM Control Program as a guide to what might be achieved in the next outbreak. The guiding principle here is that the program will achieve the greatest chance and magnitude of success if it is invested at times when the outbreaking population and its spatial extent are still small (Hulme 2006, Fletcher and Westcott 2013).

4.1 Time - we must act early

Arguably a major contributing factor in the failure of invasive and pest species management programs globally is the failure to act early in the outbreak process, before the outbreak has spread to cover a large and difficult to manage region. Any delay between detection of the species and the start of an effective control program represents time that the species is able to establish and spread. This exponentially increases the magnitude, cost and difficulty of the task, dramatically reducing the chances of a successful outcome (Fletcher and Westcott 2013). In the case of COTS, however, we have a benefit not often available to pest managers: outbreaks are cyclical, and we know very roughly when and where the next outbreak is likely to start. This provides a significant opportunity to target control effort intensively at a point where the outbreak could be subdued or even avoided if timed and targeted correctly, similar to successful efforts to detect and respond to incipient rodent (Brown et al. 2010) or locust outbreaks before they generate significant impacts (Department of Agriculture Water and the Environment 2021). Doing so effectively, however, requires that incipient outbreaks are detected and that the Control Program responds at the earliest possible point in the outbreak cycle.

The earliest point at which control can be deployed is a function of the earliest life history phase that is susceptible to the control methods. Current control is efficient and effective when deployed against adults, so a key task is to identify when in the outbreak cycle we can act against adults. During outbreak initiation there are two early intervention points where adults can be targeted. The first of these is during the inter-outbreak period when even subtle increases in adult densities, or the formation of adult aggregations, have the potential to allow for increased fertilization success that might lead to outbreak initiation (Rogers et al. 2017).

Monitoring, detecting and responding to prevent any increases above background densities could provide a means of reducing the output of such reproductive events and might prevent outbreak initiation.

The second period would be in the subsequent 1-3 years during which larvae from the initiation population are recruiting, and during which already settled juveniles and sub-adults are supplementing the adult population. In this phase control operations can erode the foundational adult population on which the larval recruits are building.

As larvae from the spawning events that initiated the outbreak begin to recruit to the adult population, we move to a second control phase targeting an established and spreading outbreak. During previous outbreaks, control has only been first implemented well into this phase. While this is very late for control action to begin, the earlier the detection of increasing adult densities occurs, and the earlier a management response begins within this phase, the greater the impact of control on broadscale spread and recruitment to the adult population is likely to be.

4.1.1 Are We Equipped for Early Detection?

While the imperative for early action is clear, we need to consider whether we have the tools that would allow us to detect what will be subtle changes in COTS densities and to respond to them in a timely fashion. Manta tows have long been used for monitoring COTS densities on the GBR (Baker et al. 1990), and in the analyses above we identified that they allow sites to be reliably assigned to above or below threshold densities in the current IPM program. In the context of early detection of the next outbreak, however, we would be seeking to detect subtle changes in density over time. To do this successfully, manta tow surveys would need to be a reliable predictor of COTS densities at a site.

To determine whether manta tows have the resolution required to discriminate COTS densities reliably we used linear modelling to estimate the relationship between the number of COTS observed on manta tows at a site with the density of COTS culled from that site over 30, 90, 180, 360 and 720 day periods after the date of the manta tow. Our data set comprised 23,896 manta tows conducted at sites distributed across 307 reefs over the control program's history. The modelled relationships between COTS observed on manta tows and the subsequent culled densities of the two smallest size classes (<15cm, 15-25 cm) over the different time periods ranged in statistical significance from 0.03 to 0.79 but in all cases explained <1% of the variation in the data. For the two largest size classes all relationships were highly significant ($p < 0.001$) but again explain almost none of the variation with the $r^2 < 0.04$ in all cases. When all size categories were combined the models were significant (< 0.001) but explained ≤ 0.02 of the observed variation. Feeding scars more reliably reflected the density of COTS subsequently culled, but the scoring of this metric into just three categories in the current IPM program makes this too coarse a measure to assess its usefulness in for discriminating COTS densities for early outbreak detection.

In short, despite providing an acceptably reliable trigger for implementing control when sites exceed the threshold of 3 COTS ha^{-1} , manta tows as currently conducted are not adequate for monitoring the subtle changes in COTS densities, particularly in the smaller size classes, that might presage outbreak initiation. Such a capability is fundamental to successful management

of future outbreaks, so alternatives must be found. The immediate option - to continue using a trigger of any detection of COTS or feeding scars - is currently the best and only solution. Happily, emerging remotely operated glider technologies have demonstrated far greater sensitivity, accuracy and precision than human manta tows, and represent a potential solution to this problem. Furthermore, these gliders can simultaneously collect high quality data on coral cover and assemblage structure, other measures of reef condition and community structure, and can do so far more rapidly and comprehensively than is possible with human based tows. In addition, analysis and interpretation can be automated and their outputs used in real time. Their development must be a priority.

4.2 Place – we must act where the greatest impact is to be had

The second consideration is the question of where we should invest effort for success. This question is more nuanced than the question of when we should act as the same objective can have very different spatial implications when considered at different scales. For smaller spatial scales (sites, reefs and reefs in a region) this question is addressed by the design of the prioritization and decision processes for the IPM program (Fletcher et al. 2020) and at larger scales is considered by Westcott et al. (2021b). However, here we focus on the large-scale question of “where on the GBR would early investment in monitoring and control be best matched to the scale of the outbreak and have the greatest impact on its trajectory?” The question is about where to act, and the evidence currently available strongly points to the Initiation Box (Figure 3: Distribution of reef number (left hand plot) and area by latitude (right hand plot).) as being an initial focus for effort during the period between outbreaks.

There are two primary reasons for this. The first is that the Initiation Box represents the region where the four recorded outbreaks (excluding the apparently on-going outbreak in the Swains) were all first detected and from whence those outbreaks appear to have spread (Pratchett et al. 2014). Assuming that future outbreaks also follow this pattern, then early detection will occur in the Initiation Box and that is where monitoring and any early response should be primarily focused.

It is worth recognising, however, that there is some uncertainty around the concept of the Initiation Box, and if it exists, around its likely boundaries (Kenchington 1977, Reichelt et al. 1990, Pratchett et al. 2017). This suggests that a broader geographical scope should be adopted as a precaution. Furthermore, even if outbreaks do start within the Initiation Box, and even if these are successfully controlled, there is the potential that some of those COTS will produce larvae that disperse downstream beyond the Initiation Box’s boundaries before they are controlled. Consequently, a successful management response would require not just management in the Initiation Box but also surveillance and culling to be conducted in the downstream areas receiving larvae. We term this area the Dispersal Box, and given that dispersal could potentially occur north or south of the Initiation Box, we would define both a Northern and Southern Dispersal Box (Figure 3). Given that COTS spawn predominantly in the monsoon season (Babcock and Mundy 1993, Uthicke et al. 2019), when the Gulf of Papua Current has weakened and the Southern Equatorial Current bifurcation drives stronger southern flow across all but the very northern section of the Initiation Box, we might expect most dispersal will be in a southerly direction. However, uncertainty about the location of outbreak initiation (Pratchett et al. 2017), variation in the bifurcation latitude (Zhai et al. 2014), and the potential for local currents and eddies to transport larvae north against the dominant flow (Hock et al. 2014), all argue for vigilance in the northern dispersal box, in addition to the

southern box. Based on Uthicke et al. (2015)'s description of larval plumes from the current outbreak, the southern limit of the southern Dispersal Box might, in the first instance, be placed at Bramble Reef, at 18° 27' S and, the northern limit of the northern Dispersal Box at 13° S in the north.

A second, and very pragmatic, reason for focusing on these areas is that the Initiation and Dispersal Boxes also represent the part of the GBR where both the number of reefs and the area of those reef area is low relative to other areas on the GBR (Figure 3: Distribution of reef number (left hand plot) and area by latitude (right hand plot).). In other words, the region between 14°S and 18°S, but particularly c. -15°S to c. -17°S, represent a choke point where control operations have a tactical advantage in terms of the potential scale of the outbreak and their resources. Furthermore, close proximity to major ports minimises transit times and costs to and from reefs, maximising resources available for control.

In summary, our current understanding suggests that the general region of the Initiation Box represents the ecologically and logistically optimal area within which to i) stop outbreak initiation, and, should this fail or should an outbreak start outside this area, ii) to have the greatest chance of significantly reducing the amplitude and severity of the ensuing outbreak. The Dispersal Boxes represent key areas for mopping up or backstopping these efforts and should be a focus of surveillance efforts to prevent further spread. Surveillance activities should continue outside these regions but perhaps with lower investment.

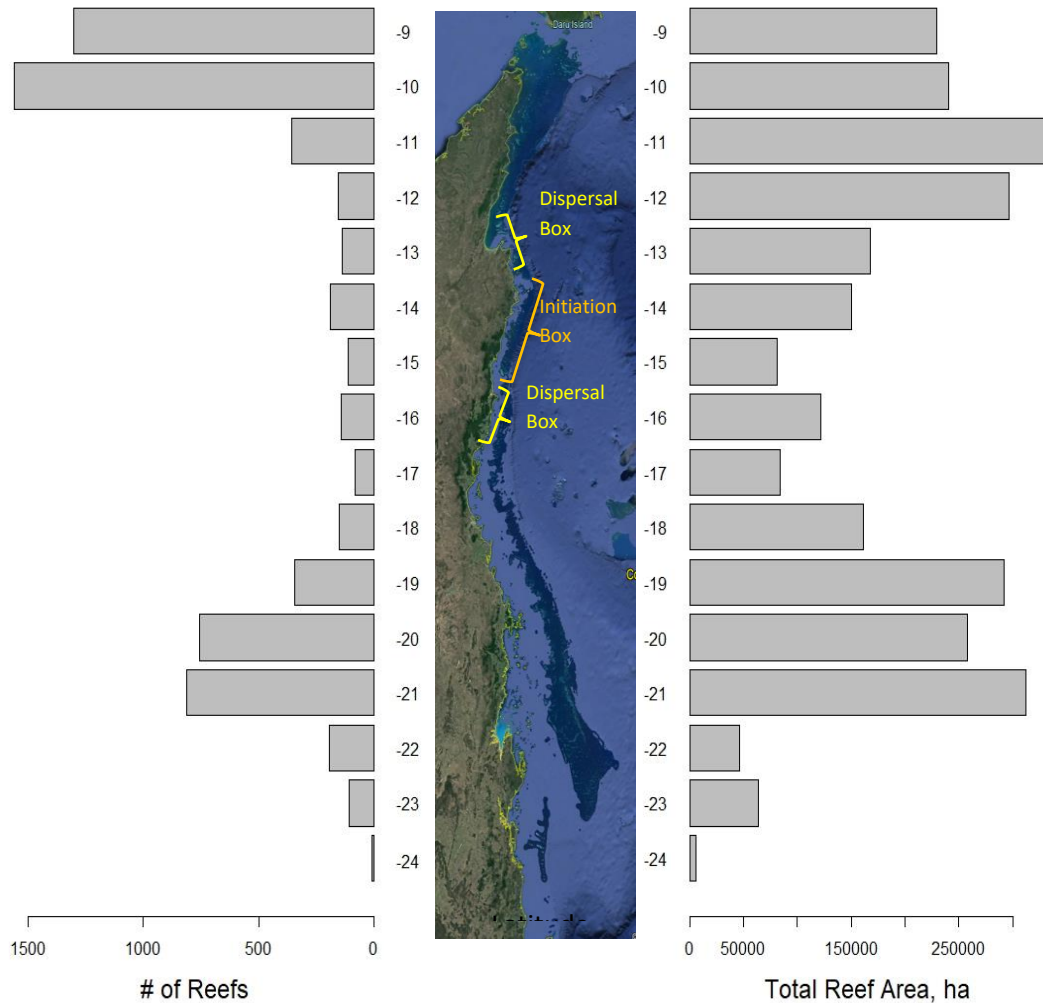


Figure 3: Distribution of reef number (left hand plot) and area by latitude (right hand plot). Alignment of the plots with the image of the GBR is approximate only.

4.3 The IPM Control Program’s Capacity and the Next Outbreak

Given that we have identified when and where manual control can be best deployed in the context of the next outbreak, we now ask whether the IPM Manual Control program has the capacity to meet such a threat. To do this, however, we need to first define what the objectives of such a program might be, and then describe the assumptions underlying the scenario we are considering.

During the inter-outbreak period in the Initiation and Dispersal Boxes, COTS control should be focused on preventing the initiation of a new outbreak by maintaining COTS densities at below the density thresholds that might trigger outbreak initiation (Rogers et al. 2017). Furthermore, in the event that outbreak initiation, or an established outbreak, are detected, a Control Program’s objective will be to suppress populations in order to minimise the size and impact of the outbreak and to restrict its spread. As a consequence, we assume that the control program’s objective will be to implement control in a manner that i) prevents increases in adult density or aggregation that might enable the enhanced spawning success that would trigger an outbreak; ii) minimizes the impact of COTS predation on coral; and iii) minimizes the

magnitude and spread of any outbreak by permanently suppressing adult COTS densities at well below the ecological and reproductive thresholds within the Initiation and Dispersal Boxes, and elsewhere as necessary.

We will also assume that the next outbreak shares the general characteristics of the current outbreak and the three that preceded it. The current outbreak is generally considered to have begun in the Initiation Box in 2010 (Kenchington 1977, Reichelt et al. 1990, Pratchett et al. 2014). Data from GBRMPA's field monitoring program and the Control Program that operated between 2012 and 2015 (unpubl. data) support this and indicate that it was largely, but not entirely, contained within the Initiation Box until c. 2014, before spreading through the Dispersal Box and beyond. We assume, then, that the next outbreak will have generally similar characteristics including, i) beginning in the Initiation Box, ii) a four-year residency time in the Initiation Box, and iii) a further four-year residency period in the Dispersal Box. We assume that the next outbreak shares the distributional characteristics of the current outbreak as experienced during the current control program. This includes how densities of >3 COTS ha⁻¹ are distributed across the control area (in the IPM program such densities were reported from 32% of sites and 60% of reefs) and a similar frequency distribution of population densities.

We also make assumptions about the control fleet and its operations. We assume that a similar sized fleet continues to operate through the inter-outbreak period and into the next outbreak. Furthermore, we assume that the fleet retains their current capabilities and operates at approximately the same rate and efficiency.

The performance of the control fleet in terms of reefs and sites manta towed and culled in the first 1.73 years is summarized in Table 3 (column 2) alongside the annualised assessment for the 'average' vessel (column 3). We extrapolate those figures to provide the expected performance of a fleet of five vessels over four and eight-year periods, corresponding to residency times in the Initiation and Dispersal Boxes (Columns 4 and 5). These extrapolations suggest that the IPM program as currently configured and resourced not only has the potential to conduct control operations over enormous areas of the GBR but to achieve its objectives at these very large spatial scales.

However, the area which the IPM Control Program has managed at individual reefs is only a proportion of the total area of those reefs as measured by existing reef mapping due to the fact that reefs are mapped as polygons that incorporate significant non-coral habitat. This makes direct extrapolation of areas managed to the mapped reef areas difficult. To ground these predictions in the overall scale of the reefs in the Initiation and Dispersal Boxes, in Table 4 we compare the number and mapped area and perimeter of the reefs in these Boxes with the same metrics for the reefs managed during the IPM program. This comparison suggests that every year the IPM Control Program could: i) conduct operations at 43% of the reefs within the Initiation Box; ii) cull reefs with an area c. 1.6 times that of the reefs in the Initiation Box; and iii) conduct manta tows along c. 2 times the perimeter of reefs in the Initiation Box. This extrapolation also suggests that, over a 4-year period (half the assumed residency time in these Boxes), the program could work at 468 reefs with an area c. 3.5 times and perimeter length 4.5 times that of the combined Initiation and Dispersal Boxes. In short, these estimates suggest that the IPM Control Program as currently operating is realistically matched to the task of controlling COTS densities in the Initiation and Dispersal Boxes.

Table 3: Performance metrics of the current fleet, standardized to single vessel performance and projected over four and eight years. Performance up to 2020-07-03 is the total work accomplished by all vessels.

Activity	Performance up to 2020-07-30	Annual Performance Per Boat	4 Year Potential, 5 boats	8 Year Potential, 5 boats
Reefs Manta Towed	202	23.5	469	939
Perimeter Towed (km)	8,394	975	19,510	39,019
Reefs Towed Only	99	11.5	230	460
Reefs with Culls	103	12	239	479
Reefs with Culls, all sites reduced <3 ha ⁻¹	92	10.7	214	428
Culled Reefs with sites still >3ha ⁻¹	11	1.3	26	51
Total Area Culled, ha	8,411	977	19,549	39,098
Area Culled <3 ha ⁻¹	6,266	728	14,564	29,127
Area Culled still >3 ha ⁻¹	2,145	249	4,985	9,971

Table 4: Comparison of the number, area and perimeter lengths of reefs in the Initiation Box, the Dispersal Box and these combined with the reefs managed in the IPM Control Program in the 1.73 years up to 2020-07-30.

	Initiation Box -14° 32'S to -16° 48'S	Dispersal Box -16° 48'S to -18° 27'S	Combined -14° 32'S to -18° 27'S	Reefs to 2020-07-30	Annual Performance 5 Vessels
# of Reefs	270	171	440	202	117
Measured Reef Area, ha	209,528	179,116	388,644	585,500	338,439
Reef Perimeter, km	2,448	1,803	4,251	8,394	4852

5.0 DISCUSSION

5.1 Performance of Manual Control

5.1.1 Performance in the 1st, 2nd and 3rd Outbreaks

Management responses during all four COTS outbreaks on the GBR have been based on manual control. Despite a gradual evolution in the magnitude of the investment and in the methods used, the experience of manual control as a management tool during the first three of these outbreaks has contributed to the perception that large scale COTS control is unlikely to be successful. This contrasts directly with the results of our analysis.

The 1962 outbreak was first detected at Green Island but, despite the recruitment of volunteers and employed divers and the culling of 27,000 COTS, the reef was devastated and not even the 4 ha coral viewing area was saved (Barnes 1966, Moran 1986). Reports from elsewhere in the Pacific at the time also suggested that the magnitude of an outbreak either swamped manual control efforts or meant that they had to be long-term, local and well-funded (Cheney 1973, Wass 1973). In the light of this experience, the 1970 Australian Academy of Sciences *ad hoc* Committee on the Problem of the Crown-of-Thorns Starfish recommended that broadscale control was not feasible and that control should be limited to established tourism areas (Walsh et al. 1971).

Despite the experience of the first outbreak, manual control was again employed in the second outbreak beginning in 1979-1987, this time with more mixed results. Significant investments in control, including the use of military divers and systematic search and destroy protocols at one part of John Brewer in 1987, at Grub Reef in 1983-1986, and at Holbourne Island in 1987 (Zann and Weaver 1988) were all judged failures with high COTS densities persisting and coral cover lost. However, at John Brewer Reef in 1984-1986, c. 4 ha of reef was controlled, and 30,000 COTS removed. This exercise was considered a success because final coral cover in the control area was 5-30% with just 20-30% standing dead coral, whereas elsewhere on the reef it was 1-5% live coral cover and 40-70% standing dead coral. Tourism operators also considered their operations at the Codhole in 1984 and Credlin Reef in 1987 successes as they also reduced COTS numbers and retained coral cover.

These instances of success were sufficient for acceptance that control on the scale of a few hectares could be successful (Kenchington 1977, Moran et al. 1988, Reichelt et al. 1990). This led to an overall conclusion that "mesoscale controls (i.e. several hectares) are feasible only if a hand control program can be sustained for the duration of the outbreak on that reef..." (Zann and Weaver 1988, p 187) and consequently that "...control of COTS outbreaks on the macroscale (many reefs) is not possible using currently available methods" (Lassig 1991, p 31). Some concluded that, even if it was possible to scale up to entire reefs, ultimate success at the scale of the entire GBR would require an unattainable investment (Birkeland 1989, Edean and Cameron 1990). These conclusions were the accepted wisdom going into the third outbreak on the GBR (Birkeland and Lucas 1990), and additional research on control methods assumed that control would only be attempted at high value sites and sought means of improving the efficacy of control only at the site scale (Fisk and Power 1999).

5.1.2 Performance in the 4th Outbreak: Pre-IPM Performance

In the early years of the fourth outbreak, which started in c. 2010, the prevailing wisdom was still that manual control was only of limited utility (Fabricius et al. 2010, Bos et al. 2013, Pratchett et al. 2014). However, concurrent with these perceptions, changes to how manual control was conducted were radically altering management outcomes and driving a fresh consideration of what the approach might achieve. These changes were introduced incrementally and included: i) dedicated control vessels staffed by trained divers, ii) the introduction of single-shot injections for culling (Rivera-Posada et al. 2013, Moutardier et al. 2015, Boström-Einarsson and Rivera-Posada 2016), and, nominally at least, iii) a focus on a suite of Priority sites.

The impact of these changes on control performance was dramatic. The Pre-IPM program was highly effective in culling COTS, as it was able to reduce COTS densities significantly across hundreds of 20 ha sites distributed across scores of reefs. At a sub-set of sites where sufficient effort was invested (i.e., repeated voyages), the Pre-IPM was successful in reducing COTS numbers to below threshold levels (this report) and facilitated coral recovery (Westcott et al. 2020). These outcomes represent a significant departure from previous perceptions of manual control outcomes on the GBR, or elsewhere, and provided confidence to seek further improvement.

5.1.3 IPM Performance

The introduction of the IPM Control Program sought to build on these outcomes by taking a culling method that the Pre-IPM program had shown to be effective, and deploying it in a strategic manner to reliably achieve the program's desired outcomes at the site, the reef and regional scales. To do this, two structured decision processes were employed. The first of these decision processes determines which reefs are prioritised for control based on the available data on their condition and coral cover, their economic value, and their estimated role in dispersing COTS and coral larvae on the GBR. The second of these processes then sequence control: i) at sites, ii) across sites at reefs, and iii) across reefs on the priority list. These decision processes are designed to achieve the program's stated objectives in a manner that is efficient and effective given the program's logistical constraints and the realities of the ecological processes it is trying to manage (Fletcher et al. 2020).

The results presented in this report clearly show that the IPM Control Program has been highly successful in scaling successful control at the site up to the reef, the region and beyond. During the study period, the IPM COTS Control Program monitored COTS densities at 202 reefs distributed across the GBR from latitudes 12.9° to 24.1°S and determined their management requirements based on the simple decision rule "dive if a COTS or feeding scar is observed". One hundred and twenty-one reefs were identified as having COTS densities above the 3 COTS ha⁻¹ threshold and therefore requiring culling. Culling was completed at 103 of these reefs with the entire perimeter of 92 (89%) being brought to below the threshold in an ordered and ecologically informed manner by the end of the analysis period. Culling was yet to begin at the 18 remaining reefs at the time of writing.

5.1.4 Comparison of the Pre- and IPM Programs

The Pre-IPM program was far more effective in killing COTS – 50% more cots were culled in this program and they were culled at c. 2.5 times the rate achieved in the IPM program. However, that high rate of culling in the Pre-IPM program did not reliably translate into the desired COTS density reductions at sites and was never scaled up to provide outcomes across an entire reef. This was due to the Pre-IPM's failure to re-visit sites and do so with sufficiently frequency. This was due to its focus on culling high density aggregations of COTS rather than persisting with control at sites in order to achieve densities that would protect coral and achieve their overall objectives. This difference in performance is clearly demonstrated by the fact that the final density of COTS at Pre-IPM sites was c. six times that of IPM sites and that the Pre-IPM program returned to sites and achieved target densities at control sites at roughly half the rate that was delivered by the IPM program. All of these metrics contribute to the Pre-IPM having COTS present in high numbers and consequently losing much more coral than would have occurred under the IPM Control Program

This is not to suggest that the Pre-IPM Control Program did not achieve its stated objectives in some instances. However, while some individual sites were successfully controlled at some reefs, this did not happen reliably and occurred in isolation, with the remainder of these reefs, in almost all cases representing the vast bulk of the reef's area, left unmanaged. This left controlled sites vulnerable to re-infestation and meant that protection of priority reefs as discrete biogeographic management units was not achieved.

In contrast, while the IPM Control Program culled fewer COTS than the Pre-IPM Control Program, it did so in a strategic manner designed to meet its objectives at site, reef, and regional scales. Under the IPM Control Program sites (88% of 884 versus 53% of 314 in the Pre-IPM) and entire reef perimeters (89% of 103 versus 0% of 102 in the Pre-IPM) were more reliably reduced to below the 3 COTS ha⁻¹ threshold. On-going monitoring in the IPM Control Program also ensured that these sites and reefs were maintained at these densities over the long term (Fletcher et al. 2020). The fact that densities were reduced far more rapidly under the IPM than the Pre-IPM Control Program also meant that less coral was lost to COTS predation in the time it took to reduce densities to the threshold.

In short, the IPM Control Program has taken an effective means of culling COTS at an individual site, developed in the Pre-IPM Control Program, and turned it into an effective, efficient and robust means of protecting coral cover through reductions in COTS densities to below ecological and reproductive thresholds. It has done so in a manner that achieves control objectives at the site, the reef and regional scales through its focus on Priority Reefs.

5.1.5 IPM Potential

A question often asked is 'How many control vessels would be required to control COTS?' The problem with answering this question is that 'control' is rarely defined. With no defined objective for control it isn't possible to assess when that objective might be reached and, consequently, to estimate its cost. In developing the IPM COTS Control Program, our approach has been to accept that a successful program would prevent coral loss to COTS predation, and that the scale at which this could be achieved would ultimately be determined by the capacity of the program. Until now, this capacity has not been known, and could have varied from protecting a small number of high value sites, to moderating outbreaks and

minimising their impact at the scale of the GBR, through to stopping the spread of outbreaks entirely. The key to identifying which objectives might be most appropriate lies in understanding the program's capabilities and how they might be best deployed.

Our summary of the program's capabilities and our simple extrapolation against a new outbreak indicate that the IPM Control Program would be capable of protecting coral by reducing COTS densities to below the ecological and reproductive thresholds, and, if strategically deployed, would be capable of doing that at scales that would have meaningful ecological outcomes at the scale of the GBR. This would include significantly reducing the magnitude and spread of any new outbreak and, if sufficiently resourced, might even aspire to stopping an outbreak in the Initiation and Dispersal Boxes.

This conclusion is independently supported by the broad outcomes of the companion report *Regional-scale modelling capability for assessing crown-of-thorns starfish control strategies on the Great Barrier Reef* (Fletcher et al, 2021). This report used entirely different methods to estimate the program's potential. These were based on detailed regional scale metapopulation models of COTS and coral across the GBR, incorporating regional scale COTS management strategies. Although assessment of a GBR-scale strategy like the one considered here was beyond the scope of that report, it did estimate the number of reefs that could be controlled by a fleet of five vessels. Even in the southern regions currently experiencing outbreaks, where reefs are more numerous and cover larger areas, a fleet of five vessels is predicted to be able to successfully control several hundred reefs to below the ecological threshold at which coral growth can outpace COTS damage. Transposed northward to the Initiation and Dispersal boxes, this same effort would be enough to significantly or completely control the next COTS outbreak.

In the current analysis, our estimation of the program's potential capacity in the face of a new outbreak makes a number of significant assumptions. These include that: i) the next outbreak shares similar distributional characteristics with the current outbreak; ii) the control fleet is maintained throughout the inter-outbreak period, enabling rapid detection and response to increases in COTS densities; iii) we have an enhanced monitoring capability that can monitor and- detect changes in low density COTS populations and enable a rapid control response to an initiating outbreak; and iv) culling in the currently accessible parts of the reef is sufficient to control the section of the COTS population that drives outbreak dynamics. There is support for each of these assumptions, and so while we recognise the need for caution, we feel that our extrapolations do provide an indication of how well the program's scale and capabilities are matched to the problem that we anticipate in the next outbreak. Successfully achieving this outcome will be entirely dependent on the objectives of the program and on the strategic deployment of control resources in both space and time.

5.2 Blueprint for Improving Control of Crown-of-Thorns Starfish

For much of the past two decades the strategy for influencing COTS populations at the GBR scale has focused on preventing outbreaks through water quality improvement (WQI) programs intended to prevent enhanced recruitment (State of Queensland 2013). Manual control has not been emphasised as a GBR-scale COTS control strategy, due to perceptions of its high cost and low effectiveness at broad scales (Walsh et al. 1971, Lassig 1991, Pratchett and Cumming 2019). This approach had support from the scientific community well into the

current outbreak (Doherty 2012). For example, in their analysis of drivers of COTS outbreaks, Fabricius et al. (2010) suggested a three-pronged strategy for COTS management based primarily on WQI supplemented by targeted fisheries closures, with manual culling relegated to targeted effort by divers at limited temporal and spatial scales, after floods and at important sites.

Given the outcomes of this report into the effectiveness of manual control at the GBR scale, and other assessments on the performance of alternative strategies (Westcott et al. 2020), we would suggest that these assumptions should be reconsidered. Manual control, operating within the structure provided by the IPM COTS Control Program, is clearly effective in reducing and suppressing COTS densities to below outbreak thresholds, of achieving this outcome at the scale of sites, reefs and of hundreds of reefs, and, has the potential to achieve GBR scale outcomes if it is appropriately deployed (this report, Fletcher et al. 2021). Furthermore, control of COTS provides immediate protection to existing coral cover and facilitates its recovery (Westcott et al. 2020) thereby achieving the primary objective of COTS management – coral protection. Zoning also appears to have a demonstrable if moderate effect on COTS dynamics and contributes to reef resilience overall in the face of an outbreak (Sweatman 2008, Mellin et al. 2016, Sweatman and Cappo 2018, Westcott et al. 2020). In contrast, WQI, despite huge investment, has had only minimal impact on water quality itself (Brodie and Pearson 2016, Bartley et al. 2017, Office of the Great Barrier Reef 2019) and there is little reason to expect it has had flow on effects for COTS outbreaks, particularly given that the current outbreak began in c. 2010, well into the implementation phase of these WQI programs (Westcott et al. 2020). In the light of these observations, we would suggest that strategic investment in manual control as is achieved by the IPM COTS Control Program should be the foundational component of COTS management on the GBR, and remain so until we are confident that we have a better and operational alternative. Zoning, the benefit of which seems to lie primarily in ensuring reef health and resilience in the face of COTS outbreaks by protecting predators, should continue to play a role and effort should be exerted to enhance how reefs are selected and in expanding its application to reefs that play key connectivity roles. The failure to achieve WQI and the debate around its role as a driver of outbreaks (Pratchett et al. 2017) suggest that, while it is important for a range of other reasons (Brodie and Waterhouse 2012, Kroon et al. 2016, Waterhouse et al. 2017), WQI should not be relied upon for COTS management and the immediate protection of coral from COTS predation today (Westcott et al. 2020). That does not imply that it should not be part of a wholistic and integrated approach to COTS management (Pratchett and Cumming 2019), but rather that we be realistic about our confidence in its contribution and potential.

To ensure that the IPM COTS Control Program and its operating strategy continue to evolve and improve in achieving COTS control objectives moving forward, and based on our analyses to date across the breadth of the program (Fletcher et al. 2020, Westcott et al. 2020, Fletcher et al. 2021, Westcott et al. 2021a), we suggest the following as priority steps for moving forward:

- 1) **Maintaining a standing COTS control fleet through all outbreak phases with long-term and sustainable funding across outbreaks.** The key to managing the next outbreak will be to effectively manage COTS populations before they reach outbreak densities, and ideally by preventing an outbreak (Babcock et al. 2020). The failure to support COTS control through all phases of the outbreak cycle, including once densities fall, has had dire consequences in the current and past outbreaks and must

be avoided if we are to have any hope of success in managing COTS impacts (Lassig 1993, Pratchett et al. 2014, Westcott et al. 2021a). The scale of this task suggests that the current scale of investment should be maintained.

- 2) **Developing and implementing a COTS control specific monitoring program as an integral component of the IPM COTS Control Program.** Effective control requires a monitoring program that is designed to address its specific information needs at the places, times and resolutions relevant to COTS management (Westcott et al. 2021a). It must monitor COTS themselves, their abundance and population structure, how these are distributed within and across reefs and the GBR, and trends in these measures. Furthermore, monitoring must provide the necessary information on the distribution and value of the assets that we are protecting appropriately collected data on coral cover, coral community structure and more general reef health measures. The implementation of such a program is a priority and would be the primary role of the COTS fleet during any inter-outbreak period.
- 3) **The development of new monitoring technologies.** New monitoring technologies, in particular new Towed Underwater Vehicles to replace manta tows but also eDNA techniques, will be central to improving the scope and quality of monitoring, and will lead to vastly improved decision making in the IPM COTS Control Program going forward. Not only should these tools be designed to provide information about COTS dynamics across the GBR, but associated data on the distribution and value of the assets that are being protected. This is fundamental information for decision making in any control program. The development of these tools is a priority.
- 4) **COTS control should continue to operate under an ecologically informed and adaptive strategy.** The IPM Control Program strategy (Fletcher et al. 2020) currently provides such a framework, is effective in achieving its goals (this report) and should continue to be the foundation of COTS management on the GBR. This program is not perfect, however, and ongoing research to refine and improve its performance must be a focus of investment into the future.
- 5) **The prioritization process on which reefs are selected must also continue to evolve in response to program needs.** As the current outbreak winds down, prioritisation must increasingly switch its emphasis from controlling the current outbreak to establishing baselines and vigilance for the next outbreak. This is a complex task and will require significantly more complex analyses than are currently employed. Such analyses should be a focus of the design of a Monitoring Program for COTS control.
- 6) **COTS control will be a long-term investment and, consequently, alternative and improved control technologies must be sought.** This should include approaches that could contribute in the short term, e.g. strategic implementation of zoning to reflect patterns of connectivity, and in the longer term, e.g. new technologies such as the application of semio-chemicals and gene-editing (Hoj et al. 2020).

6.0 SUMMARY

Manual control of COTS on the GBR has long been perceived to be ineffective and expensive. While this perception may once have been reasonable based on the data available, it is now outdated and fails to reflect the documented performance and the potential of the IPM COTS Control Program.

The analyses in this report demonstrate that manual control has evolved to become a potent means of achieving COTS management objectives on the GBR. It is capable of suppressing COTS populations densities at the scale of sites, reefs and of hundreds of reefs, and, this suppression protects coral and facilitates its recovery (Westcott et al. 2020). Our analyses, and those of the companion report (Fletcher et al. 2021), show that the program currently has the potential to achieve ecologically meaningful outcomes at the GBR scale if support is maintained and resources continue to be deployed strategically. Our analyses show that the IPM COTS Control Program achieves its outcomes far more reliably and far more efficiently than its predecessors.

Our intention here is to not claim that the IPM COTS Control Program is the perfect tool; it has limitations and there are many opportunities for its improvement. Consequently, continued investment in analysing its performance, and using that information to improve both its efficacy in the field and its cost effectiveness overall, will be crucial to improving the performance and cost-effectiveness of the Program going forward. These improvements may well include the incorporation of new technologies into components of the existing Control Program, and subsequent refinement and modification to the Program to make the most of these innovations. The integration of new COTS Control Program specific monitoring technologies into control and the expansion of the Control Program's current monitoring activities will provide a vastly improved basis for decision making and is without doubt a high priority. Vitality, these refinements can be readily incorporated within the framework of the current IPM COTS Control Program, amplifying the performance of the program while guaranteeing the same ecological outcomes demonstrated in this report.

Overall, we conclude that the IPM COTS Control Program is a potent tool for achieving COTS control objectives on the GBR and has the potential to play a foundational role in our efforts to enhance reef condition and resilience into the coming decades. It can only do this with continued investment.

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