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How Effective Are Management Responses In Controlling Crown-of-Thorns Starfish and their Impacts On The Great Barrier Reef?

A Report for NESP Tropical Water Quality Hub Integrated Pest Management Program

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9th November 2018

Contents

1 Summary

This Report provides an assessment of the effectiveness of management responses to the current crown-of-thorns starfish (*Acanthaster* spp., hereafter CoTS) outbreak. A full journal paper will follow.

In the Indo-Pacific region, CoTS outbreaks are a major contributor to the loss of coral, and to estimated trajectories of coral reef decline in coming decades. Implementing an effective management response to CoTS outbreaks represents a key opportunity to reduce pressure on reefs, in turn providing them with the best opportunity to adapt to climate change. On Australia's Great Barrier Reef (GBR), management interventions have evolved over the period of the four CoTS outbreaks since 1960 to include: i) localized manual control (1962, 1979, 1990), ii) establishment of protected areas (1981, 2003), iii) implementation of water quality improvement plans (2003 onwards), and, iv) implementation of a coordinated and strategic manual control program (2013 onwards). These interventions represent measures that focus on hypothesized drivers of CoTS population dynamics (water quality improvement, zoning) or that attempt to moderate those dynamics directly (manual control).

We use published information and field data from the CoTS control and the Great Barrier Reef Marine Park Authority's reef health monitoring programs to assess the contribution each of these three approaches has made to managing CoTS impacts. We ask whether these measures have been effective in reducing CoTS numbers, and importantly, if they have resulted in increased hard coral cover.

First, on-going assessments of water quality improvement have provided little evidence at this stage of an improvement in GBR water quality. As a consequence flow-on impacts in terms of reductions in CoTS numbers are as yet unlikely. This suggests that water quality improvement cannot be solely relied upon for managing CoTS. Second, protected reef sites had fewer CoTS than unprotected sites at the start of the control program, and these differences were maintained to the end of the study period. Third, manual control proved effective in reducing CoTS numbers at sites and removed the most damaging and fecund, larger individuals from a site within the first two or three voyages. Along with greater protection and greater hard coral cover at the commencement of the control program, shorter revisitation intervals were associated with higher final hard coral cover at a site. Furthermore, sites which received more control were more likely to show larger and positive changes in hard coral cover than sites which received less control investment. These results suggest that manual control, and to a lesser extent zoning, are effective in managing CoTS densities at the scale of a control site and in ameliorating their impact on hard coral cover. They also suggest modifications to the control program which, when incorporated into its design, will render management objectives at regional scales potentially feasible.

2 Introduction

The Great Barrier Reef Marine Park (GBR) is one of the world's largest marine protected areas and an iconic world heritage site. Despite its status, the GBR is subject to a number of anthropogenic threats, and its coral reefs have experienced significant degradation in recent decades. During the period 1985 -2012, hard coral cover on the GBR decreased by approximately 50%, with storm damage, predation by crown-of-thorns starfish (CoTS; *Acanthaster cf solaris*), and coral bleaching identified as the major contributors to this loss (De'ath *et al.* 2012). Subsequent to De'ath *et al.* (2012)'s study, mass bleaching events during 2016 and 2017 further reduced coral cover over much of the GBR, which could have resulted in local ecological collapse (Claar *et al.* 2018; Hughes *et al.* 2018a; Hughes *et al.* 2018c). While much recent research and public attention has focused on these two bleaching events and their impacts, the GBR is also experiencing its fourth major CoTS outbreak since the 1960s. The current outbreak, which began in 2010 (Pratchett *et al.* 2014), continues to move through the central section of the GBR and will move further south over the coming years. Meanwhile, a separate outbreak is occurring in the Swains section in the southern region of the GBR. As the outbreak moves along the GBR, it will result in high levels of coral loss at individual reefs and across the area of the outbreak wave. This loss of coral to CoTS predation amplifies the impacts of other threats and reduces the resilience of the GBR's coral reef ecosystems.

Whereas climate-related threats, such as increased sea surface temperature, increased storm severity and ocean acidification, are beyond the direct control of the communities and agencies responsible for coral reef management, controlling CoTS numbers is not. On the GBR a variety of management responses have been implemented, either wholly or partially, in response to CoTS outbreaks. These efforts initially relied on culling CoTS to reduce numbers. However, the identification of hypothesized drivers of CoTS outbreaks, including water quality impacts on larval survival and as well as the role of predation on larval and juvenile stages (Pratchett *et al.* 2014), have also meant that management action around these issues has been justified on the grounds of an impact on CoTS dynamics. Both water quality improvement and measures to enhance predation represent indirect management interventions, working to reduce recruitment by reducing end-of-river pollutant discharges or through zoning to enhance predator communities, as opposed to direct control of the CoTS themselves. All have been the subject of significant investment in recent decades.

2.1 Water Quality Improvement

River loads of terrestrial sediments and nutrients discharging into the GBR lagoon have increased significantly since European settlement (Kroon *et al.* 2012; Bartley *et al.* 2017). For example, the most recent catchment modelling estimates that river loads of nutrients that are readily biologically available, such as dissolved inorganic nitrogen (DIN), have increased 1.2–6.0-fold relative to their pre-colonization levels (Kroon *et al.* 2012; Bartley *et al.* 2017). One hypothesis for the initiation and maintenance of CoTS outbreaks states that high nutrient availability increases phytoplankton biomass, which enhances larval growth and survival leading to mass recruitment events and outbreaks (Birkeland 1982; Fabricius *et al.* 2010; Wolfe *et al.* 2015). Despite ongoing scientific debate about the validity of the hypothesis (Pratchett *et al.* 2014; Pratchett *et al.* 2017), the link between CoTS outbreaks and water quality has become a central argument for policy and investment on water quality improvement on the GBR (Brodie *et al.* 2012; Anthony 2016; Roth *et al.* 2017; Waterhouse *et al.* 2017).

To protect the GBR from diffuse source pollution from agricultural land uses, the Queensland and Australian Governments jointly released the Reef Water Quality Protection Plan in 2003 (The State of Queensland and Commonwealth of Australia 2003). The Reef Plan 2003 was revised and updated in 2009 (Reef Water Quality Protection Plan Secretariat 2009) and in 2013 (Reef Water Quality Protection Plan Secretariat 2013b), with new goals and associated water quality targets and land management and catchment targets. In March 2015, the Reef 2050 Long-Term Sustainability Plan (hereafter 'Reef 2050

Plan') was released, including an outline of actions on water quality (Commonwealth of Australia 2015). In 2017, the Reef Water Quality Protection Plan 2013 was restructured to link directly with the overall Reef 2050 Plan and updated into the yet-to-be-implemented Reef 2050 Water Quality Improvement Plan (2017-2022) (The State of Queensland 2017). Over the period 2009 to 2018, Federal and Queensland governments have invested approximately $850M on the implementation of these various water quality plans (Brodie & Pearson 2016; The Great Barrier Reef Water Science Taskforce & The Office of the Great Barrier Reef Department of Environment and Heritage Protection 2016), with an additional $200M of Federal funding announced in 2018.

2.2 Marine Protected Areas

The loss of predators has long been suggested as a potential contributory factor to CoTS outbreaks (Endean 1969). Predators potentially include invertebrate and vertebrate species preying on planktonic larvae and post-settlement CoTS life stages. (Pratchett *et al.* 2014). Despite little field data on predation, this hypothesis has received support from modelling (McCallum 1987, 1990) and from an apparent reduction in the incidence of outbreaks on protected reefs (Sweatman 2008; Vanhatalo *et al.* 2016).

One management approach for conserving marine ecosystems, including predatory species, is through the use of marine protected areas (Lubchenco & Grorud-Colvert 2015). Protected areas (or "zoning" in the context of the GBR) have been a key component of the management of the GBR since the introduction of the first zoning plan for the Marine Park in 1981 (Day 2002). The 1981 plan was revised in 2004, with the no-take zones increasing from 4.5% to 33% of the Marine Park, and the representation of habitat types in the no-take zones improved (Fernandes *et al.* 2005). The measured benefits of this approach range from the effective conservation of key species (Emslie *et al.* 2015), including potential predators of CoTS, through to enhancing ecosystem resilience (McCook *et al.* 2010a, b; Mellin *et al.* 2016; Yates *et al.* 2016; Castro-Sanguino *et al.* 2017). Indeed, recent work suggests that the impacts of CoTS outbreaks were reduced in no-take zones (Mellin *et al.* 2016).

2.3 Manual Control

While water quality improvement measures and zoning act to moderate hypothesized drivers of CoTS outbreaks, manual control acts to reduce CoTS populations directly. Over the last 50 years, CoTS control programs have been implemented in a range of sites across the Indo-Pacific. These programs have had, at best, a mixed history of success (Zann & Weaver 1988; Pratchett *et al.* 2014) and this has led to debate about whether large-scale control is feasible, particularly at the scale of the GBR (Pratchett *et al.* 2014). On the GBR, local control efforts have been deployed in response to each outbreak since the 1960s. However, while these efforts achieved some success, they were overwhelmed by sheer numbers of starfish (Kenchington 1978) or had no discernible impact beyond the immediate managed site. On the GBR, this has led to a focus on protecting high-value tourism sites rather than broad-scale control in subsequent outbreaks on the GBR (Pratchett *et al.* 2014).

This situation changed with two new developments during the current outbreak. The first of these was the move to a coordinated control program. While this new approach still incorporated the management of key sites by tourism operators, it added a dedicated control program to supplement those efforts and include additional sites. This had the effect of standardizing the approach and improving data collection. The second development was the discovery that a single small volume injection of oxbile was an effective means of killing CoTS (Rivera-Posada *et al.* 2014). This method revolutionized CoTS control by enormously reducing the effort required to kill an individual and increasing the probability of a successful kill to close to 100%. The net result has been a control program that has focused on key tourism and selected ecologically important sites since 2013 and throughout the current outbreak period. This program has also acted as the foundation for the development of a more structured Integrated Pest Management approach to CoTS control, that offers the potential for achieving meaningful outcomes at the scale of the GBR (Westcott *et al.* 2016).

2.4 Aims of this Report

As pressures such as the mass bleaching events of 2016 and 2017 on the GBR have increased, the debate over the appropriate management actions has also increased. In the context of managing the impacts of CoTS population outbreaks, this debate has focused on the relative efficacy in reducing CoTS numbers through i) water quality improvement efforts, ii) zoning, and iii) manual control. Assessment of the relative effectiveness of these three different approaches to CoTS management is now possible given that water quality improvement and zoning have been in place since at least the early 2000s, and manual control has been in place locally since near the beginning of the current outbreak. Here we use reports from the Queensland and Australian Governments, data on CoTS abundances from the CoTS control program, and coral cover from GBRMPA's reef health monitoring program to examine the impact of i) water quality improvement, ii) zoning, and iii) manual control in controlling CoTS populations. Specifically, we ask whether these approaches are: i) effective in reducing CoTS densities, ii) effective in keeping densities low, and critically, iii) result in a response in hard coral cover. Finally, we consider the implications of our results for how CoTS control programs are designed. While our work is focused specifically on the GBR, CoTS outbreaks are commonly experienced elsewhere in the Indo-Pacific. As a consequence our results will have implications for control efforts across the range of *Acanthaster* spp.

3 Methods

3.1 Water Quality Improvement

To examine the effectiveness of water quality improvement on CoTS, we have relied on the seven annual report cards published by the Queensland and Australian governments since 2011 (https://www.reefplan.qld.gov.au/measuring-success/report-cards), and associated publicly-available scientific and technical publications. These annual report cards measure progress towards the goal and targets outlined in the two Reef Water Quality Protection Plans that have been implemented to improve GBR water quality since 2009 (Reef Water Quality Protection Plan Secretariat 2009, 2013b). The first Reef Plan Water Quality Protection Plan (The State of Queensland and Commonwealth of Australia 2003) did not have any quantitative water quality targets and as such progress towards these was not reported upon. The last annual report card was published in 2017 and reports on progress towards the goal and targets of the Reef Water Quality Protection Plan 2013 (Office of the Great Barrier Reef 2017).

3.2 Zoning

The zoning for each of the 53 sites considered in this study where manual control was implemented was determined by reference to GBRMPA's zoning maps, available at https://eatlas.org.au/data/uuid/92e4a530-6cbc-456b-918d-55d97c610e01. Twenty-six of these sites were classified as Marine National Park or 'no-take' areas, ten were classified as Conservation Park, i.e. areas where recreational and limited commercial fishing (excluding trawling) are permitted, and the remaining 17 were zoned as Habitat Protection, i.e. areas where fishing and other harvest activities are permitted with the exception of trawling. For the purposes of this work we refer to these zoning categories as 'no-take', 'limited take' and 'take' zones, respectively.

3.3 Manual Control

Data on CoTS abundances at manual control sites came from the CoTS Control Program which operates at reefs in the Cairns section of the GBR. During the period of this study, this program's control activities were conducted by one and, more recently, 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 focused on sites at 21 reefs (hereafter Priority Reefs) in the Cairns region considered to be either economically important as tourism sites, or ecologically important in that local currents gave them high connectivity to other reefs and consequently they were considered to be significant in the pattern of CoTS spread. Due to stakeholder pressure the control program also conducted control operations at reefs other than the 21 Priority Reefs. These reefs did not have permanently marked Reef Health Impact Surveys (RHIS) sites and consequently are not considered further here.

The 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. Each of these sites were defined by mapped polygons. During a voyage each polygon was searched and CoTS culled until no more detectable CoTS were available. 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 multiple divers. Because, during a voyage, dives continued to be made at a site until no CoTS were available to cull, the voyage represents a standard unit of management outcome at a site. Hence we use the number of voyages to visit a site as an independent variable in our analyses. During each dive, a tally of CoTS killed was kept by each diver and these tallies were summed across divers to give a total number of CoTS removed from each site during a voyage. CoTS densities are compared to the outbreak thresholds estimated by Babcock *et al.* (2014) which correspond to the densities above which hard coral cover is expected to decline.

3.4 Reef Health Impact Surveys

Reef Health Impact Surveys (RHIS) are the standardized monitoring protocol used by the GBRMPA for monitoring coral condition as part of their Reef Health Incidence Response System (Beeden *et al.* 2014; Great Barrier Reef Marine Park Authority 2014). RHIS Observers must complete a formal training course and, in the case of the data used in this study, all observers were highly experienced in conducting RHIS as employees of the CoTS Control Program or of GBRMPA's Field Management Program.

The RHIS protocol is based on point surveys (Beeden *et al.* 2014). Within a 5 m radius of these points observers estimate a range of coral health indicators including coral cover and the presence and extent of impacts such as bleaching, storm and anchor damage, disease, and CoTS and *Drupella* predation. Percentage coral cover is estimated visually for the following categories: total, live, dead, soft, hard, and for each of the major coral lifeforms, e.g. massive, plate, branching, etc. Surveys are repeated to enable assessment of their robustness and this indicates that accuracy and precision are high, making the method a robust and effective means of efficiently assessing coral health (Beeden *et al.* 2014).

RHIS were conducted at all sites where control occurred, however in this study we use only data from polygons which had permanently marked RHIS points for the entire period of the study (2013-2017). We limited the analysis to these sites because the lack of permanent markers at other sites means that the locations surveyed within a polygon differed between surveys and risked confounding change in coral cover over time with sampling location. At each control site, three permanently marked RHIS sites were located at roughly equal distances across the site giving a total surveyed area of 235 m^2 per polygon (average polygon size = 14 ha). In total, 53 control sites (hereafter 'sites') at 21 Priority Reefs had permanent RHIS markers for the full duration of the study period (2013-2017) and so are included in this analysis.

3.5 Analysis

The effect of zoning and manual control of CoTS was assessed using ANOVA, linear mixed models and linear regressions between dependent and independent variables. Dependent variables were hard coral cover at a site at different times during the study period, or the change in hard coral cover over the period of the study, i.e. from the first year a site was visited to the last year it was visited. Independent variables used in the analyses were the zoning of a site, the total number of voyages to visit a site during the study and the mean interval between voyages to a site.

All analyses were conducted in R (R Development Core Team 2018). Assumptions for ANOVA, linear regression and mixed models were tested as appropriate. Normality was assessed through inspection of Normal Q-Q plots and when required the dependent variable was square-root transformed to meet the assumption of normality. The mean of the residuals was zero in all models. Assumptions of skewness, kurtosis, homoscedasticity and the performance of the link function were assessed by visual assessment of the distribution of residuals relative to fitted values and their leverage, and confirmed using the *gvlma* package (Pena & Slate 2006). One highly leveraged point was removed in some analyses to meet skewness assumptions. Linear mixed models were conducted using the *lme4* package (Bates *et al.* 2015), and tests of the significance of random and fixed effects were performed using the *lmerTest* package (Kuznetsova *et al.* 2017).

Due to spatial dependence between sites at individual reefs the variable 'reef' was included as a random effect, with the other dependent variables as fixed effects. Linear mixed models comprising of all combinations of fixed and random effects were compared using AIC and BIC with the model with the lowest of these values chosen. Linear regression was used in the analysis of change in hard coral cover as the random effect reef identity was not significant in any of the models.

4 Results

4.1 Effect of Water Quality Improvement

The most recent GBR Report Card 2016 reports that 36% of grazing land, 32% of sugar cane farmland, 47% of horticultural farming, and 57% of grain growing land were managed under best management practices. For each land use the 2018 target is 90% (Reef Water Quality Protection Plan Secretariat 2016). The river pollutant loads reported in the GBR Report Card 2016 were modelled estimates of the long-term annual load reductions since 2009 and based on the reported improvements in agricultural management practice systems (Reef Water Quality Protection Plan Secretariat 2016). For each of the key pollutants this estimated progress was: i) DIN reduction of 20.9% against a 2018 target of 50%, scored as very poor progress, ii) sediment reduction of 13.9%, against a 2018 target of 20%, scored as moderate progress, (iii) particulate nitrogen reduction of 12.5%, against a 2018 target of 20%, scored as poor progress, (iv) particulate phosphorus reduction of 15.6%, against a 2018 target of 20%, scored as good progress, and, v) a pesticide reduction of 36%, against a 2018 target of 60%, scored as moderate progress. Since 2009, the overall score for water quality on the GBR given in the seven annual report cards has fluctuated between 'poor' and 'moderate' (Reef Water Quality Protection Plan Secretariat 2011, 2013a, 2014; Queensland Government 2015; Reef Water Quality Protection Plan Secretariat 2016; Office of the Great Barrier Reef 2017).

4.2 Effect of Zoning

At the start of the study in 2013 there was no difference in hard coral cover between differently zoned sites (ANOVA, $p=0.236$). Zoning influenced the number of CoTS encountered in the first year (ANOVA, $F_{1,46}=8.07$, $p<0.007$) with more CoTS found in 'take' zones than in 'limited -take' or 'no-take' zones ($p<0.009$ and $p=0.0033$ respectively).

Over the course of the five years considered in this study, sites in 'take' zones were visited less frequently than sites zoned 'limited take' or 'no take' ($F_{1,50}=15.98$, $p=0.0002$; 'limited-take' and 'no-take' vs 'take' zoned sites ($p<0.072$ and $p=0.00023$ respectively), though visitation to "no-take" and "limited-take" did not differ ($p<0.18$). Given this effect of zoning on visitation, further analysis is required of the effect of zoning on hard coral cover and change in coral cover, in tandem with the effect of visitation or visit interval for manual control is required.

4.3 Effect of Manual Control on CoTS Densities

The density of CoTS encountered during a voyage at a site declined as a function of the number of voyages that had previously visited that site (Figure 1). This decline continued until approximately the eleventh voyage, whereafter CoTS densities begin to fluctuate while remaining low. Beyond 22 visits, sample sizes decline significantly (Figure 1); just six sites were visited 23 or more times, and variation in CoTS densities increases dramatically as a result.

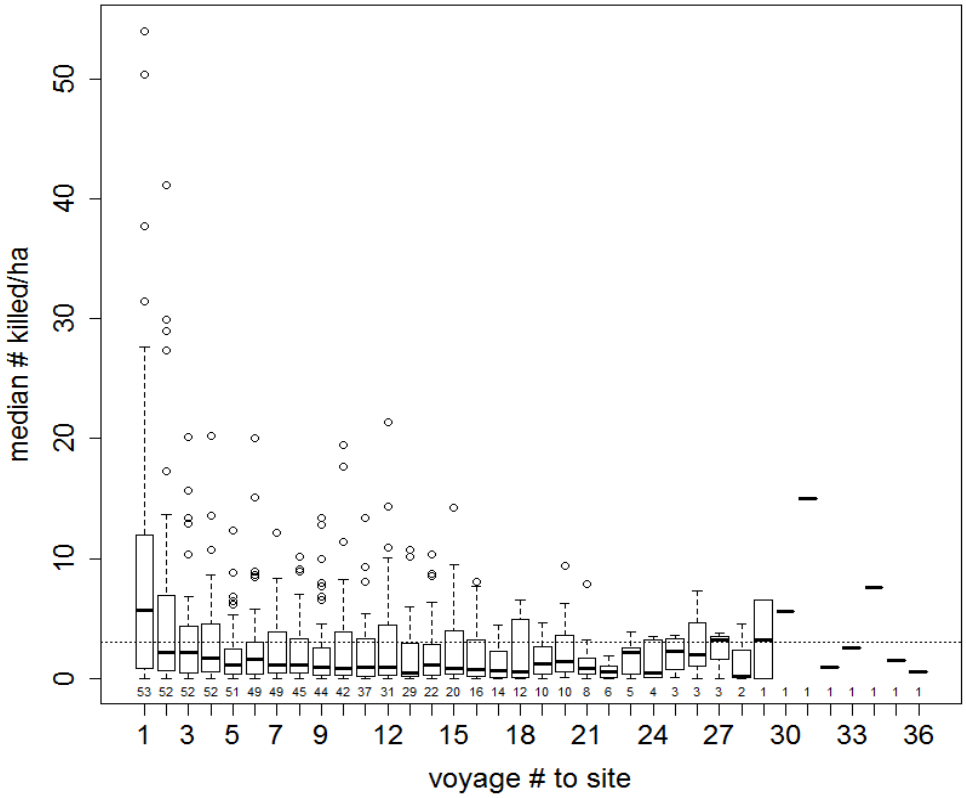

Figure 1 ***Number of CoTS culled per hectare plotted against the number of voyages to have visited the control sites at the 21 Priority Reefs. Dashed line = the threshold for CoTS outbreaks (Babcock et al. 2014), Solid bar = median, box=quartiles, whiskers=extremes, circles =outliers. Sample sizes sit above the x-axis.***

When the four different size classes of CoTS are considered separately two different patterns of response are observed (Figure 2). First, the three largest size classes show a decline followed by fluctuation around low numbers. In contrast, the smallest size class shows a slight and longer term reduction but remains at relatively high numbers thereafter. It is the variation in this age class that contributes to the increase in variation in the population overall when only the total population is considered (Figure 1).

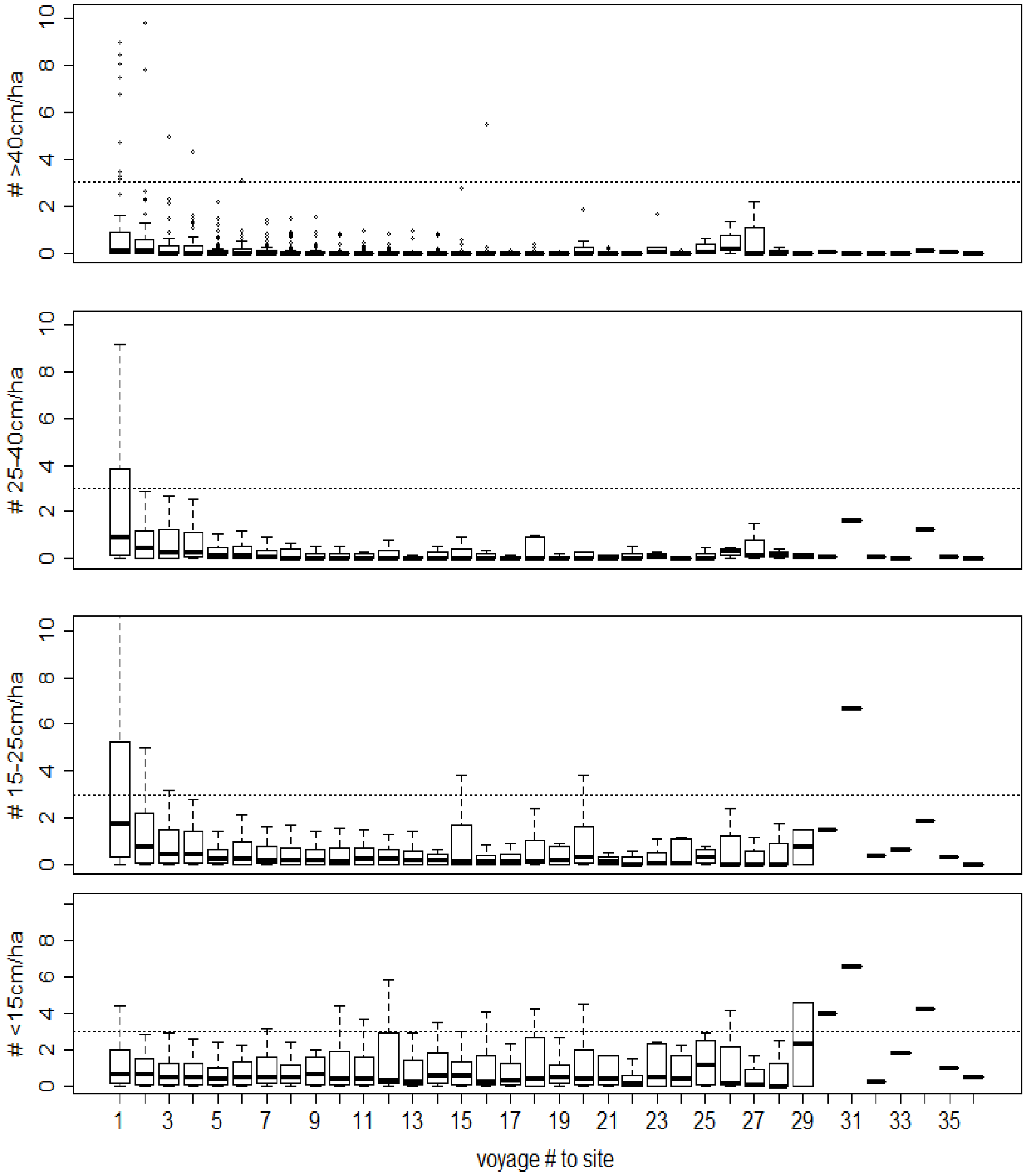

Figure 2 ***Number of CoTS culled per hectare in each size class plotted against the number of voyages to have visited control sites at the 21 Priority Reefs. Dashed line = the threshold for CoTS outbreaks (Babcock et al. 2014), Solid bar = median, box=quartiles, whiskers=extremes, circles =outliers. Sample sizes can be found in Figure 1.***

4.4 Effect of Manual CoTS Control on Coral Cover

The number of voyages to visit a site over the five-year study period was not related to hard coral cover at the start of the study in 2013 (P=0.73).

A fixed effects model indicated that hard coral cover in the last year that a site was visited was related to the number of voyages to have visited that site previously (R^2= 0.13, $F_{1,39}$ = 5.9, $p < 0.02$). However a linear mixed model including the random effect 'reef' was significant for the random effect (P=0.02) while the fixed effect number of voyages only reached a trend ($F_{1,49}$=3.44, P=0.07).

The proportional change in hard coral cover at sites over the five-year period of the study was significantly and positively related to the number of voyages that visited them (R^2= 0.19, $F_{1,50}$ = 11.99, $p < 0.0012$; Figure 3). Linear mixed modelling showed that the random effect 'reef' was not significant (P=0.24).

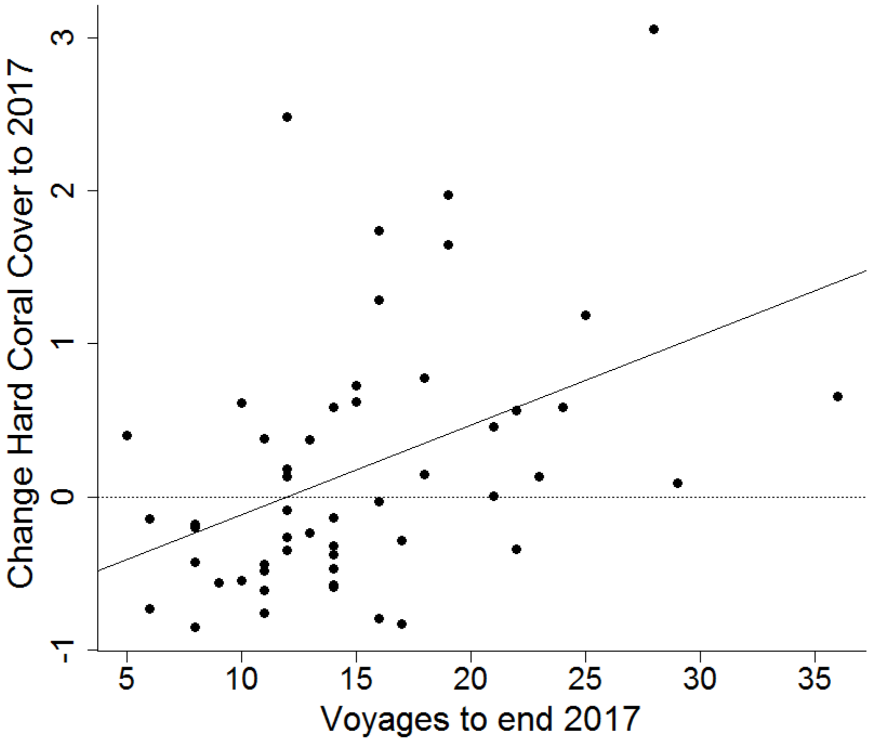

Figure 3 ***Change in hard coral cover to 2017 as a function of the total number of voyages to the end of that year. The dotted line represents no change in coral cover and solid line the regression equation (*****R^2= 0.19, $F_{1,50}$ = 11.99, $p < 0.0012$).**

4.5 Combined Effects of Zoning and Manual Control

Hard coral cover at a site at the end of the study period was best explained by a linear mixed model incorporating the fixed effects of hard coral cover at the start of the manual control program, zoning, the mean interval between voyages that visited a site and the random effect, reef identity. Specifically, greater initial hard coral cover ($t_{49.3}$=2.54, p=0.014), greater protection ($t_{24.8}$=2.01, p= 0.055) and shorter voyage intervals ($t_{47.8}$=2.6, p=0.012) were associated with higher coral cover. The random effect, reef identity, was also significant (LRT_1=4.1, p=0.042).

The proportional change in hard coral cover was best explained by a linear mixed model which incorporated just the fixed effect number of voyages ($t_{32.7}$=3.34, p=0.002), however, the random effect reef identity, was not significant (LRT_1=0.0956, p=0.7568). The fixed effects model explaining the greatest proportion of the variance in the proportional change in hard coral cover included the effects of manual control and zoning ($R^2 = 0.21$, $F_{2,49}=6.20$, $p= 0.004$). The effect of zoning alone was not significant ($p=0.32$) while the effect of number of voyages remained significant ($p=0.015$).

5 Discussion

5.1 Water Quality Improvement

The 2016 GBR Report Card indicated limited progress towards 2018 targets for management practice and catchment loads (Office of the Great Barrier Reef 2017). In addition, the seven annual report cards showed a water quality score for the GBR that has fluctuated between ‘poor’ and ‘moderate’ since 2009. Overall, this points to slow, if any progress having been made in achieving and measuring GBR water quality improvements (Waterhouse *et al.* 2017). Therefore, there is little reason to expect that water quality improvement has influenced CoTS dynamics or that any such influence could be detected at this point in time.

Improving the quality of water flowing through the GBR catchment and into the GBR has a range of terrestrial, aquatic and marine benefits (Brodie & Pearson 2016; Kroon *et al.* 2016; Waterhouse *et al.* 2017) beyond any anticipated impacts on CoTS population dynamics. Securing those benefits will require that water quality improvements are sought irrespective of whether an influence on CoTS population dynamics is demonstrated. In the meantime, while water quality improvement may ultimately prove efficacious in influencing CoTS outbreak dynamics, it cannot yet be solely relied upon for CoTS control.

5.2 Zoning

Zoning has been linked to a range of ecosystem benefits on the GBR (Mellin *et al.* 2016; Yates *et al.* 2016; Castro-Sanguino *et al.* 2017), as well as to the potential of a site to experience a CoTS outbreak (Sweatman 2008; Vanhatalo *et al.* 2016; Sweatman & Cappo In Press). Our results support this conclusion: sites zoned with greater protection, i.e. Marine National Parks and Conservation Park zones, entered the study with fewer CoTS than sites zoned Habitat Protection. In combination with starting hard coral cover and the mean interval between voyages to a site, zoning remained a significant predictor of hard coral cover at the end of the study. This effect of zoning was less clear in terms of the proportional change in hard coral cover at a site over the study period. In this instance, while zoning contributed to the overall effect of control, this contribution was small relative to that of manual control. These results, and those of the previous studies, suggest that protecting reefs through zoning is a means of moderating the impact of an active CoTS outbreak, but that its role in a CoTS control program will be as a complementary action used to support manual control or where manual control cannot be employed.

5.3 Manual Control

Manual control was effective in reducing CoTS numbers at a site and in keeping CoTS numbers suppressed over the life of the five-year program (Figures 1, 2). This outcome, however, was not achieved with a single voyage to a site. While one voyage was sufficient to bring the median density of CoTS to below the outbreak threshold, five or more voyages were required to bring the 75th percentile of sites to this threshold. This result points to not all CoTS present at a site being available to be culled during a single voyage, and the need for sufficient repeat voyages to a site to achieve reliable reductions below the outbreak threshold.

While repeated voyages are successful in suppressing overall CoTS densities, these densities showed some increase in the long term and this increase was strongest for the smaller size classes (Figures 1 and 2). This effect appeared to largely be a consequence of recruitment of existing and recently settled juveniles. This suggests that while intensive manual control will in the short term suppress the adult population at a site, less frequent visitation after this will be sufficient to control subsequent recruitment into the adult population.

Manual control was very effective in removing individuals of the larger size classes (Figure 2). This is important because it is the larger individuals which consume most coral (Keesing 1990), are most fertile (Kettle & Lucas 1987), and contribute most to population reproductive success (Rogers *et al.* 2017). Rapid removal of these individuals from the population at a site will produce the greatest reduction in the amount of coral predation by CoTS that occurs at that site, and will simultaneously provide the greatest reduction in the local CoTS population's contribution to the outbreak's downstream dynamics and impact. Realising these benefits will be most efficiently achieved by balancing revisitation intervals to the minimum that is sensible given the behaviour of CoTS and the economics of revisitation.

Determining exactly how short revisitation intervals should be is a focus of our current work. The fact that within a voyage all available CoTS were culled, but that subsequent voyages to the same sites encountered diminished but similar densities, indicates that not all CoTS are available to cull at any one point in time. Furthermore, the fact that culling skewed the population towards smaller size classes suggests that the CoTS encountered on subsequent voyages were, in general, not immigrants to the site but were more likely individuals missed in previous voyages. Temporal dynamics in CoTS behaviour may be differentially influencing their detectability at short and long timeframes. While our analyses to determine the optimal revisitation schedule are yet to be completed, we suggest that revisitation intervals to sites and reefs should be reduced from months to weeks in order to maximise the reduction in CoTS damage achieved for a given number of visits to a site.

5.4 Does Coral Cover Respond to CoTS Control?

Reduced densities of CoTS are a promising indication of the effectiveness of the manual control program. However, the ultimate objective of CoTS control is not to kill starfish but to protect live hard coral. Consequently, the effectiveness of the program should be gauged by the response of hard coral to control efforts. Our results indicate that during the period this study manual control of CoTS was effective in achieving this goal, with the final hard coral cover and the percentage change in coral cover at a site being positively related either to more frequent visitation or to the number of voyages to have visited the site up to that point in time. This was not a function of 'better' sites being visited more frequently, as there was no relationship between hard coral cover at the start of the study and the number of visits to a site during the study.

Though the effect of manual control on live hard coral was significant, the amount of variation explained by manual control and zoning, ~20%, might be considered to be low. This low explanatory power, however, is not surprising. A multitude of factors, in addition to CoTS, influence coral cover dynamics at a site on the GBR, including bleaching, cyclones, disease, and human impacts such as anchor damage and water quality; and the impacts of these factors vary geographically (De'ath & Fabricius 2010; De'ath *et al.* 2012). Consequently, we cannot expect CoTS to explain all, or necessarily the majority, of the variation in coral cover dynamics. De'ath *et al.* (2012) estimated that CoTS were responsible for c. 40% of coral mortality on the GBR in the absence of mass bleaching events and this figure gives an initial upper estimate of the magnitude of the impact we might have expected from manual control. During the period of this study two mass bleaching events occurred, in the early months of 2016 and 2017 (Hughes *et al.* 2018b; Hughes *et al.* 2018c), and their impacts in the study area were severe, though spatially uneven (Stuart-Smith *et al.* 2018). As a consequence, it is reasonable to conclude that these additional non-CoTS mortality factors will have also influenced coral dynamics during the study period at our sites. Despite these significant non-CoTS drivers of hard coral population dynamics operating during the study period, the signal of the effect of manual control of CoTS control persisted, suggesting that its effect is strong.

5.5 Summary

Our comparison of the three approaches to CoTS control used on the GBR to date suggests:

i) Based on information from the seven annual Report Cards, there was no evidence that water quality improvement efforts had resulted in detectable changes in water quality on the GBR to date. Given this, water quality improvements cannot currently be solely relied upon for managing CoTS abundances or dynamics.
ii) Zoning appeared to influence the starting conditions at a site, with sites zoned with greater protection (i.e. zoned Marine National Park and Conservation Park) having smaller and fewer CoTS in the first year of control than less protected sites (i.e., zoned Habitat Protection). However, zoning appeared to have had limited additional influence on CoTS abundances once manual control was implemented.
iii) Manual control proved an effective means of reducing CoTS densities and sizes at a site and, most importantly, resulted in improved hard coral cover at a site.
iv) Our results suggest a range of opportunities for improving the strategy underpinning the CoTS Control Program and for scaling-up manual control to achieve ecologically meaningful outcomes for hard coral cover at regional scales on the GBR.
v) The learnings from this work are currently being incorporated into the operations of the expanded CoTS Control Program in collaboration with the GBRMPA and the commercial control program operators, both as part of their current operations and in the strategic and operational plans that guide the program.

6 Acknowledgements

The Association of Marine Park Tourism Operators and the Great Barrier Reef Marine Park Authority provided access to data and important contextual information about the field operations of the control program. The work presented here developed from discussions with a broad range of researchers, managers and on-water manual control operators, especially the contributors to the Crown-of-Thorns Working Group of the National Environmental Science Program Tropical Water Quality Hubs' Crown-of-Thorns Integrated Pest Management Program. Mary Bonin (GBRMPA) provided useful insights during the analysis and improved our approach. This research was funded by Australian Government's the National Environmental Science Program through its Tropical Water Quality Hub. We thank Dan Gladish, Eva Plaganyi, Russ Babcock and Frederieke Kroon for their helpful critiques of previous versions of this report.

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