Tropical Water Quality Hub

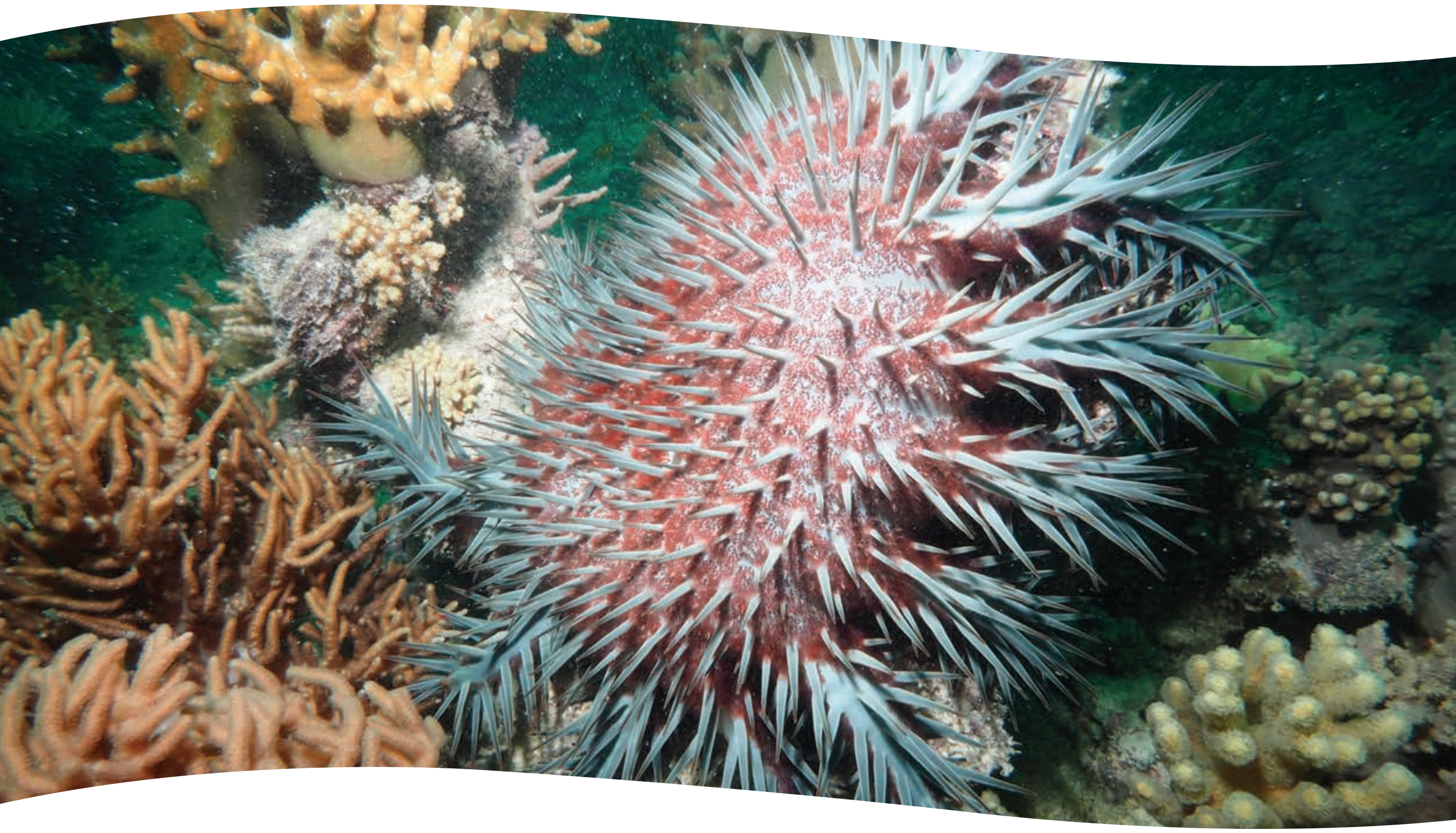
National Environmental Science Programme

Interim Report

Strategies for Surveillance and Control

Using Crown-of-Thorns Starfish management program data to optimally distribute management resources between surveillance and control

Cameron Fletcher and David Westcott



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Strategies for Surveillance and Control

Using Crown-of-Thorns Starfish management program data to optimally distribute management resources between surveillance and control

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Cover photographs: David Westcott

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ACRONYMS

AMPTO	Association of Marine Park Tourism Operators
CoTS	Crown-of-Thorns Starfish
CPUE	Catch per unit effort
DOE	Department of the Environment
GBR	Great Barrier Reef
NESP	National Environmental Science Programme
RRRC	Reef and Rainforest Research Centre Limited
TWQ	Tropical Water Quality

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EXECUTIVE SUMMARY

Crown-of-Thorns Starfish (CoTS) population outbreaks are one of the major threats to the Great Barrier Reef (GBR) and arguably are the threat that is most directly and immediately amenable to management action. It is therefore vitally important that CoTS control activities are conducted as efficiently and effectively as possible.

Surveillance and control activities can be considered at a range of scales. Surveillance, at least, can also have a range of functions, from large-scale surveillance to detect the emergence of pre-conditions for outbreaks, through to surveillance at regional and local scales to determine the current distribution of CoTS. In this report we concentrate on surveillance at the local scale of the sites and reefs visited during a single ten day control voyage, with the goal of identifying the distribution of CoTS and informing how control will be invested during that voyage. We focus on this scale because this is the scale on which current control programs are built - failure at the voyage scale will inevitably mean failure of the program overall.

Surveillance has the potential to improve the effectiveness of CoTS control activities by ensuring that CoTS are removed efficiently from areas of ecological or economic importance, or from areas which foster the growth and spread of the population. Ensuring that effort is optimally distributed will be fundamental to maximising the impact of control efforts and to achieving management goals. Surveillance, however, comes at a cost because its implementation diverts resources from physical control. Knowing the conditions under which the benefits of surveillance outweigh its costs will ensure the most efficient control strategy can be chosen and that effective CoTS control is achieved.

We used data from control voyages conducted by the Association of Marine Park Tourism Operators (AMPTO) during 2013 – 2015 to parameterise a model that compared the performance of surveillance-and-control and control-only management strategies. We found that a surveillance-and-control strategy was likely to outperform a control-only strategy under the conditions that AMPTO currently conducts control activities. When a typical crew of seven were available a surveillance-and-control strategy removed over 35% more CoTS than the equivalent control-only strategy. With greater numbers of control staff up to 57% more CoTS could be removed by a surveillance-and-control strategy. These results were insensitive to the accuracy and precision of surveillance.

In the medium term, as the model is refined with new management data incorporating surveillance-and-control strategies, the spatial scale and structure of control activities should be adapted using model outcomes. This may include increasing the spatial range of each voyage to ensure that the highest density CoTS aggregations are being controlled. This will require further collation of management data to identify ecologically or economically important reefs, the economic costs of control activities, and long-term surveillance obligations and benefits. In the short to medium term this will need to be underpinned by focussed data collection and analysis by scientists during management voyages.

Recommendations for management

1) Surveillance, in the form of manta-tows conducted using a high speed tender, should be implemented at the beginning of each voyage and at any time the vessel moves into a new area.

2) The information obtained through surveillance should be used to prioritise potential sites for control activities.
   a. Where the goal of the voyage is simply to remove the greatest number of CoTS then control activities should be focused on those locations where the greatest numbers of CoTS are reported during surveillance.
   b. Where the voyage includes key tourism sites these sites will be prioritised. Where dives additional to those required for the key tourism sites are available, then they can be prioritised according to the information derived from the surveillance.

3) At locations that exhibit a control CPUE of less than approximately 0.1 CoTS / minute bottom-time, control staff should reconsider their need to invest further control resources. To define this threshold in terms of a manta tow density requires further analysis of control program data in locations with both surveillance and control records. As a matter of urgency, therefore, the control program should commence recording manta-tow density at control polygons they intend to manage for comparison to the achieved control CPUE data at the same location.

4) The benefits derived from surveillance are insensitive to the quality of surveillance. Thus, where the goal is to efficiently distribute control effort during the current voyage, surveillance should be conducted using i) minimum team sizes (diver, observer and boat operator) and ii) only single tows across each site. In locations where surveillance must simultaneously fulfil other goals, such as comparison with long-term monitoring programs, it should be structured to maximise compatibility with those datasets.

5) Surveillance should not be restricted to just currently defined control polygons but where ever possible should include areas between polygons on the reef edge and through reef flats.

6) The keeping of good records of the surveillance conducted, as per AMPTO's surveillance protocols, is a priority that will allow the refinement and improvement of the program.

1.0 INTRODUCTION

The Great Barrier Reef (GBR) is widely acknowledged to be facing a range of significant threats to its ecological health and function, including coral bleaching, damage due to environmental factors such as cyclones, and Crown-of-Thorns starfish (CoTS). The various threats interact to increase the overall stress on the reef, and each has been projected to worsen in future. CoTS, and especially their propensity for outbreaks, are a significant stressor of coral health both in isolation and combination with other factors (De'ath *et al.* 2012; Baird *et al.* 2013; Brodie *et al.* 2013; Pratchett *et al.* 2014). Vitally, however, they are also the only one of the major threats that is directly and immediately controllable by managers at the scale of the GBR and individual reefs themselves (De'ath *et al.* 2012; Rivera-Posada *et al.* 2012; Baird *et al.* 2013).

As a result, significant resources have been invested in attempting to reduce CoTS populations across the GBR and at specific locations of economic or ecological importance (Rivera-Posada and Prattchet 2012; Westcott *et al.* 2016). Despite recommendations for a variety of control methods (Rivera-Posada and Prattchet 2012; Westcott *et al.* 2016, Appendix 2), the primary approach used in practice remains physical control of individual CoTS by divers on the reef (Rivera-Posada and Prattchet 2012; Firth and McKenzie 2015; Westcott *et al.* 2016). The very labour-intense nature of CoTS control means that available control funding must be invested in the most efficient manner possible if management goals are to be achieved (Rivera-Posada and Prattchet 2012; Westcott *et al.* 2016). In the short-term efficient control requires that CoTS removal divers are directed to the locations that will most effectively constrain the size and impact of the CoTS population, and that in those locations they remove the greatest number of CoTS with the resources available.

One key component of CoTS management on the GBR is the control program implemented by the Association of Marine Park Tourism Operators (AMPTO) (Firth and McKenzie 2015). AMPTO has operated two vessels (Venus II and Hero) in the program to control CoTS in the economically important tourism reefs between Cairns and Lizard Island in the Cairns Section of the GBR (Firth and McKenzie 2015). Over the period from 2013 – 2015, each boat typically ran 25 ten day voyages a year (Figure 1, lines). The Voyage Plan, including Target Area and other details, is determined in conjunction with managing agencies including the Great Barrier Reef Marine Park Authority (GBRMPA) and the Reef and Rainforest Research Centre (RRRC).

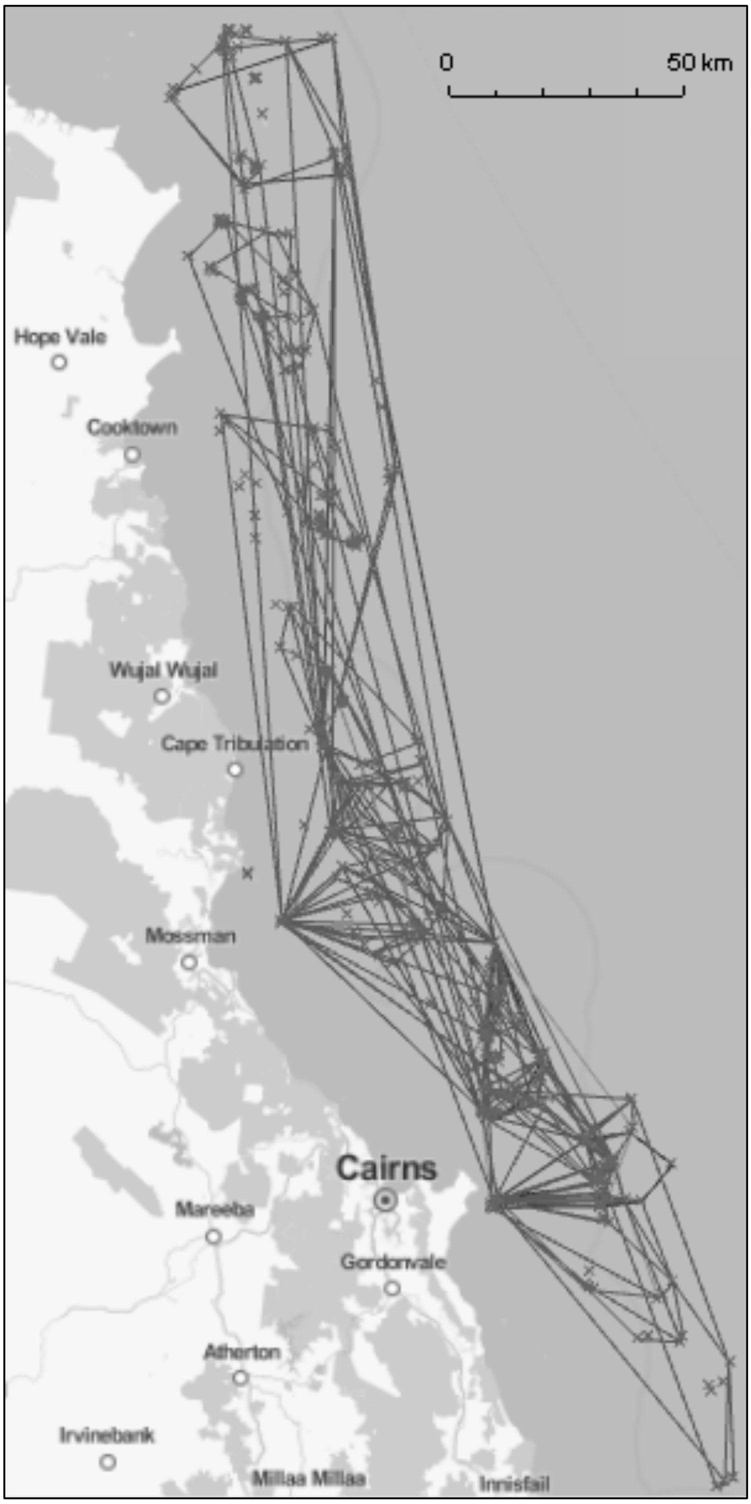

Figure 1: Map of the study region with the centroid of control polygon sites (crosses) and convex hulls of individual voyage (lines) marked.

Each voyage consists of up to 36 control dives (two dives each the first and last days, 4 dives each intervening day) by a control crew typically consisting of 4 - 12 divers. Each control dive occurs within a pre-mapped control polygon of varying size and shape, but a typical example might be approximately 1000 m long by 150 m wide. Polygons are scaled to be covered by eight divers over two control dives (Figure 1, centroids marked as crosses). The location of the pre-mapped polygons are based on data from tourism operators, surveys conducted by Marine Parks staff, and scouting trips conducted by crew on board the AMPTO vessels.

Each dive employs all available control staff and typically lasts 40 minutes. Divers may be split into groups to coordinate coverage of the control polygon, dependent on the total number of staff available. Divers search their designated area looking for CoTS or the white scarring on the coral surface indicative of recent CoTS feeding. When fresh scarring is discovered, the responsible CoTS can generally be located within 1 m^2 (Firth and McKenzie 2015). CoTS are injected with a bile salt solution from a 50 cm long spear-mounted needle, after which they die over a period of hours and dissolve over a period of days (Rivera-Posada *et al.* 2011; Firth and McKenzie 2015). If divers locate a dense aggregation of CoTS as they move though their designated region of the polygon, they typically concentrate their effort there to fish it down, before attempting to cover the remaining polygon. Several control dives can take place at each polygon, and if high densities of CoTS are controlled there, the polygon can be revisited again several days later during the same voyage when the effects of prior control can be visibly discerned (Firth and McKenzie 2015).

In the second half of 2015, the availability of a new tender (Audamus) that could be towed behind the control vessel (Venus II) introduced the possibility of incorporating an explicit surveillance component in the control activities (Gempearl Pty. Ltd. (private comm.) 2015). In preliminary surveillance efforts at the end of 2015, AMPTO deployed the Audamus towards the conclusion of each control voyage to provide surveillance that could inform long term strategies "outside the control sites" and provide baseline fine scale data within control polygons (Firth *et al.* 2015). In the short and medium term, such data is likely to be an important factor in improving our understanding of CoTS populations and ecology across the region, as well as to validate the efficacy of the current control program. In addition, however, the availability of this new tender provides a perfect mechanism for implementing manta tow surveillance of control sites at the beginning of voyages to structure control activities within that voyage. Within areas prioritised for control because of their ecological or economic importance, this has the potential to increase the effectiveness of the current control program, by ensuring that control resources are directed to the locations within each voyage where the greatest impact can be realized.

Here we report on an analysis that seeks to identify the most efficient strategy for the deployment of the surveillance tender to help structure control actions at the scale of individual voyages. The analysis represents a first attempt to improve the efficiency of management using surveillance and the data already collected during AMPTO control programs from 2013 – 2015. This data allows us to assess the efficiency of such surveillance-and-control and control-only programs based on the maximum number of CoTS removed during each voyage. Factors other than total number of CoTS removed, such as the importance of the locations they are removed from in terms of driving and spreading the population, will also be important to the long-term success of the control program. These factors are being considered as part of the next phase of this study.

2.0 METHODOLOGY

2.1 Model structure

The model measures the relative performance of two voyage-scale CoTS management strategies: 1) a control-only strategy where all divers are used to remove CoTS from a "pre-voyage determined" subset of the control polygons within the voyage area; and 2) a surveillance-and-control strategy where some of the divers are diverted from control to surveil the polygons within the voyage area at the beginning of the voyage, and the remaining divers are used to control the polygons found to have the highest densities of CoTS. If a surveillance-and-control strategy allows voyage managers to focus control efforts on polygons with high densities of CoTS then it's possible they will remove more CoTS than an equivalent control-only strategy despite having fewer divers in the water removing CoTS at the beginning of the voyage. The goal of our model is to elucidate the conditions under which this scenario is likely and the scale of the benefit of a surveillance-and-control strategy under these conditions.

The management process is modelled as a simplified system, based on real data collected by the AMPTO control program 2013 - 2015. Each model run describes a ten day "voyage (V)" encompassing a total number of “voyage dives (VD)” in a region containing a number of “voyage polygons (VP)”. Some fraction of these are chosen to become “controlled polygons (CP)” that are visited during a number of “control dives (CD)”, respectively. Within each voyage, we draw from appropriate statistical distributions (illustrated in Figure 2 below):

1. A total number of voyage polygons within the voyage region (N_{VP}) (Figure 2 a)
2. A list of average Catches Per Unit Effort (CPUEs) for each of the polygons within the voyage region ($CPUE_V = (CPUE_{V_1}, CPUE_{V_2}, \dots, CPUE_{V_{N_{VP}}})$) (Figure 2 b)
3. The number of dives undertaken during the voyage (N_{VD}) (Figure 2 c)
4. The number of polygons controlled during the voyage ($N_{CP} < N_{VP}$) (Figure 2 d)
5. The subset of polygons within the voyage region ($CPUE_V$) that are selected for control, listed by their CPUE, ($CPUE_C = (CPUE_{C_1}, CPUE_{C_2}, \dots, CPUE_{C_{N_{CP}}})$), where:
    a. the $CPUE_{C_i} \in CPUE_V$ are selected from the $CPUE_V$ randomly in the case of the control-only strategy, or
    b. based on the estimated maximum CPUEs in the list in the case of a surveillance-and-control strategy. The estimate of the CPUEs can either be exact, or with accuracy and precision given by the distributions in Figure 2 f).
6. The number of control dives that occur in each of these polygons, based on each polygon’s CPUE ($N_{CD}(CPUE)$, Figure 2 e)

The total number of CoTS collected over the voyage ($CoTS_{Voyage}$) by management actions is then calculated as:

$$CoTS_{Voyage} = \sum_{j=1}^{N_{CP}} CPUE_{C_j} \times N_{CD}(CPUE) \times \overline{N_{CS}} \tag{1}$$

where the mean number of control staff ($\overline{N_{CS}}$) available from the total dive staff (N_{DS}) is:

$$\overline{N_{CS}} = \begin{cases} N_{DS} & , control\ only \\ N_{DS} - N_{SS}\dfrac{N_{VP}/2}{N_{VD}} & , surveillance\ and\ control \end{cases} \tag{2}$$

where $N_{SS} = 3$ is the number of surveillance staff, and it is assumed two control polygons can be surveiled in the same amount of time as a single control dive. The number of times each controlled polygon is revisited is weighted by its CPUE relative to the other CPUEs of the controlled polygons during the trip, using the observed weighting in control program data (Figure 2 e):

$$N_{CD}(CPUE) = \frac{0.071 + 0.034 \times CPUE}{\sum_{j=1}^{N_{CP}} 0.071 + 0.034 \times CPUE_{C\,j}} N_{VD} \tag{3}$$

In general, the surveillance-and-control strategy will achieve a list of CPUEs ($CPUE_C$) totalling a greater amount than the equivalent control-only strategy, but will have a lower mean number of control staff ($\overline{N_{CS}}$). It is this trade-off that determines the situations in which a surveillance-and-control strategy is likely to outperform control-only strategy, or vice-versa.

2.2 Calculating statistical distributions from AMPTO data 2013 – 2015

2.2.1 Total number of polygons within voyage region

For each of the 38 voyages of Venus II and 52 voyages of Hero from 2013 - 2015 for which data were analysable, the relative positions of the control polygons visited were combined to create a minimum convex hull of the "voyage region". The number of the defined control polygons that completely or partially fell within this convex hull was counted to determine the average number of polygons within each voyage region. The distribution for each vessel individually and both vessels combined were well fit by similar gamma distributions. The combined dataset was best fit by a gamma distribution with shape parameter 7.15 and scale parameter 3.18 (Figure 2 a).

2.2.2 Average CPUE for each control polygon

The average CPUE for each control polygon was calculated from all the observed CPUEs contained during "dive" activities in the Venus II and Hero 2013 - 2015 data. The data for each vessel and the combined data were all approximately fit by an exponential distribution, with a half-width of 7.4 in the case of the combined dataset (Figure 2 b). This exponential, however, significantly underestimated the proportion of high CPUEs in the tail of the distribution. Therefore, the model runs drew CPUEs from the observed data itself.

2.2.3 Number of control dives undertaken each trip

Although voyages can involve up to 36 separate control dives, external factors such as weather or other activities can reduce the number of control dives available per voyage. This puts an upper bound on the number of control dives likely to occur during a voyage, which were well described by a reversed gamma distribution for both the individual vessel datasets and the combined overall dataset. The combined dataset was best fit by a reversed gamma distribution of shape parameter 13.4, scale parameter 0.87 and offset 43.5 (Figure 2 c).

2.2.4 Number of control polygons visited each trip

Although voyages involve a large number of control dives, many control polygons are revisited more than once in a voyage. This means that the number of polygons visited each trip is significantly lower than the number of control dives. The number of polygons visited each trip from the combined dataset was well fit by a normal distribution with mean 13.05, and half-width of 3.23 (Figure 2 d). The data from each individual vessel exhibited statistically similar responses.

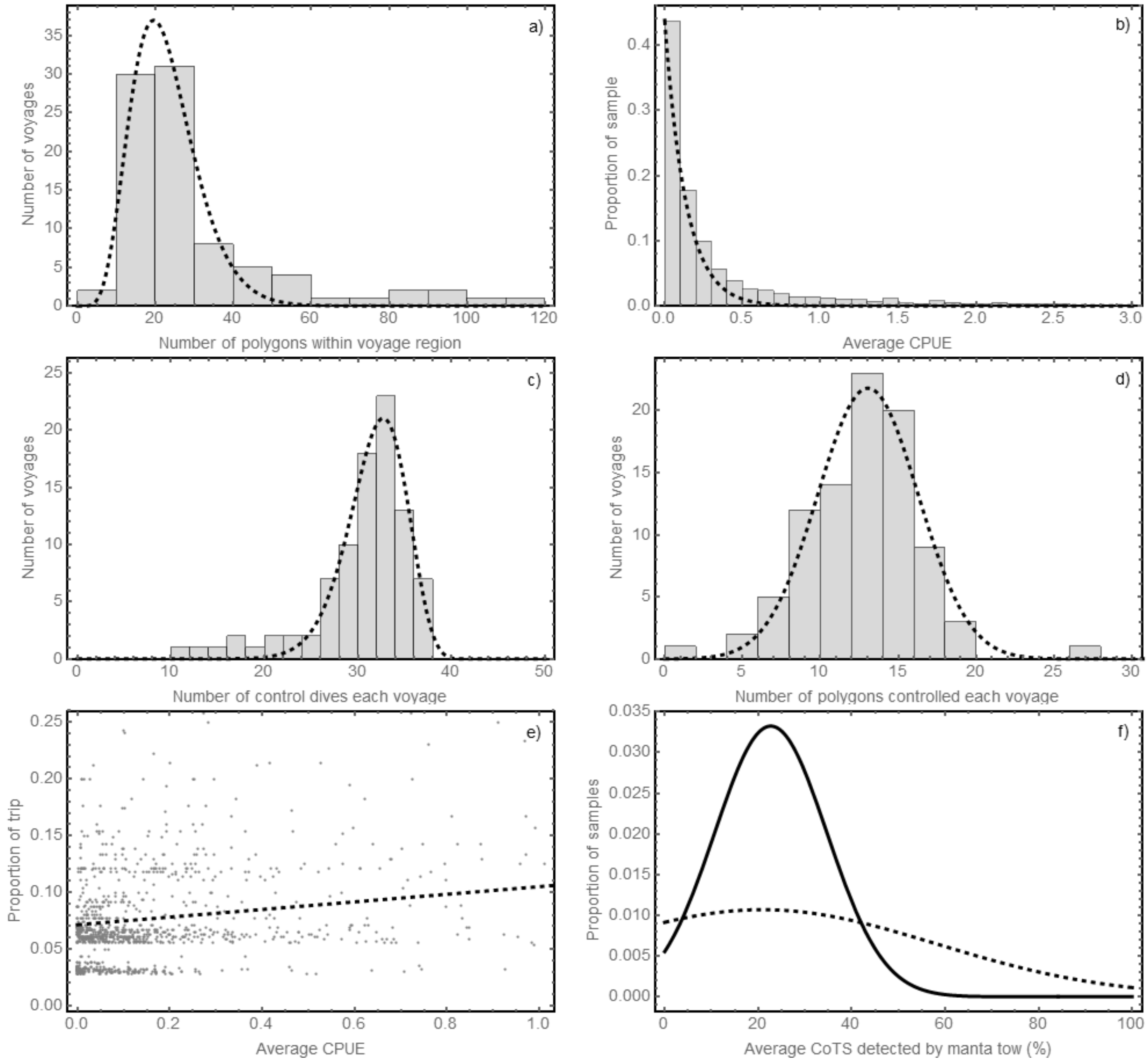

Figure 2: Distribution of control program data (histogram bars) and modelled fits (dashed lines), including: a) number of polygons within each voyage region; b) average CPUE for all control polygons; c) number of control dives each voyage; d) number of polygons controlled each voyage; e) the proportion of each voyage spent at each polygon as a function of its CPUE; and f) the detectability of CoTS during Manta tows reported in the literature.

2.2.5 Proportion of the time each polygon is visited

The number of times each control polygon is revisited on a given voyage is correlated with its CPUE, with sites exhibiting higher CPUE revisited more often. The data exhibited noticeable variation, but the proportion of visits to each polygon during a voyage was, on average, weighted as w = 0.071 + 0.034 x CPUE (Figure 2 e) for the combined dataset, with statistically similar relationships with the data for each vessel.

2.2.6 Detectability of CoTS using manta tow

The AMPTO dataset does not yet contain a sufficient quantity of correlated data to estimate the statistical relationship between manta tow CPUEs during surveillance and realized CPUEs during control. Fernandes et al. (1990) measured the detectability of CoTS in different habitats comparing manta tow data to detailed surveys by SCUBA divers. They estimated that manta tows located 22.7% of CoTS present, on average, with a standard deviation in their detection of 12.0% (Figure 2 f, solid line). De'ath (1992) mentions a count rate with a similar average of 20.9%, but a much higher standard deviation of 37.3% (Figure 2 f, dashed line). In terms of estimating the relative abundance of CoTS to structure management decisions, it is the precision, represented by the standard deviation of detectability, which has the largest impact on reliably discriminating sites exhibiting high densities from average sites. In addition to the detectability with standard deviation of 37.3% (De’ath) and 12.0% (Fernandes), we also analysed results for perfect detectability of 0% standard deviation.

2.3 Analysis

The basic parameters of the model such as CPUE per voyage and total number of CoTS removed per voyage were calculated for each scenario for comparison with the dataset.

2.3.1 Number of CoTS removed for surveillance-and-control and control-only strategies

Each run of the model drew: 1) the number of polygons within the voyage region; 2) the CPUE for each of these polygons; 3) the number of control dives completed during the voyage; 4) the number of polygons visited during control activities; 5) the number of visits to each of the controlled polygons; and 6) the proportion of CPUE detected by surveillance at each polygon, from the distributions described above and illustrated in Figure 2. The “total number of dive staff” was taken as a key model variable, with a minimum of five staff, because three staff are required for surveillance and at least two are required for control dives. For the parameters and variables so specified the total number of CoTS removed by surveillance-and-control and control-only strategies was calculated using Equation 1, where the polygons estimated by surveillance as having the highest CPUE were selected for the surveillance-and-control strategy, and the appropriate number of randomly selected polygons were selected for the control-only strategy. The total number of CoTS removed for each strategy, and the difference between them, was recorded.

Detailed results from ten repetitions of the above process were plotted using Fernandes *et al.* (1990)’s estimate of CoTS detectability during manta tow, to illustrate the mean and range of model outcomes, and a linear fit of the number of CoTS controlled vs total control staff was estimated. The difference between the number of CoTS removed by the surveillance-and-control and control-only strategies for each corresponding model run was also plotted, and a linear fit estimated.

2.3.2 Relative performance of surveillance-and-control and control-only strategies

To calculate the average performance of surveillance-and-control and control-only strategies, the model was run 1000 times at each parameter combination and the mean and standard error of the total number of CoTS removed calculated. The results were plotted and linear fits were estimated. The slope of the fitted line represents the efficiency of CoTS removal per staff member (proportional to CPUE), and the intersection of the surveillance-and-control strategy with the negative vertical axis represents the fixed cost associated with running the surveillance program. Results were calculated for estimates of CoTS detectability during manta tow from Fernandes *et al.* (1990) and De'ath (1992), as well as for "perfect" detectability. In addition, results were calculated using one and two sessions of surveillance for each polygon managed during the voyage, to identify whether additional surveillance that improved the certainty of CoTS density estimates would increase the number of CoTS removed.

2.3.3 The benefits of surveillance in terms of increased overall catch

The benefit of surveillance in terms of the percentage increase in overall catch was calculated for conditions in which surveillance-and-control was expected to outperform a control-only strategy. For each model instance drawn from the randomized distributions above, the total catch for both surveillance-and-control and control-only strategies were calculated. The proportional difference between the two was calculated for each case. The relationship between the total number of dive staff and the proportional extra CoTS removed by a surveillance-and-control strategy was fit to an asymptotic Type II functional response.

3.0 RESULTS

The model performed as expected, estimating an average CPUE per voyage of 0.42 (S.D.: 0.26), compared to the dataset average of 0.37 (S.D.: 0.43). The average inferred number of crew per voyage across the dataset was 6.45 (S.D.: 1.74). Averaging the total catch per voyage with six and seven staff per voyage estimated a total catch per voyage of 3169 (S.D.: 1893), compared to the dataset average of 2973 (S.D.: 4001).

3.1 Number of CoTS removed for surveillance-and-control and control-only strategies

On any given run of the model, the number of total dive staff affected the average performance of both surveillance-and-control and control-only strategies directly and proportionally, as expected (Figure 3 a, dashed and dotted lines, respectively). Figure 3 shows the outcome for 110 runs of the model for each of the surveillance-and-control (filled circles) and control-only (empty squares) scenarios. In each case the model was run across total crew sizes from 5 - 12, when three crew members are diverted from control to one session of surveillance per polygon visited. The variability from run to run was significant for both surveillance-and-control and control-only (Figure 3 a, filled circles and empty squares, respectively).

On any given run, this variability could mean that a surveillance-and-control strategy outperformed control-only strategy, or vice versa (Figure 3 b, crosses). However, on average a surveillance-and-control strategy removed more CoTS than a control-only strategy for any total number of crew, even starting at the minimum possible crew of five (Figure 3 b, solid line). In addition, when the total crew was five or greater, surveillance-and-control outperformed control-only the great bulk of the time (>70%, distribution of crosses around the axis, Figure 3 b)).

3.2 Relative performance of surveillance-and-control and control-only strategies

A surveillance-and-control strategy outperformed a control-only strategy for the minimum modelled total crew size of five staff, independent of which data set was used (Venus II,

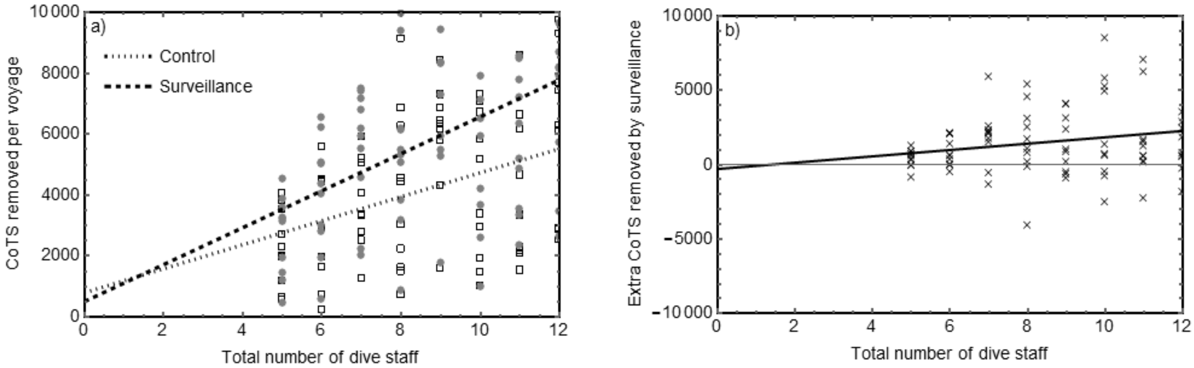

Figure 3: Relative performance of surveillance-and-control on individual model runs

Hero, or the combined data set), and independent of the precision or accuracy of the surveillance. Figure 4 shows six plots, three (a, c and e) for a single surveillance session, and three (b, d and f) for repeated surveillance sessions to improve the accuracy of population estimates. A surveillance-and-control strategy clearly outperforms a control-only strategy for all configurations when a single session of surveillance is used per polygon in the voyage area. When two surveillance sessions are used in an attempt to improve the population estimates at each site, more resources are redirected from control to surveillance. Overall, the benefit of improved knowledge of CoTS densities does not outweigh the increased cost of surveillance, leading to fewer overall CoTS removed using a surveillance-and-control strategy with two surveillance sessions (Figure 4 b) than a single surveillance session (Figure 4 a).

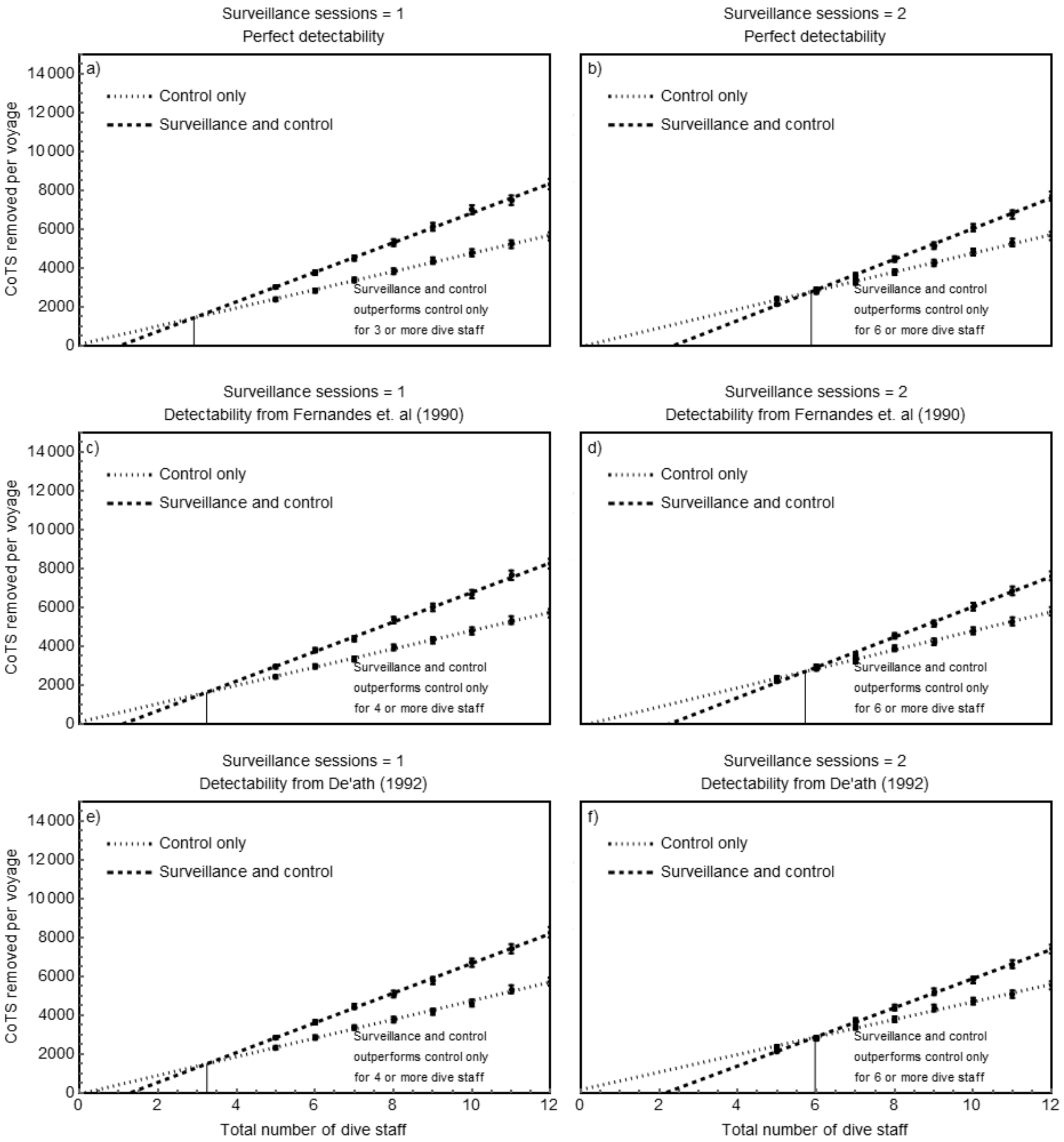

Figure 4: Relative performance of surveillance-and-control and control-only strategies

The average efficiency per staff member (in terms of CPUE) was represented by the slope of the lines in Figure 4. The benefits of surveillance in terms of locating higher CPUE control polygons on which to focus control activities are clear in the steeper slopes shown in Figure 4 a) - d). The extra cost of surveillance was indicated by the negative y-axis intercept of the surveillance-and-control fitted line (not visible).

Figures a) and b) show performance when surveillance perfectly detects all CoTS in each polygon, while figures c) and d), and figures e) and f) show performance when detectability is more realistically imperfect, as measured and reported by Fernandes et al. (1990) and De'ath (1992), respectively. Imperfect detectability had an imperceptibly small impact on performance.

3.3 The benefits of surveillance and control

Surveillance-and-control outperformed control-only with the potential benefit in terms of increased CoTS removed being as high as 44.9% for commonly reported crew sizes (Figure 5). The level of the benefit, however, depends on both the total number of control staff available and the number of surveillance sessions used at each site. For a typical total crew of seven staff members where three are diverted to surveillance, a surveillance-and-control strategy is likely to remove roughly 34.4% more CoTS than a control-only strategy.

The benefit asymptotes for very large total crew numbers, and is well-fit by a Type II functional response (Figure 5 b, dashed, dotted, dash-dotted and solid lines). The asymptote was roughly 61.7% greater CoTS removed with a surveillance-and-control strategy than with a control-only strategy. As an indication of how this theoretical upper limit might be approached in practice, a maximum crew size of 24, double that observed in AMPTO records, could control 53.8% more CoTS using a surveillance-and-control strategy and control-only. The asymptote was independent of the number of sessions of surveillance used, although the total number of staff at which the observed performance approached the asymptote did depend on the number of surveillance sessions.

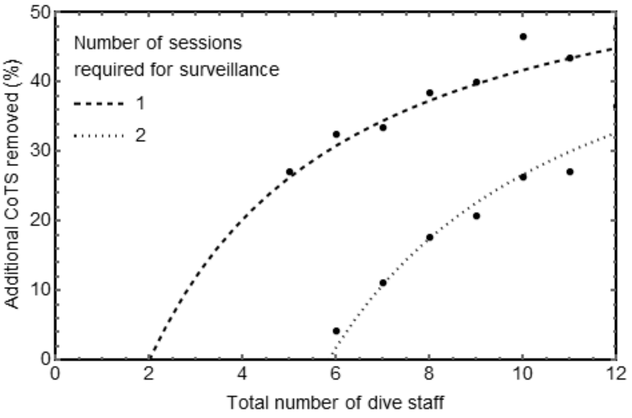

Figure 5: The proportional benefit realised by a surveillance-and-control strategy over and above a control-only strategy

4.0 DISCUSSION

These results provide simple but important insights into how and when a Crown-of-Thorns starfish surveillance-and-control program is likely to outperform a control-only program with the same total number of dive staff. Most importantly, surveillance-and-control is likely to be the optimal strategy at both the typical and the lowest total crew sizes currently employed in the AMPTO control program. For average crew sizes of 6 – 7 staff, surveillance-and-control may improve the number of CoTS removed by more than 33% over a control-only strategy (Figure 5). For large crew sizes (i.e. 12 staff), over 45% more CoTS may be removed, and for crews even larger than those currently employed (i.e. 24 staff) over 55% more CoTS may be removed. Importantly, it is not necessary to achieve high accuracy or precision during surveillance to realise these benefits.

Within the bounds of the problem considered in this study, the performance of a surveillance-and-control strategy relative to a control-only strategy is a simple trade-off: by diverting some divers to surveillance during a voyage, control areas with higher number of CoTS can be found and focused on, generating higher average CPUEs; but at the same time, the staff diverted to surveillance leave fewer staff in the water to remove those CoTS. Whether surveillance-and-control outperforms control-only in practice depends on the total number of control staff and the statistical distributions of CoTS, control staff, and control effort around the study voyage region. Despite the complicated details of the model, however, the simple outcome of the analysis is straightforward: employing even cursory surveillance at the beginning of voyages to choose which control polygons to focus on during the trip is likely to increase the number of CoTS removed.

4.1 A simple explanation

There is a simple explanation for this. Figure 2 b) shows the distribution of control polygon CPUEs across the entire data set. It is apparent that the great bulk of control polygons generate a low or zero CPUE. The "average" voyage from the dataset encompasses a region with 32.6 (S.D 28.2) control polygons, of which 12.4 (S.D. 4.1) are actually controlled on any one trip, over 29.6 (S.D. 6.1) separate control dives. To analyse this “average” voyage, we could draw CPUEs for 33 control polygons, at random, from the distribution in Figure 2 b). If our management strategy let us choose from this sample the twelve highest CPUE polygons, for instance by using surveillance to estimate and rank the CPUE of each polygon, then 59.8% (S.D. 11.6%) of the total CoTS removed during the voyage would come from the three control polygons with the highest CPUEs (i.e. ranked 1 - 3) in the voyage region. In contrast, only 9.9% (S.D. 6.4%) of those removed would come from the three polygons chosen for control with the lowest CPUEs (i.e. ranked 10 – 12). This highlights the absolute importance of identifying those few control polygons with the highest CPUEs within the voyage region - if even one is missed the total number of CoTS removed during the voyage will likely fall significantly.

On the other hand, the very fact that these few polygons have such pronouncedly higher CPUEs than the "average" polygon should make them easy to locate with even imperfect surveillance. The three control polygons with the highest CPUEs in the voyage region have, on average, a CPUE exceeding 1.5 (S.D. 0.41), whereas the three polygons ranked 10 - 12 have, on average, a CPUE exceeding only 0.23 (S.D. 0.04). Even highly imprecise surveillance should be able to distinguish polygons with CPUEs of 0.23 from those with CPUEs of 1.5. The most conservative estimates of the precision of manta tow surveys from the literature estimate an accuracy (mean) and precision (S.D) of 20.9% (S.D. 37.3%) for manta tow surveys (De'ath 1992), and at this level surveillance should clearly delineate high CPUE polygons from low and average CPUE polygons.

4.2 Stopping rules

A similar logical argument can be used to delineate control polygons at which control actions should not be taken. These “stopping rules” can be defined as threshold levels of surveillance manta tow densities below which no control dives should be conducted at a given control polygon. On the “average” voyage, in addition to the 12 polygons within the voyage area that are visited for control actions, there are approximately 20 polygons that are not visited. The simplest stopping rule might be that managers should not implement control at polygons with estimated control CPUEs of less than, say, the average CPUE of the three polygons chosen for control with the lowest CPUEs (i.e. ranked 10 - 12), as noted above. Although it may be difficult for managers to discern the relatively small 0.03 difference in CPUE between polygons ranked 12 and 13 with imprecise surveillance, it should still be relatively easy to identify the 0.16 difference in CPUE between the twelfth highest ranked polygon and the ten lowest ranked polygons in the voyage area (average CPUE 0.05), and decide not to manage them. A practical threshold for this stopping rule might therefore be set at a control CPUE of 0.1, below which control actions should not be carried out at a site if the goal is to remove the greatest number of CoTS during a voyage.

This threshold is designed to maximise the number of CoTS removed during control activities, but it is comparable to the target CPUEs currently implemented in the control program to maintain coral health. When coral cover is >40%, the current control program aims to keep the control CPUE below 0.1, and when is approaching 20%, the program aims to keep the control CPUE below 0.05 to provide the potential for coral to recover (Babcock *et al.* 2014). Recent detailed population modelling has suggested slightly lower control CPUEs of 0.06 CoTS/minute and 0.04 CoTS/ minute may be necessary to maintain coral cover at high (40%) and moderate (20%) levels, respectively (Babcock *et al.* 2014). Ongoing studies will investigate the relative costs and benefits of achieving these more conservative ecologically-informed coral maintenance CPUE targets in terms of overall control program efficiency (NESP Project 2.1.1 Integrated Pest Management of Crown-of-Thorns Starfish)

Implementing this CPUE based stopping rule as part of surveillance requires further interpretation. Most importantly, this CPUE threshold is based on the number of individuals removed during control activities. Surveillance activities instead report a manta tow density rather than a control CPUE. To identify a surveillance threshold manta tow density below which managers should not implement control activities at a given control polygon would require a conversion between surveillance manta tow density and control CPUEs. Some estimates exist in the literature (Ayling and Ayling 1991; Moran and De'ath 1992; Babcock *et al.* 2014), but both the densities reported by manta tows and the CPUEs achieved by control programs are very sensitive to how each process is implemented. As a result, converting

CPUEs in this way is a notoriously difficult problem (Firth and McKenzie 2015), and not possible with the historical AMPTO data set used in this analysis. However, the control program itself should provide the means of achieving this conversion in the near future as it compiles a large dataset of collocated surveillance manta tow densities and control CPUEs for comparison. Future analyses will use this data to redefine this stopping rule in terms of surveillance manta tow densities.

4.3 Strengths and weaknesses of the model

The model is built around the actual statistics achieved by the CoTS program from 2013 - 2015 in a simple but statistically appropriate manner. For instance, it is notoriously difficult to compare CPUEs between different reefs, or precisely relate observed CPUE to the total number of CoTS on a single reef, because CPUE is known to vary with sampling technique and reef structure as well as CoTS density (Firth and McKenzie 2015). However, because our model simply employs the observed distribution of CPUEs recorded during control activities in the same manner in which they were recorded, it sidesteps the statistical difficulties associated with comparing CPUEs between reefs, or relating observed CPUEs to the actual number of CoTS present on the reef.

At the same time, the simplicity of the model means simple assumptions are made, and it is worth considering how these constrain the generality of our results, and extrapolation beyond the cases explicitly modelled. Most importantly, perhaps, the model maximises the number of CoTS removed during a voyage to a given area, but it does not model population processes, nor the ecological or economic importance of the individual reefs being managed. It is possible that the reefs with the highest CPUE within a voyage region are not the reefs that would most effectively control the CoTS population in the way desired, for instance, due to population processes such as immigration or emigration, or due to management goals at specific locations. These questions were outside the scope of this preliminary analysis of the CoTS management system, but are the focus of ongoing research (NESP Project 2.11 Integrated Pest Management of Crown-of-Thorns Starfish). Despite this, the results from the current analysis are important, because all current management techniques depend on manual removal as the implementation phase of larger management strategies (Westcott *et al.* 2016). Specific regions prioritised for control by management priorities or their importance to the growth and spread of the CoTS population will still require removal of the greatest number of CoTS in the most efficient manner (Westcott *et al.* 2016). Current and future work aimed at identifying and improving our understanding of regions of the reef important to the initiation of CoTS outbreaks, or the super-spread of outbreaks southward along the reef, will require individual vessels and divers to visit those areas and remove CoTS in the most effective manner (Westcott *et al.* 2016). The model presented here provides one method of optimising the efficiency and ultimately the effectiveness of these individual manual removal voyages.

The current analysis employs statistical distributions of the modelled parameters from past control voyages, implicitly assuming that, other than employing surveillance, future voyages will be structured similarly to past voyages. In the short term, this is likely a valid assumption, but it probably underestimates the scale of benefits achievable if the intelligence gained from surveillance is used to restructure the scale and scope of voyages themselves. It seems likely, for instance, that within the current simple model, operating voyages at larger spatial scales would lead to even greater numbers of CoTS removed, because more very high CPUE control sites could be located on each voyage, at the relatively meagre cost of not being able to control quite as many low or average CPUE polygons. However, because the current model is based on actual past voyages, care would need to be taken extrapolating parameter distributions to larger regions. For instance, if current voyage regions have been selected because they tend to be separated by areas unlikely to support CoTS, expanding them slightly may provide no appreciable improvement at all. To be able to draw well informed conclusions of this sort, the model would also have to be extended to incorporate factors including increased fuel and transport costs.

Just as extending the voyage area would be expected to result in greater increases in CPUE, extending the area eligible for control within a voyage area might also be expected to result in increases in CPUE. In this case any benefit would accrue without the costs associated with travel. In this interim model, control and surveillance is considered within currently identified control polygons only. These polygons rarely cover entire reefs or reef complexes and the scope of the surveillance and control activities could be extended simply by including areas outside currently defined polygons. The benefit derived from doing this would be dependent on the spatial variation in the density of CoTS at the reef, and, field surveys suggest the benefit could be large. Of 118 reefs surveyed between 2012 and 2015 (GBRMPA 2015) the coefficient of variation in the mean number of CoTS reported from manta-tow surveys at different sites on a reef was 246% (S.D. 279). For CoTS feeding scars the CV was 279% (S.D. 169). This indicates very high variation in the density of CoTS at different locations on individual reefs with as many as 68 and as few as 0 CoTS reported from tows at the same reef and conducted on the same day.

At the same time the simple model does not consider all the benefits a surveillance program can generate beyond focussing control efforts during the current voyage. Surveillance is likely to underpin control strategies at larger spatial and temporal scales, such as inter-voyage planning, and regional control of CoTS populations. Surveillance will also underpin improved understanding of how effectively our control programs are operating and improve our ecological understanding of the system to allow us to design more efficient and effective management programs in future. All of these factors are likely to increase the importance of a well-designed surveillance component to future CoTS control programs. The current model does not consider "prospective" surveillance outside the voyage region or previous control polygons to help structure future management activities.

In addition to these larger-scale considerations, the current model considers one mode or "intensity" of surveillance, based on the preliminary surveillance protocol proposed by AMPTO. In the model, this is simply characterised as fifteen two-minute manta tows per two control polygons, which with travel time and other overheads is assumed to take the same amount of time as one 40 minute control dive. The extreme insensitivity of the model to the accuracy of surveillance suggests that, for the purposes of structuring control activities, at least, these assumptions may be unnecessarily conservative. Those sites within the voyage area exhibiting high CPUEs are so much higher than the other sites that it's possible that even cursory surveillance may be sufficient to discriminate them effectively. This would reduce the costs of implementing surveillance in the simple model and significantly increase the benefits.

Despite these various considerations, however, the underlying results from the model are qualitatively sound: surveillance-and-control is likely to outperform control-only strategies by removing more CoTS at the staffing levels currently being used in the AMPTO CoTS program, and those affects become more pronounced the more dive staff are available on a voyage.

4.4 Management recommendations

What do these results mean for how CoTS management should be conducted? Our results point to a number of changes that will improve the efficiency of the program's current operations.

First, we recommend that surveillance, in the form of manta tows conducted using high-speed tenders such as Audamus, should be implemented at the beginning of each voyage and at any time the vessel moves into a new area. Where the goal is to efficiently distribute control effort during the current voyage, manta-tows for surveillance should be conducted as quickly and efficiently as possible, within the constraints of the protocols developed by AMPTO for this purpose (Gempearl Pty. Ltd. (private comm.) 2015). Where surveillance must simultaneously fulfil other goals, such as comparison with long-term monitoring programs, it should be structured to maximise compatibility with those datasets.

Second, the information obtained through this surveillance should be used to structure the sites visited throughout the voyage. Exactly how this is done will be determined by the goal of the voyage.

a) Where the goal of the voyage is simply to remove the greatest number of CoTS then control activities should be focused on those locations where the greatest numbers of CoTS are reported during surveillance. This will be an appropriate strategy in a range of circumstances, particularly when the rapid reduction of CoTS densities is required, e.g. to reduce the likelihood of dense spawning aggregations forming as part of larger program objectives.
b) Where the voyage includes key tourism sites a key objective will include protection of those sites. In the future it is hoped to also include key ecological sites, i.e. sites whose connectivity means that they are important nodes for receiving or producing CoTS or coral larvae and therefore sites whose protection has significant consequences for the health of downstream reefs. When key economic or ecological sites are present in the voyage area a decision must be made about the urgency of visiting those sites relative to other sites within the voyage area. In the short term, where dives additional to those required for the key tourism sites are available, then they can be prioritised according to the information derived from the surveillance. Alternatively, where surveillance indicates low densities of CoTS at key sites, a decision may be made to ignore those sites and concentrate effort at nearby high density sites.

Third, although in the longer term our model will incorporate additional information on costs, objectives and ecological context, and allow specific predictions to be made about the optimal locations to invest control resources, in the short term, we can interpret the results of the current analysis to suggest that below a threshold control CPUE of about 0.1 CoTS / minute bottom-time, managers should reconsider their need to invest control resources.

Further analysis of control program data in locations with both surveillance and control records will be required to translate this to a surveillance manta tow density threshold. Therefore, as a matter of urgency, the control program should commence recording manta tow counts at control polygons they intend to manage and the control CPUE data at the same location should be collated for analysis.

Fourth, surveillance should be conducted by the minimum team size possible and using the minimum investment possible. Our analyses indicate that high density CoTS populations are easily detected and sufficiently different to other populations that they swamp any concerns about surveillance accuracy or precision. Consequently, the current data suggests that single observer, single manta-tow passes across polygons should be adequate to prioritise polygons.

Fifth, where logistic constraints permit, consideration should be given to conducting surveillance over all parts of a reef and not just within the current management polygons. Initial analyses of control performance suggest that successful control activities within polygons will in many cases hinge on conditions in adjacent areas. The analyses presented here suggest that the expansion of surveillance beyond the current polygons at a reef is likely to result in increased CPUE and the freeing up of resources to allow for better targeting of resources to high density parts of the reef. This is likely to slow recolonization of control polygons.

Finally, in addition to collecting co-located manta tow surveillance densities and control CPUEs to define surveillance thresholds for control actions, these records should be collected, as per AMPTO surveillance protocols (e.g. distance, speed, visibility, CoTS, coral cover, time of day, depth, etc.), alongside the control data to establish: i) the degree to which surveillance modifies the pre-determined trip plan and estimated changes to voyage CPUE; and ii) the more accurate assessment of the minimum intensity of surveillance necessary to help sequence control activities most effectively. These factors will form a key metric of performance and a critical determinant of how surveillance data is used in the program into the future.

5.0 CONCLUSION

Surveillance has the potential to improve the effectiveness of CoTS control activities by ensuring that the greatest numbers of CoTS are removed within target areas of importance. However, implementing a surveillance program diverts resources from physical control, so it's important to know under what conditions the benefits will outweigh the costs. For the size of voyage region, number of polygons controlled, and CPUEs typically experienced during AMPTO control voyages between 2013 and 2015, a surveillance-and-control strategy would outperform a control-only strategy even when only the minimum crew of four control staff were available. When a typical crew of 6 – 7 were available, over 33% more CoTS could be removed using a surveillance-and-control strategy. With even greater numbers of control staff greater than 60% more CoTS could be removed by a surveillance-and-control strategy.

However, it is the general relationship between management actions and CoTS ecology driving these performance differences, rather than the precise estimates of performance, that is most important. Ultimately, surveillance-and-control is likely to be a superior strategy because CoTS populations tend to be distributed patchily, and on any given voyage, a small proportion of control polygons contribute the great bulk of the overall voyage CPUE. To maximise voyage CPUE it is vital that these few control polygons with high CPUEs are discovered efficiently and control efforts focussed there. Even cursory surveillance should be sufficient to detect the difference between control polygons with very high CPUEs and those with more average results. The mechanism to implement these surveillance practices already exists on the vessel Venus II, with the recent procurement of a tender vessel, the Audamus, for long-term manta tow surveillance. Deploying this vessel at the beginning of each voyage to survey the control polygons within the voyage region would allow managers to identify these high CPUE polygons, focussing control efforts more effectively, and increasing the total number of CoTS removed by 33 - 60% under current management processes.

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