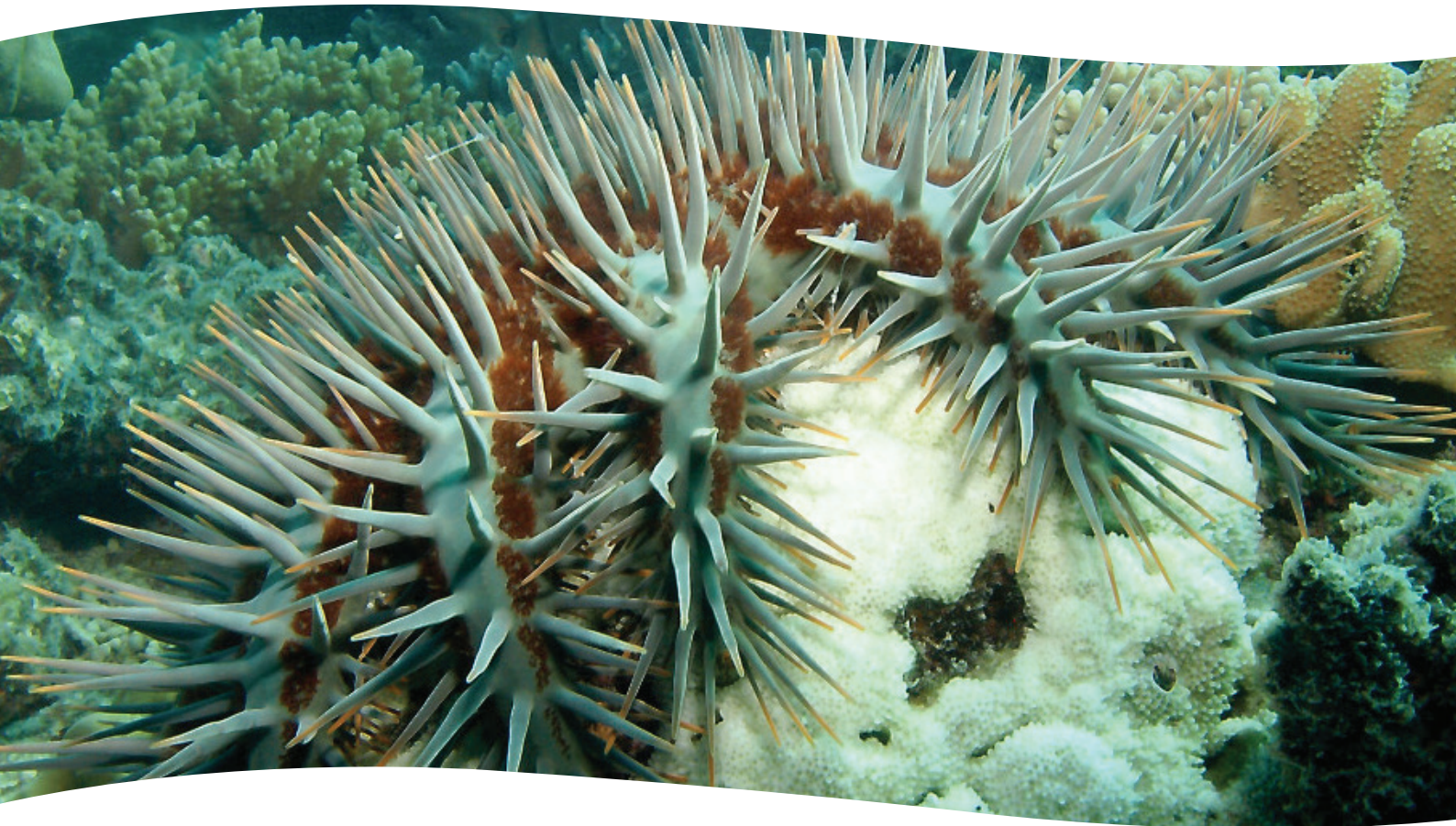


# **A Strategy to Link Research and Management of Crown-of-Thorns Starfish on the Great Barrier Reef: An Integrated Pest Management Approach**

David Westcott, Cameron Fletcher, Russ Babcock,  
Eva Plaganyi-Lloyd and the CoTS Working Group



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David A. Westcott<sup>1</sup>, Cameron S. Fletcher<sup>1</sup>, Russ Babcock<sup>2</sup>, Eva Plaganyi-Lloyd<sup>2</sup>  
and the CoTS Working Group.

<sup>1</sup> CSIRO Land and Water, Atherton, Queensland

<sup>2</sup> CSIRO Oceans and Atmosphere, Dutton Park, Queensland



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## ACRONYMS

**CoTS**.....Crown-of-Thorns Starfish

**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) cause widespread loss of hard coral cover on reefs and are considered to be one of the most significant threats facing the GBR. Indeed, it is estimated that successful CoTS management could turn the GBR's current long-term decline in coral cover around. As a consequence, CoTS control and the mitigation of their impacts is emerging as a priority for management and for research.

There is a long history of research into CoTS biology, ecology, and the causes of their outbreaks. Although by no means complete, this legacy provides a solid foundation for future work. In contrast, there has been only slow improvement in CoTS control programs. Other than the development of the single-injection method for culling and the deployment of a dedicated control program, there has been no significant advance in how control activities are implemented or in their effectiveness.

This report seeks to change this. In it, we outline a research strategy firmly focussed on informing and refining management actions to improve the performance of control programs, now and into the future. The process that produced this strategy drew on a broad range of experience, from managers with policy backgrounds, to managers with on-water control experience, and from Australia's CoTS research community to researchers with experience in designing pest control approaches.

In developing the strategy we applied what is essentially an integrated pest management approach. We asked how CoTS outbreaks arise, how they spread, and in the light of this, what management goals and responses are most likely and most appropriate. We then used this information to identify how research could contribute to achieving management solutions that are as efficient and effective as possible.

We identified six current and future management contexts: 1) control at sites and local areas; 2) protection of assets; 3) reduction of the spread of the current outbreak; 4) prevention of future primary outbreaks in the initiation box; 5) managing ultimate causes; and 6) the implementation of non-manual controls. We then considered the relevant management goals, how implementation management would be implemented, and the knowledge gaps preventing either implementation or limiting effectiveness in each of these contexts. This process points to four clear areas for research investment. Prioritized according to scheduling and the scale of investment recommended these are:

1. Optimisation of control at sites and local areas – these represent the basic units of management. Success at other scales requires success at these scales.
2. Optimisation of control at regional scales – influencing the trajectory of outbreaks and coral health requires successful strategies implemented at regional scales.
3. Addressing ultimate causes – While we must manage current outbreaks, we need to build the knowledge and management expertise now that will one day prevent future outbreaks.
4. Developing new control technologies – There are limits to the gains that can be obtained from current control technologies and new options must be explored.

Within each of these areas we identified the research required, how this research would link to management, and the associated research timelines. We have attempted to strike a balance between i) optimising current tools and approaches, ii) developing currently identified new approaches, and, iii) advancing 'over-the-horizon' technologies. This results in

a strong focus on current control methods and the development of decision support tools. This focus recognises that we will be reliant on manual control for the short to medium term and that we need to deploy that manual control as strategically and effectively as possible. These tools will ensure that management actions are implemented as effectively and deployed as efficiently as possible, by allowing us to select meaningful and realistic management goals, and assess and optimise alternative management responses that will achieve those goals.

The research strategy (summarised graphically in Figure 2, Figure 3 and Appendix 1) provides a sequence of work that delivers improved operations immediately, and, ensures that each piece of work provides the groundwork for the subsequent research steps. Thus, maximising efficiency and effectiveness of operations at the site scale (i.e. individual control locations or polygons on a reef) provides the approaches required to successfully implement control at the scale of local areas (i.e. at the scale of reefs and reef complexes). This in turn provides the foundations for developing regional scale strategies. The concurrent development of new control technologies means that as their viability is demonstrated, they can be incorporated into the decision making tools developed in the rest of the research strategy as well as incorporated into management. This sequence also ensures that the results of each research step will feed into on-water operations as they become available rather than waiting until the completion of the strategy.

# 1. BACKGROUND

*Acanthaster planci* L., or the crown-of-thorns starfish (CoTS), is a carnivorous starfish that preys on the polyps of reef-building corals. The species is widely distributed across the Indo-Pacific in tropical and sub-tropical latitudes and occurs in most locations where scleractinian corals, the primary food of adult CoTS, are common. Scleractinian corals are fundamental to the form and structure of coral reefs and therefore the structure and diversity of the communities of those reefs. As a consequence, high levels of CoTS predation on these corals has the potential to fundamentally alter both the reefs themselves and their biological communities.

CoTS have been associated with the widespread loss of hard coral cover on reefs during periodic outbreaks across their entire range. Hard corals on the Great Barrier Reef (GBR) face a number of threats, including increased frequency and severity of bleaching events, and increased severity of cyclones. The impacts of CoTS on the GBR adds to these pressures on coral health, while directly driving a significant portion of overall coral decline (Baird, Pratchett *et al.* 2013; Brodie, Waterhouse *et al.* 2013; De'ath, Fabricius *et al.* 2012; Pratchett, Caballes *et al.* 2014). Of the significant threats that face the GBR, investment in CoTS management is the only action we can take on individual reefs today that will reduce the cumulative stresses experienced by the reef. It is therefore the primary option to promote reef health and resilience in the near future. Mitigation of the impacts of CoTS is urgent, and must become a primary focus of both management and research.

## 1.1 The history of management concerns about CoTS

Until the advent of scuba and reef tourism, CoTS aroused little more than scientific interest and were not considered to be common in any part of their range (Madsen 1955). This changed, however, when outbreaks of CoTS were first reported from Miyako in the Ryukyu Archipelago in Japan in 1957 (Yamaguchi 1986) and again in an outbreak on the GBR near Green Island in 1962 (Endean 1969; Endean 1982). These incidents were quickly followed by similar reports from Guam in 1967, Palau in 1969 (Chesher 1969), and the Ryukyu Archipelago again from 1969 onwards (Yamaguchi 1986). The nature and extent of the damage observed and the perceived threat posed both to reefs and the economic activities they supported quickly led to calls for management intervention (Barnes 1966; Chesher 1969; Yamaguchi 1986).

The rapid move to control was not, however, without its critics. A number of writers, noting anecdotal and historical reports that CoTS were at times common, raised the possibility that outbreaks were in fact a natural phenomenon (Dana 1970; Vine 1973). In his 1973 review of *Acanthaster planci* and the threat it posed to coral reefs in the Indo-Pacific, Branham (1973) noted that the common names given to the species, “crown-of-thorns” and “mother-in-laws cushion”, reflected the strong emotions its impact evoked. He suggested that, like these names, the move to control was driven more by an emotional response rather than by an objective assessment of the species’ impact. Despite a lively debate about the naturalness of the outbreaks (Branham 1973; Chesher 1969; Dana 1970; Vine 1973) the available ecological and anecdotal information proved mostly equivocal and was ultimately insufficient to resolve the issue. Subsequent examination of the geological record suggested a long history of CoTS outbreaks (Frankel 1977; Frankel 1978; Walbran, Henderson *et al.* 1989a;

Walbran, Henderson *et al.* 1989b) however these studies were quickly challenged on technical grounds (Fabricius and Fabricius 1992; Henderson and Walbran 1992; Keesing, Bradbury *et al.* 1992; Pandolfi 1992). While the issue remains unresolved, recent research has led to reports of past high CoTS densities from around the Indo-Pacific (Doherty 2012) and the suggestion that echinoderms as a phylum tend to exhibit boom-bust cycles (Uthicke, Schaffelke *et al.* 2009). This suggests that it is reasonable to expect that outbreaks did occur in the past, though less frequently (Done 1987).

Though the uncertainty surrounding the “naturalness” of outbreaks provided for a stimulating scientific debate, it left managers with something of a conundrum; whereas the damage caused by CoTS was obvious and its extent was concerning, if outbreaks were a natural phenomenon should CoTS be managed at all (Gladstone 1993; Kenchington and Kelleher 1992; Kenchington 1978)? This question combined with concern about the evidence which Endean (1969) had used to conclude that CoTS outbreaks represented a significant threat to the GBR, led to recommendations that CoTS did not pose a threat to the GBR as a whole and that, instead, more research into outbreaks was required to guide the decision of whether and how to manage them (Lassig and Kelleher 1991; Walsh, Harris *et al.* 1971). While research into control was also recommended, it was relegated to a lower priority, perhaps based on the assumption that it was unlikely to be successful at relevant scales. Despite this, some funding was made available for research into risk assessment and the need for control, monitoring the effectiveness of current control and monitoring methods, and the potential utility of biological control (Lassig 1991; Lassig 1993). Subsequent CoTS research on the GBR has maintained this primarily focus on explaining outbreaks and the processes that underpin them rather than how best to directly reduce their impacts.

While no definitive resolution to the question of whether outbreaks are natural or what causes them has been achieved (Pratchett, Caballes *et al.* 2014; Wooldridge and Brodie in press), the debate has moved on and justification for control no longer presupposes that outbreaks are human induced. Instead, an understanding of the ecological impacts of CoTS outbreaks in the broader context of threats to reefs means that that CoTS control is recognised as required if we are to maintain reefs and their resilience into the future. The impacts of an outbreaking CoTS population can be severe. An outbreaking CoTS population is estimated to be capable of consuming 0.18% of hard coral biomass per day on an average reef, with significant coral loss occurring when densities climb beyond 1000 individuals/km<sup>2</sup>. The loss of live coral cover drives significant decreases in fish diversity and abundance through the loss of food resources and habitat structure (Bouchon-Navaro, Bouchon *et al.* 1985; Sano, Shimizu *et al.* 1984). This effect is strongest in scleractinian-feeding groups, e.g. chaetodontids (Hart, Klumpp *et al.* 1996; Sano, Shimizu *et al.* 1987; Williams 1986), but loss of structure and refuges through increased bioerosion (Musso 1993) can be expected to lead to more general loss of fish diversity and abundance (Caley and John 1996; Jones, McCormick *et al.* 2004; Wilson, Graham *et al.* 2006). We now recognise that outbreaks can influence vast areas of the reef (De'ath, Fabricius *et al.* 2012). The suggestion that outbreaks are becoming more frequent (Done 1987) and the long recovery times required by scleractinian corals (9-100 years (Colgan 1987; Done 1988) suggests that complete recovery between outbreaks is increasingly unlikely and that long-term degradation is inevitable.

Our understanding of the consequences of the interaction between CoTS impacts and other drivers of coral decline leave little doubt that action is required (De'ath, Fabricius *et al.* 2012). While tropical storms and bleaching events may combine with CoTS to drive coral declines, it

is only CoTS that can be managed immediately and at the scale of the reef itself. Consequently it is through CoTS control that we stand the greatest chance of reversing coral declines in the near future (De'ath, Fabricius *et al.* 2012; Rivera-Posada, Owens *et al.* 2012). This conclusion, however, is based on the assumption that we have approaches that can be implemented and appropriately scaled to address the issue, or that we can develop them as a matter of urgency for research and management.

## **1.2 The history of CoTS control programs and their success**

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. While an immediate response to the initial outbreaks on Green Island on the GBR in 1962 achieved some early success, the program was eventually overwhelmed and deemed a failure (Kenchington 1978). This, and similar failures at other locations, led to a focus on protecting high-value tourism sites rather than broad-scale control in subsequent outbreaks on the GBR. Similarly, an enormous investment over a period of more than a decade that removed approximately 13 million CoTS from the Ryukyu Archipelago was ultimately considered to have been a failure (Yamaguchi 1986). Elsewhere, some successes seemed more substantial. For example, population declines across the Mariana and Caroline Islands were ascribed to control efforts during the 1969-1973 outbreaks (Marsh and Tsuda 1973). To date some 84 CoTS control programs have been conducted globally removing > 17million CoTS at a cost of USD 15-44 million (Pratchett, Caballes *et al.* 2014).

In their reviews of control programs, Zann and Weaver (1988) and Birkeland and Lucas (1990) suggested that the success of programs was inversely related to the scale of the outbreak with which they were concerned. The probability of success further increased with greater warning of an outbreak, when CoTS were tightly aggregated and accessible, when CoTS populations were small; when lethal injections were used, and, when resources were adequate and allowed for repeated control efforts (Fisk and Power 1999; Zann and Weaver 1988). Programs failed when CoTS were superabundant, when there was unfettered migration into the control area, and when they were difficult to detect (Gladstone 1993).

The overall impression that programs were not successful led to the assumption that manual control methods could not be scaled up to provide effective control at large spatial scales (Kenchington and Kelleher 1992). This led the Australian Academy of Sciences committee that reviewed responses to the 1960s outbreak to recommend that future controls be conducted only around high-value tourism sites as broad-scale approaches weren't available and biocontrol was deemed too risky (Walsh, Harris *et al.* 1971). In the subsequent outbreak on the GBR in 1979, the focus of management remained at high-value tourism sites with a research focus on site-level control methods, e.g., fencing and copper sulphate injections. Again, while macro-scale controls were deemed of limited value in controlling the spread of outbreaks, consideration was given to the possible development of biocontrol agents, though ultimately this option was rejected due to the uncertainties and risks involved (Gladstone 1993).

Today, there is an increased realization that hard corals on the GBR face a broad range of threats, the impacts of which are cumulative. Dominant amongst these are coral bleaching and increasingly severe cyclones. This has driven a recognition that managing CoTS outbreaks is one of the only options we have to implement direct action to promote reef

resilience. With improvement in control methods and the potential for a more strategic distribution of management resources, there is more optimism that manual control of CoTS can be successful at meso- and maybe macro-scales and a strong feeling that an attempt must be made.

### 1.3 The history of control methods

Action against CoTS requires a means of killing them. Unfortunately, since the 1960s there has been only a slow evolution in the methods used to kill CoTS. Initially, the animals were either cut up in-situ or removed and buried ashore. These techniques could be implemented anywhere and required no special equipment, but they required time-intensive handling of each animal. To overcome this, lethal injection methods based on copper sulphate and sodium bisulphate were developed (Moutardier, Gereva *et al.* 2015; Rivera-Posada, Pratchett *et al.* 2011). While these methods provided a significant improvement in efficiency they still required a large investment per individual animal due to the need to inject multiple arms and their <100% kill efficiency. More recently, the development of single injection methods based on bile salts and vinegar (Moutardier, Gereva *et al.* 2015; Rivera-Posada, Caballes *et al.* 2013; Rivera-Posada, Pratchett *et al.* 2014) have dramatically improved the speed with which individual animals can be handled and current control programs on the GBR are reliant on the bile salts approach (AMPTO 2015).

This improvement in control methods has resulted in a steady increase in efficiency of the control programs, though this is not easily detected from the data due to differences in sampling. The early control programs were focused almost entirely on outbreaking reefs and recorded CoTS killed per minute of dive time (CPUEs) with an average of 0.71 (Zann and Weaver 1988). Current programs, in contrast, focus on both outbreaking and non-outbreaking reefs. This makes it difficult to directly compare current CPUEs to those achieved during early programs because CPUE is strongly related to CoTS density. Fisk and Power (1999), who used early kill methods focussed on reefs at Lizard and Green Island throughout the outbreak cycle, reported average CPUEs of 0.15 across the outbreak. The current program, which visits reefs across the range outbreak statuses, has achieved an average of 0.36 (SD 0.65) (2013-2014, MV Hero and MV Venus). This suggests that the development of single lethal injection methods has resulted in programs that are 2.4 times as effective as the previous lethal injection approach, although care should be taken in drawing strong conclusions from comparison of means because the data are strongly exponentially distributed. It is, however, the only measure reported in the early studies for comparison. The median, a more meaningful statistic, is 0.13 in the current program, with a range from 0 to 6.99 for individual sites.

### 1.4 The future of CoTS control

Single-injection methods are now so efficient that divers spend the great bulk of their time underwater searching for CoTS, and it is unlikely that further significant improvements will be realised through changes in how the animals are handled. Despite this, improvements in control are necessary if goals to manage CoTS impacts on the GBR are to be met. If refinements to handling are unlikely to achieve this, improvements to manual control must come from ensuring that divers are put in the water at the location where their efforts will control the short, medium and long-term size of the CoTS population most effectively and

most strategically. Such an approach differs significantly from current approaches where control voyages focus on assets and nearby reefs with little consideration of current densities or connectivity. These approaches can be improved upon at a variety of scales and represent new ground for CoTS research and management.

In the absence of any immediately available alternative, control efforts will continue to focus on manual killing of individual CoTS for the foreseeable future. It is therefore vital that this is achieved as efficiently and effectively as possible. Research into ecologically-informed, population-level CoTS control will improve the implementation of manual control. At the same time, however, manual control will always be a resource-intensive solution to a large-scale problem, so some research effort must be invested into solutions that can work at regional and whole-of-GBR scales. Ideally, research and management across these disparate scales should be structured to complement and contribute to other scales where appropriate.

Bearing these factors in mind, improvements to management in the short, medium and long term are most likely to come from the following three areas:

- 1) Improvements in how manual control is deployed, today and tomorrow
- 2) The development of non-manual control methods in the medium term
- 3) The effective removal of the causes of outbreaks in the medium to long term

#### **1.4.1 Effective deployment of manual control: designing control programs**

The documentation of past CoTS control programs provides little indication that any significant consideration was given to issues of the design of the activities. With very few exceptions, programs appear to have focused simply on putting divers in the water at locations with lots of CoTS and killing as many individuals as possible until management resources or the coral were depleted (Zann and Weaver 1988). This failure to take a strategic approach has been identified as a contributor to program failure (e.g. Yamaguchi 1986; Zann and Weaver 1988).

This problem is not limited to CoTS management. The history of pest management generally is dominated by attempts to manage species by killing as many individuals as possible with little consideration of where and when efforts will have the biggest strategic impact. This history has few examples of success (Hulme 2006; Pluess, Cannon *et al.* 2012). Despite the vast resources committed to managing native and invasive pest species, unless the pest has a limited distribution or management region, a k-selected life history, or the resources available to deal with it are overwhelming, management programs almost invariably have temporary success at best (Goldson, Bourdot *et al.* 2015; Panetta 2015; Pluess, Cannon *et al.* 2012). Phillip Hulme has characterised the process through which brute force invasive management progresses as a “slippery slope towards management failure” – management first focuses on eradication, when this fails the strategy switches to containment, when containment fails the switch is made to managing impacts, and, ultimately, to adaptation to the new situation (Hulme 2006). Hulme suggests that avoiding this scenario requires that management strategies have a wider perspective, that they not only include management of the species in question but also incorporate an understanding of relevant ecosystem processes, the influence of external environmental drivers, the landscape, the capabilities of management, and the impact of management activities on the pest species itself.

It is worth bearing in mind that even when a brute force approach is possible, the success of a narrowly focused approach to pest management can still be short lived. The rise of pesticide-resistant pest species and the collapse of natural predators following the use of broad-spectrum insecticide provides the classic example from intensive agriculture (Stern, Smith *et al.* 1959). Dealing with these issues resulted in a push for a more strategic approach, combining environmental, ecological, economic and agricultural approaches to management. This ultimately resulted in the development of Integrated Pest Management (IPM)

While individual CoTS can now be controlled with a single injection, the overall efficiency and effectiveness of the manual control program can be significantly improved by ensuring that divers are being put in the water at locations that will generate the greatest medium and long-term reduction in the CoTS population or in the impacts they create on coral. These locations can be identified with the holistic, strategic and evolving approaches of IPM and environmental management (Buckley 2008; Cumming and Spiesman 2006; Thresher, Hayes *et al.* 2014) to ensure the long-term sustainability of control measures (Barzman, Barberi *et al.* 2015). They can be integrated into on-water management using Decision Support Tools (DSTs) that provide actionable management recommendations, such as which reefs and specific dive sites to target on a given voyage, and goal levels for stopping CPUEs at those sites. These DSTs should be underpinned by detailed ecological and management models, but provide management recommendations in terms that managers and divers are familiar with.

A key challenge for implementing IPM based approaches in environmental management is that natural systems are complex, unbounded and usually only partially understood. Temporal and spatial variation combine to make generalisation difficult and predicting outcomes fraught. Improving ecological knowledge and the development of advanced computational, analytical and spatial analysis capabilities has led to the development of computational modelling frameworks capable of testing outcomes and exploring the consequences of uncertainty and variation (Buckley 2008; Westcott and Fletcher 2011). These tools summarise and integrate the many interacting processes occurring in complex ecological systems to predict likely patterns of spread (Buckley, Rees *et al.* 2004; Murphy, Hardesty *et al.* 2008) and the assessment of alternative management options. They act as both a means of assessing the logic underpinning a strategy and as a decision support tool that allows exploration of likely outcomes in scenarios not practically testable in the field (Fletcher and Westcott 2013; Fletcher, Westcott *et al.* 2015).

The advantages of IPM-based Decision Support Tools are particularly attractive in the context of CoTS management. Their holistic approach, informed by an integrated understanding of the processes driving the system, emphasises efficient resource use to achieve objectives that actually contribute to reaching explicit and system-informed goals. This represents a means of dealing with much of the confusion and uncertainty around how to plot a path forward for management and research (see Doherty (2012) and Appendix 2 for examples of debate around these issues). Furthermore, if that platform is designed to explore management outcomes of our current knowledge, rather than inferring management outcomes from an exploration of our understanding, we can expect that it will provide rigorous advice to management without compromising the science.

An IPM approach can not only clarify goals and objectives, but can also point to the fundamental data requirements and gaps in our current knowledge. CoTS control requires

that we deal with a broad range of data types, from the molecular biology of larvae through to ocean-scale atmospheric and current dynamics and to the economics of control. Action could be taken at any and many of these scales and all are likely have some influence, small or large. In addition, right across this broad range of areas there is a great deal of uncertainty. An IPM approach that allows integration of knowledge, exploration of uncertainty, and an assessment of outcomes, would allow both managers and researchers to work in a structured way to identify the data needs most to relevant to the delivery of effective control options. If we are to be successful in ensuring that research contributes to the timely development of solutions then that research investment must be focused and conducted in a coherent and planned fashion.

### **1.4.2 Non-manual control**

Manual control is the only management option available today, but it is fundamentally resource intensive making it expensive to scale up beyond a site or regional scale. From a management perspective the least disruptive management intervention in many respects would be a control technology that could be applied once and which acted without further investment over long time periods and was effective at large spatial scales in preventing outbreaks. Unfortunately, no such ‘silver bullet’ exists.

The search for a silver bullet began early. In 1974, Endean (1974) suggested breeding and distributing the CoTS predator the giant triton, *Charonia tritonis* (Endean 1974). Triton are known to have been heavily hunted on the GBR and also to be enthusiastic predators of CoTS. To date, however, attempts to rear the giant triton in captivity, a critical step in any seeding program, have not been successful. While it is possible to get triton to breed successfully, rearing larvae has proven to be to difficult a hurdle (M. Hall, pers. comm.).

At roughly the same time that Endean called for triton breeding, the committee established to review management options for CoTS examined the question of broadscale controls, in particular biocontrol. They concluded that no practical methods were yet available and that the impact of CoTS wasn’t deemed sufficient to warrant the investment (Walsh, Harris *et al.* 1971). As a consequence their recommendation was that local action only be considered. Subsequently, the Crown of Thorns Committee (COTSAC) supported research into diseases of CoTS as a first step in investigating biocontrol but found no primary pathogens of utility (Lassig 1991). Following the same logic, COTSAC’s successor, the Crown of Thorns Research Committee (COTSREC), recommended against any funding for biocontrol research (Gladstone 1993).

Despite this history, biocontrol retains its allure (e.g., Doherty 2012). The requirements for such an approach are, however, restrictive. First, it would have to be possible to apply the agent at a macro-scale, requiring either that it be self-propagating or that its application could be targeted at a meso-scale, e.g. to critical locations and stages of an outbreak. It would need to be CoTS-specific as it would be used in a system where echinoderms are of ecological and commercial importance. It would ideally be sub-lethal or reversible, and operate to reduce abundance rather than eliminate the species since CoTS are native. It would need to be containable to prevent spread beyond the GBR to areas outside Australia. Finally, and perhaps crucially, it would need to be publically acceptable. This alone represents a challenge as public suspicion is likely irrespective of whether or not there are valid causes for concern. The list of candidate agents or technologies that could satisfy these criteria is vanishingly small. However, it should be remembered that in the years since

COTSREC's assessments of biological control, our understanding of the field, in terms of both the technologies and pathogens available, has improved dramatically. Despite the lack of any obvious candidates (Doherty 2012), a re-examination of the prospects for some form of biocontrol is appropriate.

### **1.4.3 Removal of the causes of outbreaks**

Both manual and non-manual control methods focus on reducing the impacts of outbreaking CoTS populations after the outbreak has begun. CoTS outbreaks would, however, be most efficiently controlled by removing the causes of primary outbreaks. Unfortunately, despite decades of research, scientific consensus about the underlying drivers of CoTS outbreaks remains elusive. A range of hypotheses have been proposed to explain the causes of CoTS primary outbreaks (Engelhardt and Lassig 1992; Pratchett, Caballes *et al.* 2014). These range from outbreaks being the inevitable result of the life history characteristics of a boom-bust taxon (Vine 1973) through to their being the product of anthropogenic interference (e.g., Birkeland 1982; Endean 1969). In the context of the GBR, attention has progressively narrowed to two hypotheses; the nutrient enhancement hypothesis, and the predator removal hypothesis. These hypotheses focus on factors which influence survival and recruitment at different life history stages.

The nutrient enhancement hypothesis focuses on factors that promote larval survival and growth rates, resulting in increased settlement (Birkeland 1982). High nutrient levels in terrestrial runoff, particularly associated with flood plumes, are suggested to lead to enhancement of the phytoplankton food that supports CoTS larvae. This is posited to allow larvae to progress more rapidly through this sensitive life stage, leading to higher settlement of larger and more successful larvae. Observations inconsistent with the hypothesis, e.g. outbreaks in locations without nutrient runoff or without preceding flood plumes, have led to its criticism (summarised in Pratchett, Caballes *et al.* 2014). Wooldridge and Brodie (in press) have attempted to counter some of this criticism by presenting a more complex version of the hypothesis which requires high nutrient carrying flood plumes to occur at times when currents are weak due to El Niño conditions. Their analysis suggests that these conditions are most likely to occur in the vicinity of Green Island, the location from which a number of outbreaks have been first reported. They suggest this coincidence of conditions results in high larval retention and recruitment onto reefs in the vicinity of Green Island. Their analysis of historical data provides successful hindcasting of outbreak densities in this area and of subsequent movement of the outbreak north on inshore currents before subsequently turning south on mid and outer-shelf currents. Their modelling successfully recreates the reported behaviour of these particular outbreaks but whether the hypothesis and similar mechanisms (high nutrient levels, high larval retention, and high recruitment) apply elsewhere on the GBR remains to be seen.

The predator removal hypothesis focuses on factors that promote survival post-settlement and suggests that CoTS populations are ultimately regulated by predation, perhaps particularly on juveniles, with the removal of predators through human exploitation resulting in outbreaks (Endean 1969). Observations such as the fact that some known CoTS predators are, or have been, heavily exploited, e.g. tritons; that reefs closed to fishing were less likely to experience outbreak densities than those open to fishing (Sweatman 2008); and that reefs with the lowest protection tend to have the highest CoTS encounter rates (AMPTO, unpubl. data), all suggest a role for predation in mediating CoTS population dynamics. This suggestion, however, has not been without its critics (H. Sweatman in Doherty 2012). While

modelling suggested that predation was capable of regulating populations prior to outbreaks (McCallum 1987; McCallum 1990), field measurements of predation rates suggested that predation on adults was low (Sweatman 1995), and that the most likely predators were not fished. More definitive exploration of this hypothesis is hampered by the low density and dispersed nature of pre-primary CoTS populations, as well as the fact that on the GBR they may occur only during brief intervals (3-5 yrs) between outbreaks. Funding for CoTS research usually experiences a hiatus during these periods.

While debate amongst scientists still focuses on which of these two hypotheses is responsible for causing outbreaks, the fact remains that i) neither hypothesis excludes the other, ii) given the range of conditions and locations in which outbreaks occur, it is unlikely that a single hypothesis is sufficient to explain all outbreaks (Pratchett, Caballes *et al.* 2014), and, iii) even if one or the other hypothesis is not a causal agent it may well still be a contributing factor either to outbreak establishment or propagation. Furthermore, many CoTS management issues and much of the impact relate to secondary outbreaks, which appear to propagate independent of conditions that may have led to primary outbreaks. Consequently, in this document we work under the assumption that both hypotheses are likely to be contributing either as a cause of outbreaks or by facilitating the emergence and spread of an outbreak.

Both the nutrient enhancement hypothesis (Birkeland 1982; Brodie, Fabricius *et al.* 2005; Fabricius, Okaji *et al.* 2010; Houk, Bograd *et al.* 2007; Lucas 1982), and, the predator removal hypothesis (Endean 1969) point to feasible management interventions. The nutrient enhancement hypothesis suggests that reducing nutrient levels in the runoff into the GBR lagoon would remove the key trigger driving larval settlement in the initiation box, while the predator release hypothesis suggests that zoning to protect predators and the supplementation of predator populations would reduce post-settlement survival.

Appropriate implementation of these management responses should, in theory, result in no future outbreaks and therefore no need for management. Such a happy outcome is, unfortunately, unlikely. The current high levels of end-of-river nutrient loads relative to the required goals (Kroon, Kuhnert *et al.* 2012), and the bleak prospects for future performance (Kroon, Thorburn *et al.* in press; Queensland Government 2015), suggest that reliance on this approach would not be effective, at least in the short to medium term. Similarly, reefs within the initiation box, as identified by (Birkeland and Lucas 1990; Brodie, Fabricius *et al.* 2005; Wooldridge and Brodie in press), are some of the most heavily utilised in terms of commercial and recreational fishing (Great Barrier Reef Marine Park Authority 2014; Taylor, Webley *et al.* 2012). Given the difficulties experienced in the zoning and re-zoning processes overall (Lédée, Sutton *et al.* 2012; Sutton and Tobin 2012), implementing no-fishing zones in this area could only be characterised as difficult. This suggests that zoning would most likely be a medium term and partial prospect, at best. While there are clear difficulties, these considerations do not rule out acting on either hypothesis. They do, however, suggest that the responses indicated by these hypotheses cannot be relied upon in isolation from other management actions, which, at this point in time, are likely to involve manual control.

## 1.5 Summary

The GBR faces a range of interacting and cumulative threats, including increased frequency of bleaching events, increased severity of cyclone damage, development, and Crown of Thorns outbreaks. Of these threats, CoTS are the only one where today's management actions at individual reefs can provide immediate relief. Improving CoTS management is urgent, and vital to support the GBR's resilience and its ability to cope with its changing environment.

The only method of direct control of CoTS that we currently have available is manual control. If this is to be an effective tool for the mitigation and prevention of coral loss at any scale we must ensure that the manual control we are implementing is as efficient and effective as possible. Individual CoTS can be efficiently handled by divers using single-shot injection techniques. To ensure that those divers are generating the most strategic reductions in CoTS populations and the greatest mitigation of CoTS impacts, we must deploy them appropriately. This means knowing where to put them in the water, when to do so, and how long they should invest at any given site. A decision support tool based on analysis of management data and integrated into an IPM modelling approach will provide this information. Development of these tools is a matter of urgency.

As vital as manual control is to protecting key locations within the reef, it is resource intensive and unlikely to be funded at a scale that could protect the entire GBR. Techniques might achieve this are not currently available, but in the medium term it is important that we develop non-manual control methods that can scale to the entire GBR. We need to lay the research foundation for that now.

In the long run, the most effective means of controlling CoTS outbreaks would be to prevent them occurring in the first place. We've spent decades researching why outbreaks occur, but generated few concrete recommendations for implementable management options. Those that are apparent - such as improving water quality or supplementing predator populations - will take a long time to develop further, a long time to implement, and an even longer time to generate results. It is important that we keep developing our understanding of these issues, but we must focus our efforts on those questions that can generate concrete management options, and we must not focus on these issues at the expense of developing management options that we can implement today.

Historically, CoTS research has been carried out by individual research groups at different institutions, developing a range of competing theories and research programs. Continuing in this way, loosely guided by changing funding requirements and government priorities, will perpetuate a slow and meandering process towards failure. While a focus on basic understanding was deemed important under COTSAC and COTSREC, today our ecological understanding is improved, the cumulative impacts of multiple threats to the reef are more urgent, and the tools at our disposal give us practical options for management that we can refine to more effectively control CoTS today. The development of an IPM-based approach will force the clear description of how the relevant systems operate, how management intersects with this, what solutions will be achieved and what outcomes are being sought. Focusing the development around a clearly defined approach to management and the delivery of specific decision support tools will serve to not only produce useful tools for managers but also to ensure that this happens on a useful timeframe.

It is important to note that there is no need to start from scratch in this endeavour. Critical data on life history and management approaches already exist, key process information is either known or can be reasonably estimated, and the first steps in developing aspects of the modelling components required at particular scales has begun, for example, under the Accelerate Program (AIMS, UQ, JCU) and NESP (CSIRO, AIMS, JCU, UQ) (Babcock, Plaganyi *et al.* 2014; Fletcher and Westcott in prep.; Hock, Wolff *et al.* 2015; Hock, Wolff *et al.* 2014; Morello, Plagányi É *et al.* 2014; Plagányi, Babcock *et al.* 2014). While this provides a springboard, not all existing tools will be able to be incorporated and even where they can be, developing an effective suite of decision support tools that can operate across the scales of management interest will be a significant challenge. It will require contributions from a range of research groups, agencies, and managers and a range of research from modelling through to basic ecological field work. Vitally, however, these contributions will be coordinated within the whole-of-problem understanding provided by an IPM approach.

## 2. DEVELOPING AN INTEGRATED FRAMEWORK FOR RESEARCH AND MANAGEMENT

In this and the following sections we outline a framework that provides a pathway to achieving an IPM approach to the management of CoTS. The framework draws on past research and integrates current research activities to provide a link between management and research that can form the foundation for research investment. The approach is based on our understanding of the processes involved in CoTS outbreaks and spread as well as the capacity and processes that determine control operations. It uses this understanding to identify key research gaps and the pathways towards filling these gaps and ensuring that this research contributes to improved management.

Our approach is essentially an Integrated Pest Management approach and it draws on the discussions that took place in the NESP Crown-of-Thorns Starfish Workshop that took place in Townsville on the 1<sup>st</sup> and 2<sup>nd</sup> of September 2015. Workshop participants came from a range of institutions and agencies (see Appendix 3). Critically, they included experts from policy, on-water control, and across the full spectrum of research areas. The workshop produced vigorous debate about particular issues but ultimately ended with general agreement that a new approach was possible and desirable.

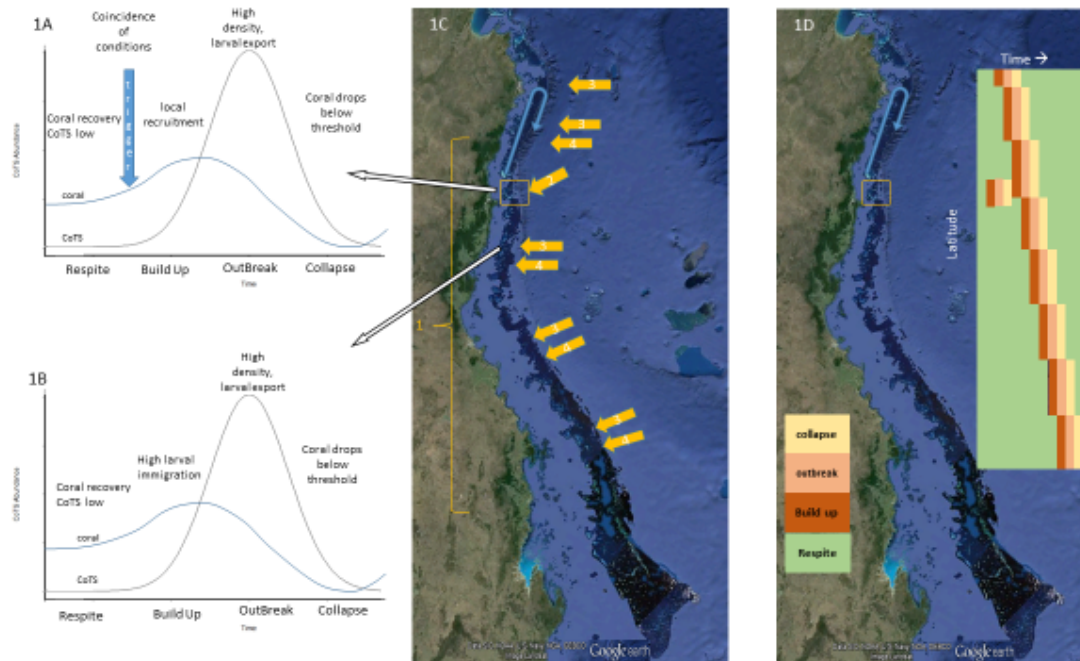
In this section we develop the strategy by reviewing: 1) the ecological phases of CoTS outbreaks; 2) identifying the goals that management might employ in each of those phases; 3) the options for control available for management; and 4) the research that would facilitate success using those management options. By simultaneously considering management across all relevant scales we ultimately integrate the research strategy and needs from the site through to the GBR-scale to provide a coherent approach and achieve additional efficiencies.

### 2.1 The ecological phases of a CoTS outbreak

The four recorded CoTS outbreaks on the GBR seem to have followed a similar pattern (Pratchett, Caballes *et al.* 2014; Wooldridge and Brodie in press). Outbreaks appear to initiate in the north-central section of the reef, roughly between Cairns and Lizard Island (Barnes 1966; Endean 1982; Engelhardt, Miller *et al.* 1997; Sweatman, Bass *et al.* 1998). In most events, outbreaks have first been detected on reefs off Cairns, specifically in the vicinity of Green Island (Birkeland and Lucas 1990; Brodie, Fabricius *et al.* 2005; Wooldridge and Brodie in press), though whether this is a function of sampling or is in fact the origin point of outbreaks is unclear given the resolution of sampling (e.g. Sweatman, Bass *et al.* 1998).

The generally accepted picture of the progress of a CoTS outbreak can be characterised as follows. CoTS populations remain at 'background' levels until the alignment of a suite of conditions allows for a sudden population build up in some part of the initiation box (Figure 1A). This allows for the development of high CoTS densities, high coral loss and high larval export to downstream sites before local coral loss results in a collapse of the population and subsequent gradual recovery of coral. Under the scenarios identified by Wooldridge and Brodie (in press) these downstream sites are likely to be to the north of the initiation area due to northerly inshore currents with the outbreak subsequently moving south on mid- and outer-shelf currents. A similar sequence of events (Figure 1B) is then repeated along the GBR as

secondary outbreaks move along the southerly downstream trajectory (Figure 1D). This means that at any one point in time, different locations along the GBR will be in different phases of outbreak, with more northerly sites generally being more advanced in the sequence. This provides the opportunity to stage different types of management at different sites (Figure 1C) and also to sequence research accordingly.



**Figure 1:** CoTS outbreak cycles. 1A the outbreak cycle at an initiation reef. 1B the outbreak cycle at a reef during a secondary outbreak. The flow of the outbreak along the reef means that different geographic areas will experience different parts of the outbreak cycle at different times (1D) and this means that different management contexts, and different management opportunities, will exist in different locations at different times (1C). This provides opportunities for staging management objectives and research.

We can think about a CoTS outbreak in the initiation zone (i.e. a primary outbreak) as having the following stages.

- 1) Respite phase – corals recover and CoTS population is at background (low) levels
- 2) Build up phase – recruitment builds populations to higher densities in a section of the initiation box
- 3) Initiation of an outbreak triggered possibly by the alignment of pre-conditions including quantity and quality of nutrients in flood run-off improving larval survival, ENSO characteristics promoting high levels of self-seeding of reefs, high coral cover, and low predator populations, all contributing to a build-up of outbreak densities of CoTS within the initiation box. Initiation possibly begins on a few reefs or it may occur across a large section of the initiation box.
- 4) Outbreak phase – population reaches high local densities within the initiation box resulting in high coral loss and very high CoTS larval export to downstream sites (potentially initially to the north).
- 5) Collapse phase – hard coral cover drops below a threshold and CoTS population crashes, potentially caused by a combination of starvation and onset of disease (Pratchett 2005; Pratchett, Caballes *et al.* 2014).

Once a primary outbreak is established and moving downstream from the initiation reefs, downstream reefs experience a similar sequence of events but with some key differences in why the population increases, how the population increases and in the potential outcomes of management intervention. These subsequent outbreaks are often termed secondary outbreaks.

- 1) Respite phase - coral cover gradually increases while CoTS densities remain at background levels.
- 2) Settlement phase – high larval settlement from upstream reefs combines with local recruitment
- 3) Build up phase – result is increasing population
- 4) Escape phase – densities become sufficient to decimate coral and to allow for mass spawning events. These trigger downstream spread.
- 5) Collapse phase - coral resource depleted and CoTS population crashes and disperses

The differences in the processes for primary outbreaks and secondary outbreaks are that i) increases are either a response to the alignment of environmental cues (primary outbreak) or to mass larval immigration (secondary outbreak), ii) early detection is difficult (primary outbreak) or heralded by outbreaks upstream (secondary outbreak), and iii) effective management might prevent an outbreak (primary outbreak) or will modify the trajectory of local impacts of an outbreak (secondary outbreak). These differences suggest different management requirements and mean CoTS management will occur in one of the following contexts:

- 1) Reducing the impact of CoTS at individual sites
- 2) Asset protection, maintaining sites of economic importance or of ecological importance, e.g. key sites for coral recovery
- 3) Preventing/modifying the spread or impact of a secondary outbreak
- 4) Preventing build up or spread of a primary outbreak by direct management in the initiation box
- 5) Preventing the development of the conditions necessary for the initiation of a primary outbreak

Each of these contexts will require goals, strategies and tactics that are tailored to the specific ecological and management processes operating at those scales.

## **2.2 What are the actions that management can take?**

In each of these contexts and at all scales CoTS managers can respond with three basic types of activities. The nature and the goal of the activities will vary depending on the context.

### **2.2.1 Surveillance**

The general purpose of surveillance is to gain information about the state of CoTS populations and coral communities at the scale of interest. In some instances surveillance may be used to trigger actions directly, e.g. monitoring of initiation conditions or of CoTS densities to trigger increased monitoring in the initiation box or deployment of control teams.

In others, it will be used to plan activities to ensure the greatest population-level outcomes. In general terms surveillance will be used in the following contexts:

- 1) To detect a primary outbreak or outbreak conditions
- 2) To delimit an outbreak
- 3) To plan for distribution of control effort

Most current surveillance is achieved through a range of monitoring programs (e.g. LTMP, Eye on the Reef, AMPTO and QPWS surveys). These programs operate at regional and GBR scales and consequently provide low temporal and spatial resolution. There is general consensus that current activities are valuable but being designed for other purposes are inadequate and not fully fit for CoTS management purposes, because they provide data too slowly or in the wrong locations. This highlights the need for CoTS program specific monitoring activities. These activities should include monitoring at the scale of sites, local areas, regions, and, ideally, the GBR if they are to provide detailed and timely results for guiding control activities.

### **2.2.2 Selection of management locations**

Selection of management locations is critical. The process should be dynamic and flexible based on an ecologically-informed understanding of the spatial and temporal interaction between CoTS populations and the control activities to provide the most effective population-level control for the goals and the scale being addressed. Effective decisions about the choice of location will rely on quality data and models of the status and dynamics of the CoTS system. Simulation and analytical models should be used to describe both current distributions and, vitally, future trajectories of the system under different management scenarios. Different models will be required at the different spatial scales and their development will be dependent on calibration against field and experimental data.

Current management is focussed on asset protection of tourism sites and a very small number of 'ecological' reefs, i.e. reefs that are important as sources of coral larvae for recovery of downstream reefs, so management locations are currently determined mainly by factors other than ecologically-informed population control. Strangely, current management sites must be identified as much as a year in advance for permitting, something that greatly reduces the programs ability to respond to current CoTS distributions on the ground.

### **2.2.3 Control**

This activity entails the deployment of resources on water to kill or remove CoTS or modify CoTS behaviour in order to modify the trajectory of outbreaks. Currently, control comprises the deployment of teams of divers manually injecting individual CoTS. With the high efficiency of single-injection techniques, any improvements, once a dive site has been selected, are likely to come from ecologically-informed rules about how much time divers should spend searching each area, based on its ecological or economic importance and the density of CoTS found there, and how the area for control should be delimited. To be practically usable by divers in the water, these rules need to be simple to summarise and implement. Current approaches are based on diver-estimated CPUE during management. Future rules could be expressed in a similar way to maintain consistency, but would be informed by ecologically-informed models and explicit ecological management outcomes.

Future control activities are also likely to rely on injecting but may include manipulating the distribution of CoTS using attractants or repellents to improve performance, enhancement of predator populations through seeding or zoning to ensure maximum natural controls, or the use of Autonomous Underwater Vehicles to automate the process. Ultimately, broadscale management of CoTS populations would ideally employ non-manual approaches such as or the release of pathological agents or predators.

It is important to be clear about appropriate measures of performance. Research in other areas of pest management clearly indicates that simplistic metrics such as total number of individuals killed or area controlled can be misleading (e.g., Fletcher and Westcott 2013), generating poorly controlled pest populations or inefficient investment of management resources. Instead, performance metrics should be developed in the light of the management goals and scale, e.g.; 1) suppression of CoTS densities below outbreak thresholds, and, 2) measures of hard coral health on reefs such as improvements in diversity, cover and hard coral abundance.

## 2.3 Management goals

Planning for management success requires explicit and agreed goals. This does not preclude different goals applying at different scales and nor does it preclude goals changing as knowledge improves or conditions change. Without goals, however, management is almost guaranteed to fail. The overarching, long-term goal of CoTS management, agreed to by policy makers, managers and researchers, is to reverse the decline in coral cover in the face of cumulative impacts, especially climate change, land-based run-off, coastal development, fishing and CoTS (Appendix 2). This can be achieved by reducing CoTS numbers and their impacts so as to maximise the potential for coral recovery on the GBR (De'ath, Fabricius *et al.* 2012). Ultimately we should seek to achieve this goal at the scale of the GBR, providing protection to both economically and ecologically important reefs and the entire regional ecosystem. In the short term, however, there is an immediate and on-going imperative to protect high value tourism sites.

Currently, CoTS control will necessarily be implemented by divers deployed from vessels travelling to particular regions within the GBR, to individual reefs and to specific dive sites. It is vital that we make this process as efficient and effective as possible, while simultaneously collecting the information we need to achieve medium- and long- term goals of regional-scale non-manual control and reduction of the ultimate causes of outbreaks. If we cannot successfully manage sites and local areas, and the evidence suggests that we struggle to do so (Engelhardt, in prep; AMPTO 2015), then only luck will bring success at any other scale. Our first management goal is therefore:

- 1) *Effective control at sites and local areas*, through efficient **surveillance** leading to informed site **selection** and the implementation of efficient and effective **control** activities.

In addition to this enabling goal, there are four management goals related to the phases of CoTS outbreaks (ordered to take into account the existence of a current secondary outbreak):

- 2) *Protecting assets at the scale of individual reefs*, by optimally distributing **surveillance** across a portfolio of assets, **selecting** sites that can be managed within budget and

logistic constraints and which provide the required economic or ecological benefit, and **controlling** them to maintain those economic or ecological assets

- 3) *Minimizing impacts and spread of secondary outbreaks*, using **surveillance** to delimit outbreak and build-up zones; then **selecting** sites within the outbreak zone to **control** in order to minimize impact; **selecting** sites within the build-up zone to **control** the spread of CoTS larvae from highly connected reefs; **selecting** sites within the build-up zone and **controlling** them to maximise the spread of coral larvae
- 4) *Preventing primary outbreaks*, by monitoring environmental conditions, **surveilling** pre-outbreak populations in the initiation box and **selecting** and **controlling** those populations to maintain densities below outbreak thresholds
- 5) *Controlling ultimate causes*, by reversing nutrient input to the GBR lagoon or preventing predator release,

While improvements in the strategic distribution of manual control will provide significant improvements in the performance of control programs, we cannot be confident that these programs can be scaled up to provide effective control at regional or GBR scales. New non-manual technologies that reduce our reliance on manual control are required. This prompts a final enabling management goal:

- 6) Effective control at regional and GBR scales, achieved through non-manual technologies that either supplement or replace manual controls.

Below, we develop each of these goals further; identifying what management steps would be required to achieve each goal, and what research activities would fill knowledge gaps to inform those management steps. These strategies are the outcome of the workshop, drawing on the experience of both policy and on-water managers, and a broad range of researchers (see Appendix 3 for a list of participants and their affiliations).

### **2.3.1 Goal 1: The fundamental management activity: Control at a single site**

Given current technologies, manual control at a site represents the fundamental unit of management action in each of the management contexts considered above. Irrespective of the scale at which we are interested in achieving our goals, as soon as we choose to use manual control we are choosing to operate at particular sites, reefs, and local areas. Manual control currently revolves around boats, divers and their time culling CoTS at a specific control site on a particular reef in a reef complex or local area during a voyage. Consequently, maximising the effectiveness and efficiency of activities at the site, reef and local area scale has the potential to free up resources within a voyage and to focus resources at the sites where the greatest strategic impact can be had. In short, it will be fundamental to achieving any success in CoTS control as we currently know it.

Current operations are based on reducing CoTS at somewhat arbitrarily defined sites on a reef to levels below outbreak and keeping them at these levels. Like CoTS monitoring, these activities are restricted to the top 10-15m of the reef and primarily to the reef edge and take little further account of the distribution of CoTS on the reef or of their spatial dynamics. Current programs can experience complete replacement of culled CoTS populations in <6 weeks (AMPTO 2105), suggesting that scope exists for improvement through better management of the size of targeted areas, control return times or addressing population reservoirs in more difficult to access habitats such as deeper waters or reef flats.

We can do better and we must. Managing fifty sites effectively will produce greater long term benefits than managing a hundred sites ineffectively. The location, spatial scale, and timing of management actions should be based on the ecological processes driving the CoTS population and focussed on removing the individuals that contribute most to long-term CoTS population growth and impacts. Available management resources should be distributed across sites and local areas such that meaningful medium- and long-term reductions in the CoTS population and impacts are achieved at each site. This will determine the number of sites, reefs and local areas that can be managed effectively, the spatial scale of management at each site, and the revisitation schedule for each site in order to provide protection of the assets there.

These considerations can be summed up as three sub-goals within the Goal 1, namely:

- Goal 1.A Reduction of CoTS to below threshold densities
- Goal 1.B Removal of the individuals that are most ecologically important
- Goal 1.C Protection of assets, both economic and ecological

A management strategy that can achieve these goals requires surveillance at the beginning of each voyage, to ascertain where CoTS densities within the voyage region are highest. This information, along with a site and local-scale ecological model of CoTS populations, would allow the selection of the individual dive sites where the biggest population-level impacts could be expected to be achieved. The site and local model should be informed by ecological data from the literature and targeted field studies of key parameters. Once sites were selected, divers should be dropped in the water, manually controlling CoTS to reduce the local density to a cost-per-unit-effort (CPUE) calculated to generate the largest population-level reduction in CoTS impacts (as distinct from simply removing the greatest number of CoTS). Further surveillance to ascertain the effectiveness of control, coupled with analysis of the site and local scale model, should be used to make a decision about whether

to redeploy divers. Finally, information about and development of new methods that might improve the effectiveness of control should be collected, where possible, during control actions to aid the development of new control technologies such as attractants and repellents.

This information about management goals, a management strategy that can achieve these goals, and the research strategy necessary to realise the proposed management strategy is summarized in Table 1 below.

**Table 1:** Control at a single site

| Management strategy                                                                                                                            | Research strategy                                                                                                         |
|------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------|
| 1.1 <b>Surveillance</b> to identify the distribution of CoTS at the site                                                                       | 1.1.1 <b>Develop</b> efficient local-scale surveillance strategy for measuring CoTS distributions in each control voyage  |
| 1.2 <b>Selection</b> of those dive locations within the site at which control will generate the greatest population-level reduction of impacts | 1.2.1 <b>Field measurement</b> of movement and spatial dynamics of individual adult CoTS                                  |
|                                                                                                                                                | 1.2.2 <b>Analyse</b> spatial dynamics of adult CoTS                                                                       |
|                                                                                                                                                | 1.2.3 <b>Analyse</b> observed distribution from surveillance, habitat preference of all life stages, and activity of CoTS |
|                                                                                                                                                | 1.2.4 <b>Model</b> the CoTs/management system at the site and local scale to assess and refine management approach        |
| 1.3 <b>Control</b> implemented at selected sites by the deployment of divers                                                                   | 1.3.1 <b>Develop</b> optimal CPUE stopping time rules to optimise population control using the model from 1.2.4           |
| 1.4 <b>Surveillance</b> to measure outcomes and decide whether to redeploy divers                                                              | 1.4.1 <b>Analyse</b> population dynamics in response to management                                                        |
|                                                                                                                                                | 1.4.2 <b>Refine</b> model of CoTS/management system from 1.2.4                                                            |
|                                                                                                                                                | 1.4.3 <b>Develop</b> redeployment rules based on model analysis                                                           |
| 1.5 Develop new technologies for <b>control</b>                                                                                                | 1.5.1 <b>Develop</b> the technology of attractants/repellents                                                             |
|                                                                                                                                                | 1.5.2 <b>Develop</b> strategy for integrating technologies into management framework                                      |

### **2.3.2 Goal 2: Protecting assets**

The current CoTS management program was designed to protect economically important reefs, namely high value tourism sites, particularly in the Cairns Region and to a lesser extent the Wet Tropics coast and the Whitsundays. Protecting these sites will remain a key focus of future iterations of CoTS management programs because tourism operators are key stakeholders in the management system and because the economic importance of the sites outweighs the costs of management.

The concept of prioritising key assets in a resource limited world is a sensible approach and should be extended to include sites that are considered important from an ecological perspective. Specifically, some reefs are likely to be important because they contain rare or uncommon coral or fish species or because of their size and condition. Similarly, because of their connectivity (Hock, Wolff *et al.* 2014) some reefs may serve as vital sources of coral larvae to promote the downstream health and resilience of the GBR (Hock, Wolff *et al.* 2015). It may be important to control other reefs because they drive the spread of the outbreak by serving as a major downstream source of CoTS larvae.

There has already been a move to manage ecologically important reefs where possible under the current program and there is an opportunity to use increased efficiencies of control and knowledge developed within the program to further increase the scope of protection of these ecologically important reefs.

These considerations lead us to define the following goals for asset protection:

- Goal 2.A To maintain the value of economic assets – coral cover, reef health and aesthetic appeal
- Goal 2.B To maintain the value of ecological assets – through the identification and protection of sites that promote coral recovery post-outbreak and that reduce the spread of CoTS during an outbreak.

A management strategy to protect key assets would first require a method of selecting which assets were important. It is easy to justify the management of economic assets based on their importance to tourism and the person paying for management actions to occur there. It is however more difficult to summarise what makes an ecological asset important, how to rank different ecological assets, and how to trade-off the importance of ecological and economic assets. Developing a set of universally-accepted criteria would require dedicated research into what characteristics were important for different assets, and an analysis of reefs within each management region to shortlist and rank the assets located there.

Once a list of assets within a management region is determined, surveillance would be required across the portfolio to ascertain the density of CoTS at each asset and the urgency of management there based on the importance of the asset and its sensitivity to CoTS damage, to select sites where control actions are to be implemented. If surveillance is required across a large region, this may require significant assessment of logistical costs.

Once control sites were selected, divers should be dropped in the water, manually controlling CoTS to reduce the local density to a target cost-per-unit-effort (CPUE) calculated using the site and local scale CoTS-management model developed as part of Goal 1. The goal of management, however, should be refined from the analysis in 1.3.1 to explicitly specify the density of CoTS necessary to protect the economic or ecological quality of each asset.

**Table 2:** Protecting assets

| Management strategy                                                                                                                                                 | Research strategy                                                                                                                                                                      |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 2.1 <b>Selection</b> of assets of concern, based on economic importance to tourism or ecological importance to coral resilience                                     | 2.1.1 <b>Develop</b> a set of criteria for valuing and ranking economic and ecological assets                                                                                          |
|                                                                                                                                                                     | 2.1.2 <b>Analyse</b> reefs to identify priority assets                                                                                                                                 |
| 2.2 <b>Surveillance</b> at selected sites, based on relevant management trigger thresholds and a logistical strategy based on site location and management capacity | 2.2.1 <b>Develop</b> an efficient regional-scale surveillance strategy of priority assets, based on ecological processes and management capabilities                                   |
|                                                                                                                                                                     | 2.2.2 <b>Refine</b> surveillance design based on analysis of management outcomes                                                                                                       |
| 2.3 <b>Control</b> selected sites by the deployment of divers                                                                                                       | 2.3.1 <b>Develop</b> optimal CPUE stopping time rules as a function of needs for economic assets and needs for ecological assets, using the model from 1.2.4 and the criteria of 2.1.1 |

### **2.3.3 Goal 3: Managing the existing outbreak**

At the end of 2015 there is an outbreak currently proceeding southwards along the GBR, with the “front” somewhere between Innisfail and Townsville. Urgent regional-scale goals of management at and just ahead of this front include minimising the impacts of high densities of CoTS at the front, disrupting the spread of CoTS larvae south of the front, and facilitating the spread of coral larvae to aid regeneration after the outbreak has passed. Realistically, current levels of CoTS management resourcing make control of the outbreak over the regional scales necessary to comprehensively disrupt the outbreak unlikely. On the other hand, current resourcing will allow an attempt to be made to reduce the impacts of the current outbreak by targeting manual control at highly connected reefs, while simultaneously allowing management strategies to be tested at different points in the outbreak cycle, and research completed to inform future management of the outbreak. Furthermore, the rolling nature of the outbreak will allow these strategies to be repeatedly refined as the outbreak moves southwards (Figure 1).

These considerations lead us to define the following goals for managing the existing outbreak:

- Goal 3.A Surveillance to detect movement of outbreak
- Goal 3.B Manage reefs within the outbreak zone to reduce/eliminate CoTS densities with the goal of preventing coral loss
- Goal 3.C Manage reefs over the larval dispersal range to prevent build up and to disrupt continued flow
- Goal 3.D Manage ecologically important reefs to protect and enhance coral recovery potential

A regional-scale strategy to manage and disrupt the current outbreak must first accurately delineate where the peak of the adult CoTS population and coral damage is located (the “outbreak zone”), and where CoTS larval and juvenile populations are currently building to a point where outbreak is imminent (the “build-up zone”). It is important to delineate these zones because management strategies will be different in each zone. Delineating the outbreak over a large regional scale will require both traditional surveillance techniques and the development of new surveillance programs, such as broad-scale larval sampling. Not everywhere will be able to be sampled, but measurements can be used to parameterise an ecologically-informed regional-scale CoTS population and current connectivity model to interpolate CoTS densities across the region. In addition to surveillance, this model will need to be informed by further field measurements to refine our understanding of larval dispersal shadows, the rate of spread of the outbreak, life history parameters from juvenile to adult CoTS. Analysis of the model will define outbreak and build-up zones.

Within the outbreak zone, further analysis of the regional scale model will allow management locations to be selected, and the local-scale model from 1.2.4 can be used to identify CPUE stopping rules with the overall goal of minimising coral loss during the outbreak. In the build-up zone, the regional scale model can be used to identify locations likely to receive high larval loads from the current outbreak zone, based on ocean current connectivity networks. To protect coral recovery potential and enhance the resilience of the reef will require the development of a model of coral dispersal using reef quality indexes based on field measurement, disturbance regimes and class of reef, plus ocean-current connectivity

models. This will allow selection of key sites within the outbreak and build-up zones as a priority for control actions.

Finally, the refinement of regional-scale downstream larval and juvenile surveillance techniques will allow both program monitoring and the development of an early warning system.

**Table 3:** Managing existing outbreaks

| Management strategy                                                                                                                                                                                                                                                                          | Research strategy                                                                                                                                                                                                                          |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 3.1 <b>Surveillance</b> to delimit build-up and outbreak zones and the distribution of CoTS abundance                                                                                                                                                                                        | 3.1.1 <b>Develop</b> surveillance program to adequately identify and delimit outbreak zone                                                                                                                                                 |
|                                                                                                                                                                                                                                                                                              | 3.1.2 <b>Develop</b> deployable surveillance technologies                                                                                                                                                                                  |
|                                                                                                                                                                                                                                                                                              | 3.1.3 <b>Model</b> the regional CoTS population on a reef connectivity network to predict the current distribution of CoTS outside sampled areas, project future CoTS distributions, and refine surveillance                               |
| 3.2 <b>Selection</b> of downstream management zones, including a build-up and outbreak zone, based on a population and connectivity model underpinned by past / current spread data to predict distribution and status of outbreak, possibly validated by targeted juvenile searches         | 3.2.1 <b>Field measurement</b> of larval dispersal shadow, larval settlement, recruitment                                                                                                                                                  |
|                                                                                                                                                                                                                                                                                              | 3.2.2 <b>Analyse</b> the rate of outbreak spread from current data                                                                                                                                                                         |
|                                                                                                                                                                                                                                                                                              | 3.2.3 <b>Develop</b> capability to detect juveniles to understand risk of future outbreak on a reef                                                                                                                                        |
|                                                                                                                                                                                                                                                                                              | 3.2.4 <b>Identify</b> extent of build-up and outbreak zones based on analysis of the regional model from 3.1.3, observed CoTS densities, and reef connectivity                                                                             |
| 3.3 Manage adults within the outbreak zone: <ul style="list-style-type: none"> <li>• <b>Selection</b> of reefs using local and regional model to minimise coral loss</li> <li>• <b>Control</b> selected sites</li> <li>• <b>Surveillance</b> to decide whether to redeploy divers</li> </ul> | 3.3.1 <b>Analyse</b> the current distribution of CoTS and the regional scale model from 3.1.3 to select sites to minimise coral loss                                                                                                       |
|                                                                                                                                                                                                                                                                                              | 3.3.2 <b>Develop</b> optimal CPUE stopping time rules to minimise coral loss, using the site and local scale model from 1.2.4                                                                                                              |
|                                                                                                                                                                                                                                                                                              | 3.3.3 <b>Develop</b> redeployment rules from analysis of the site and local scale model from 1.2.4 and the criteria of minimal coral loss                                                                                                  |
| 3.4 Manage adults within the build-up zone: <ul style="list-style-type: none"> <li>• <b>Selection</b> of reefs using regional model to prevent build-up and disrupt continued spread</li> <li>• <b>Control</b> selected sites</li> <li>• <b>Surveillance</b> to monitor outcomes</li> </ul>  | 3.4.1 <b>Analyse</b> regional scale model to select sites likely to receive high densities of larvae from current outbreak zone and sites likely to drive downstream spread                                                                |
|                                                                                                                                                                                                                                                                                              | 3.4.2 <b>Develop</b> optimal CPUE stopping time rules using the site and local scale model from 1.2.4 and based on the importance of sites as downstream sources and the likelihood of those sites as sinks from the current outbreak zone |
| 3.5 Manage to protect coral recovery potential:                                                                                                                                                                                                                                              | 3.5.1 <b>Design</b> a set of criteria for valuing and ranking reefs based on their expected quality, given their structure, their history of                                                                                               |

|                                                                                                                                                                                                                                            |                                                                                                                                                                                                                                                                                                                                                |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"> <li>• <b>Selection</b> of coral resources to be protected based on reef quality and connectivity</li> <li>• <b>Control</b> selected sites</li> <li>• <b>Surveillance</b> to monitor outcomes</li> </ul> | <p>cyclone damage, bleaching, water quality, and connectivity</p> <hr/> <p>3.5.2 <b>Model</b> the linked coral / CoTS system based on CoTS damage to coral and external factors affecting reef quality</p> <hr/> <p>3.5.3 <b>Identify</b> reefs likely to be vital to coral recovery by analysing the linked coral / CoTS model from 3.5.2</p> |
| <p>3.6 <b>Surveillance</b> of larvae, settlement and juveniles at downstream locations</p>                                                                                                                                                 | <p>3.6.1 <b>Develop</b> “maintain position” and “fallback” rules based on the density of CoTS larvae, settlement and juveniles measured by downstream surveillance</p>                                                                                                                                                                         |

### **2.3.4 Goal 4: Preventing outbreaks in the initiation box**

In the medium term, preventing outbreaks before they begin is likely to be much more resource efficient than trying to manage them once they have spread out over a large area. This approach is supported by the fact that previous outbreaks appear to have begun within a constrained area referred to as the Initiation Box. Within this region, even the manual control tools we currently have at our disposal are likely to provide a practical and affordable way of preventing the impacts of CoTS outbreaks. Vitally, for this to work, these tools will need to be applied consistently within the initiation box prior to the beginning of the next outbreak. Serendipitously, some of the management strategies we need to test and research questions we would need to answer can be informed by management in the outbreak and build-up zones of the current outbreak as part of Goal 3. Others will require focussed efforts within the initiation box well before the next outbreak.

Past outbreaks have appeared to begin in a region between Lizard Island in the north and Cairns in the south (Figure 1 B). Initial outbreak reports suggest the initiation box was probably in the southern part of this zone, between latitudes 16 and 17°S (Moran, De'ath *et al.* 1992). Recent work combining models of nutrient loads, larval survival and hydrodynamic models of dispersal has further refined this, suggesting that the unique spatial and temporal juxtaposition of rare high nutrient flood events and low current flows during some spawning periods in the vicinity of Green Island make these reefs the likely epicentre of primary outbreaks (Wooldridge and Brodie in press). Further refinement and ideally reduction of the initiation box will be vital to efficient management, including determination if initiation can occur in other regions.

These considerations lead us to define the following goals for preventing outbreaks in the initiation box:

- Goal 4.A Reduction of CoTS triggers, reduction of nutrient levels entering the GBR waters from terrestrial sources, and increased predator densities
- Goal 4.B Early detection of outbreak conditions through surveillance
- Goal 4.C Identification of likely outbreak sites within the initiation box identified early
- Goal 4.D Implementation of control to prevent full development of an outbreak through control of either settling larvae or of juveniles and young adults.

In practice, the fact that the prevention of outbreaks must occur at a time when outbreaks are not occurring presents a major problem because it is difficult to maintain funding, social awareness and management emphasis during these periods. Developing a coherent message, supported by quantitative modelling, of the benefits of consistent management of the initiation box to funders is vital.

An absolutely key component of management of the initiation box before an outbreak begins is comprehensive surveillance of larval, juvenile, and adult populations. To achieve this at a regional scale will require efficiency improvements in current surveillance methods and the development of new broad-scale surveillance methods. Identifying key precursor preconditions, such as nutrient measurements or environmental variables, is likely to be of key importance.

Within the initiation box, the regional-scale models from 3.1.3 and 3.5.2, of CoTS populations, coral populations and ocean-current connectivity will be vital for targeting both surveillance and control efforts at those locations most at risk of generating an outbreak.

CPUE stopping times calculated from the local-scale model from 1.2.4 will need to be refined to account for the severe consequences of management failure. Further refinement of downstream surveillance of larvae and juvenile densities from 3.6.1 will be vital to ensure CoTS population build-up in the initiation box has not been missed.

**Table 4:** Preventing outbreaks in the initiation box

| Management strategy                                                                                                                                                                                                                                                                                                                                                                                                     | Research strategy                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 4.1 <b>Maintain</b> funding for surveillance throughout the outbreak cycle                                                                                                                                                                                                                                                                                                                                              | 4.1.1 <b>Investigate</b> appropriate governance and financial mechanisms to facilitate management actions during non-outbreak phases of CoTS cycles on the GBR                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
| 4.2 <b>Surveillance</b> to provide early warning of the initiation of an outbreak, including: <ul style="list-style-type: none"> <li>• monitoring of pre-conditions (coral cover, predator density, nutrients, environmental variables) to provide early warning</li> <li>• surveillance of appropriate life history stage for warning, and</li> <li>• surveillance of adult CoTS to identify outbreak reefs</li> </ul> | 4.2.1 <b>Identify</b> relevant preconditions to monitor and identify relevant thresholds of nutrients, predators, coral cover, other environmental variables, or constant monitoring if confidence is low<br><hr/> 4.2.2 <b>Identify</b> the most appropriate life history stage to monitor, recognising trade-offs between timing of detection, cost effectiveness of monitoring and reliability of signal<br><hr/> 4.2.3 <b>Identify</b> the best CoTS monitoring signals of outbreak initiation based on: coral cover; feeding scars; adult count; strategies and techniques for finding juveniles on reefs<br><hr/> 4.2.4 <b>Design</b> a cost effective and efficient surveillance program based on the ecological and logistical processes driving the CoTS/Coral/Management system, including connectivity and deployable surveillance technologies<br><hr/> |
| 4.3 <b>Selection</b> of target reefs for management action based on models that combine surveillance data on the distribution of outbreak reefs, spatial and temporal dynamics and connectivity of CoTS populations, and spatial and temporal dynamics of management capacity                                                                                                                                           | 4.3.1 <b>Model</b> CoTS population/connectivity at regional scale, including: larval survival under natural conditions, life history data, particularly settlement – recruitment transition probabilities or the development of proxies<br><hr/> 4.3.2 <b>Model</b> management at regional scale, including: boats, divers, constraints, etc<br><hr/> 4.3.3 <b>Identify</b> starting and stopping surveillance CPUEs at which reefs will be selected by integrating ecological and management models to determine ecological and economic trigger levels, low-density search and destroy effectiveness, natural control methods<br><hr/>                                                                                                                                                                                                                            |
| 4.4 <b>Selection</b> of individual sites for CoTS control within target reefs using reef-complex level population and habitat models                                                                                                                                                                                                                                                                                    | 4.4.1 <b>Identify</b> sites within reef complex for management using the regional-scale models from 4.3.1 and 4.3.2 based on adult mobility and activity patterns, habitat selection, and CoTS distribution, and the local-scale models of 1.2.4 based on boats, divers and operational constraints<br><hr/> 4.4.2 <b>Analyse</b> data to examine potential of predator management through zoning<br><hr/>                                                                                                                                                                                                                                                                                                                                                                                                                                                          |

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4.5 **Control** activities implemented at selected sites

4.5.1 **Identify** appropriate CPUE stopping rules for the initiation box using the model from 1.2.4, and the importance of juvenile control

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4.6 **Surveillance** of downstream reefs guided by models of CoTS population and management capacity dynamics.

4.6.1 Develop model that integrates information on reefs controlled, reefs monitored, CoTS dynamics and management constraints to identify optimal sets of reefs for control

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4.7 Return to on-going **surveillance**, and if downstream escape is detected implement Managing Existing Outbreaks

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### **2.3.5 Goal 5: Removing the ultimate causes of outbreaks**

In the long-term, removing the ultimate causes of outbreaks is likely to be the most efficient way of controlling the impacts of CoTS outbreaks on the GBR. Unfortunately, decades of research has led to little consensus on the causes of outbreaks. More pragmatically, the solutions based on the hypothesised causes will take a long time to implement, will require further research, and will require large-scale social changes before their effects will be seen. On the other hand, even if consensus about the ultimate causes of outbreaks eludes the CoTS research community, there is a general acceptance that all of the mechanisms proposed probably contribute to the growth and spread of CoTS population, and that management actions that can address those mechanisms represent generally solid and justifiable environmental management and a no-regrets option for future work. For this reason, management actions into the ultimate causes of outbreaks and research activities that can support them should form a small but consistent and long-term part of an overall strategy for CoTS management.

The two major hypotheses proposed to explain the initiation and spread of CoTS outbreaks are: i) the nutrient enhancement hypothesis, in which larval survival is enhanced by increased nutrient runoff in flood plumes (Birkeland 1982; Brodie, Fabricius *et al.* 2005; Fabricius, Okaji *et al.* 2010; Houk, Bograd *et al.* 2007; Lucas 1982), and, ii) the predator removal hypothesis, which suggests that harvest of predator species has removed top-down regulation at one or more CoTS life history stages (Endean 1969). Both hypotheses suggest management interventions that are feasible: 1) the nutrient enrichment hypothesis suggests that activities that can reduce high levels of nutrient runoff into the GBR lagoon would remove the key trigger driving mass recruitment in the initiation box; and 2) the predator release hypothesis suggests that zoning to protect predators on reefs and the supplementation of predator populations may reduce successful build-up of adult CoTS populations within the initiation box.

These considerations lead us to define the following goals for preventing ultimate causes:

- Goal 5.A Dampening or prevention of primary outbreaks through improvements in water quality on CoTS population dynamics
- Goal 5.B Manipulation of predator populations, particularly at sites of high economic or ecological value to prevent or dampen primary and secondary outbreaks

An important consideration is the extent to which research into these causes should be funded from the current CoTS program. Water quality improvement in runoff that reaches the GBR is already the focus of a large and coordinated research and implementation program funded by the Australian Government (Reef Trust, Reef 2050, Reef Water Quality Protection Plan). Research as part of the CoTS program should therefore be limited to monitoring CoTS populations and key environmental drivers in the initiation box, to analyse the impact on CoTS populations of changes to water quality and to help provide early indications of outbreaks.

In contrast, there is little other research into the impact of zoning and predator populations on CoTS (but see Sweatman 1997; Sweatman 2008; Sweatman 1995). Research is currently being conducted into the identity and extent of predation on CoTS at various life history stages through both JCU and AIMS. Previous progress should be summarised with a review of triton ecology with respect to CoTS. While it is possible that a range of species feed on

CoTS at different stages, manipulation of the populations of most of these species will only be effective through zoning to prevent harvesting of predatory fish on ecologically significant reefs, and through the aquaculture of predatory shells, e.g. triton, for this and other commercial purposes. Therefore current data should be analysed to assess the impact of green zones on CoTS populations.

**Table 5:** Reducing ultimate causes

| <b>Management goals</b>                                                                                                                                                                                    |                                                                                                                                                                                                                   |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 5.A Dampening or prevention of primary outbreaks through improvements in water quality on CoTS population dynamics                                                                                         |                                                                                                                                                                                                                   |
| 5.B Manipulation of predator populations, particularly at sites of high economic or ecological value to prevent or dampen primary and secondary outbreaks                                                  |                                                                                                                                                                                                                   |
| <b>Management strategy</b>                                                                                                                                                                                 | <b>Research strategy</b>                                                                                                                                                                                          |
| 5.1 Reduction in nutrients received by the GBR lagoon from terrestrial runoff through improvements in agricultural practises and land management to remove a necessary driver of CoTS outbreak initiation. | 5.1.1 <b>Identify</b> key environmental drivers of primary outbreaks                                                                                                                                              |
| 5.2 <b>Monitor</b> CoTS populations and key environmental drivers within the initiation box over time to confirm the effectiveness of actions and to refine the predictors of outbreaks                    |                                                                                                                                                                                                                   |
| 5.3 <b>Monitor</b> CoTS populations and environmental drivers within the initiation box to provide early warning of outbreaks                                                                              |                                                                                                                                                                                                                   |
| 5.4 <b>Identification</b> of key ecological reefs                                                                                                                                                          |                                                                                                                                                                                                                   |
| 5.5 <b>Implementation</b> of zoning as required                                                                                                                                                            | 5.5.1 <b>Analyse</b> monitoring data to identify the effect of zoning on CoTS populations given proximity to outbreak, urban areas and other confounding factors                                                  |
| 5.6 <b>Implementation</b> of predator seeding of reefs                                                                                                                                                     | 5.6.1 <b>Review</b> triton ecology and biology with respect to the species' potential role as a natural component of CoTS management program, including a review of the prospects for captive rearing and release |

### **2.3.6 Goal 6: New technologies**

On the face of it there seems to be little hope of comprehensively controlling CoTS outbreaks on the GBR using manual control. The scale of the problem is huge. We are dealing with an area of approximately 344,000 km<sup>2</sup> and comprising 3000 reefs distributed along a 2,300 km axis. We are intending to control a species that is distributed across this entire region and whose numbers are estimated to be on the order of tens of millions, even in relatively small sections of this area. Moreover, the species has weedy traits such as high fecundity and rapid growth. For this task we are marshalling a control program that has at its disposal a single vessel that averages 25 voyages a year and 36 dive sessions per voyage, or roughly 900 dives a year (AMPTO unpubl. data). The chances of this level of investment being successful seem rather slim.

If our goal is defined crudely as “to control CoTS at the scale of the GBR” then the chances of success would seem to be indeed, slim. Those prospects improve, however, if instead our goal takes into account the staged nature of the distribution of outbreak conditions on the reef, providing the opportunity for focusing on sub-sections at a time. They improve further still if our objectives are more refined and specific, e.g. to reduce the intensity or frequency of outbreaks rather than eradicate them completely; or to limit the spread of CoTS or facilitate coral recovery. Under these regimes the linked research and management approach described above offers some prospect of success given current technologies.

Even in this optimistic scenario, however, assistance in the form of broad-scale control methods which allow for non-manual and self-propagating control would be a valuable, and possibly essential, addition to the management toolkit. While by no means a novel idea, past assessments of such options, which largely consisted of some form of biocontrol, identified little in the way of prospects worthy of further investigation. They ultimately decided that specificity of agents was likely to be too low, the risks of escape beyond CoTS to other echinoderms or beyond the GBR to other areas was too high, and the chance of public acceptance too low to warrant implementation (Doherty 2012; Gladstone 1993; Lassig 1991; Appendix 2).

Since the time of the earlier reviews, however, there have been significant advances in our approach to biocontrol, our understanding of echinoderm biology, pathology and epidemiology, and in the suite of tools available for application in the context of pest management. This suggests that a review of potential ‘silver bullets’, extending beyond biocontrol and including emerging technologies is timely.

These considerations lead us to define the following goal for new technologies:

- Goal 6.A Management of CoTS through a low cost, high efficiency non-manual control method

Developing these techniques will require significant research and time, and should not distract the current management and research program from focussing on improvements that can be made now. In the near future, therefore, the research program should review previous work in this area, and the availability of new technologies, to provide recommendations for potential new technologies to be further considered during future research programs.

**Table 6:** Non-manual control

| Management goals                                                                          |                                                                                                                                                                                                                                                             |
|-------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 6.A Management of CoTS through a low cost, high efficiency non-manual control method      |                                                                                                                                                                                                                                                             |
| Management strategy                                                                       | Research strategy                                                                                                                                                                                                                                           |
| 6.1 <b>Release</b> of an agent/s that retains CoTS populations at non-outbreak densities. | 6.1.1 <b>Review</b> potential methods                                                                                                                                                                                                                       |
|                                                                                           | 6.1.2 <b>Identify</b> likely candidates                                                                                                                                                                                                                     |
|                                                                                           | 6.1.3 <b>Describe</b> likelihood of successful development and the factors influencing this, and the likelihood of successful implementation with respect to theories of CoTS outbreak initiation, ecological and IPM theory, cost effectiveness, and risks |
|                                                                                           | 6.1.4 <b>Recommend</b> next steps                                                                                                                                                                                                                           |

### 3. A RESEARCH STRATEGY TO SUPPORT MANAGEMENT: NOW AND INTO THE FUTURE

The list of things we might study in relation to CoTS and their management on the GBR is large (see, for example, discussion in Doherty 2012; Appendix 2; Pratchett, Caballes *et al.* 2014). In the previous section we reviewed the contexts in which management is likely to be deployed at different stages of an outbreak and used this to suggest a suite of research questions and management tools that would directly and immediately contribute to successful control programs operating at the scales that are required to meet management goals. The resultant list is very different to the research questions that have been the focus of much of the discussion of CoTS research in the past (Doherty 2014; Appendix 2), and to the research strategies identified elsewhere. These differences arise from the very different objectives underpinning their development. Whereas others have sought to improve understanding generally, or improve understanding of outbreaks in order to improve management at a later point in time, we have sought to focus on ensuring that the operations of management are as strategic, as effective and as efficient as possible, as soon as possible.

In doing this, however, we have not forgotten about the future. The approach we take attempts to strike a balance between improving the efficiency and effectiveness of our current tool set on the basis of our current understanding while also exploring the development of new tools and their integration into the management of CoTS. We acknowledge that our current understanding is imperfect but have adopted this approach for two very pragmatic reasons. First, we are currently attempting to manage CoTS based on manual controls and are investing millions of dollars into this effort. Second, there are no alternative CoTS control technologies currently available and none that are likely to become available in the short to medium term. Indeed, only an uncertain few technologies show promise even in the long term. This means we must get the greatest benefit possible from our current investment and we need to do this by ensuring that the implementation of manual control methods is as effective and efficient as possible. Furthermore, to avoid squandering our investment we must determine the limits of manual control. Is it only effective at local scales, or given that only a relatively small part of the reef is outbreaking at any given point in time, can it be applied to meet larger scale goals? Can we design the tools that will enable us to design the management strategies that reflect this?

Despite focusing on improving and evolving control operations, the list of research gaps identified in the previous section still outstrips the resources available under the NESP program. As a consequence some research areas, though still relevant and desirable in our overall strategy, are likely to be funded from elsewhere. In this section and in Appendix 1 we prioritise the research activities in the order of their deployment both in the management programs and in terms of when research could be made available or is required. Individual sites and manual control are the basic unit of management, irrespective of our goals, so effort must be deployed effectively in this context as a first step. Once we can manage sites and local areas we want to integrate this understanding into the design of strategies to achieve regional objectives by identifying key reefs based on their connectivity, reef attributes and management constraints. Ultimately, we will need to design strategies that link across regions at the scale of the GBR. The development of effective strategies at each of these scales underpins the development of the strategies at the next scale and thus provides

a means of prioritising the research agenda. While we keep our focus squarely on current management methods we do not ignore the need for future technologies that would either complement or replace manual control and we intend that the decision support tools developed would be flexible enough to incorporate new technologies as they come on stream.

Below we identify in more detail the components of work that we have identified as being of greatest priority at each of these scales. These are presented in the order of priority based on their logical sequence in a structured approach to improving management performance. Later components of the strategy build off earlier components, and the scale and goals of management increase as strategies are refined and efficiencies are realised at finer scales.

### 1) Management of sites, local areas, and assets

This is the keystone activity of any CoTS management program given that all management objectives will rely on manual control at specific sites into the foreseeable future. If conducted in an efficient manner it ensures increased impact and performance from available resources and provides the potential for covering greater areas. Furthermore, if conducted effectively it becomes a key tool in the management strategies employed to achieve objectives at all scales. As a consequence, optimising site management to ensure that it is effective and cost efficient is a high priority task, as vital to current site management goals and the protection and maintenance of economic and ecological assets as it is to modifying the trajectory of outbreaks at local area and regional scales.

Management at site and local scales comprises three key tasks: i) surveillance to identify the distribution of CoTS, ii) decisions about how to distribute control effort based on the surveillance data, and, iii) decisions about when to stop investing effort. These decisions need to be made at the scale of the site and local areas (e.g. a reef or a reef complex). Subsequently, iv) surveillance to assess the effectiveness of the control is also required.

Making these decisions is a complex task best guided by a site and local-scale decision support tool. Such a tool would be based on a CoTS population and management model incorporating spatial distribution, movement dynamics and habitat use of adult CoTS, and management efficacy and constraints (Research strategy 1.2.4 from Table 1), which in turn requires field measurement and analysis of adult movement and distribution (1.2.1 – 1.2.3).

While the development of new technologies for control, specifically the attractants/repellents technologies, is of great relevance here, there remain significant uncertainties about the potential of the technology, the research timelines, and the ultimate mode of delivery. These uncertainties lead us to recommend that it is not included in the early phase of the research investment. Alternatively, other opportunities for support could be sought.

### 2) Management at regional scales to respond to the current outbreak, and prevent outbreaks within the initiation box

If site and local area control can be optimised for maximum effectiveness and efficiency it provides the basis for deploying control to achieve coral- and CoTS-specific goals at regional scales. The current outbreak provides the opportunity to test our capability to achieve particular goals in relation to modifying patterns of spread, improving coral recovery potential,

and to optimise management operations at this regional scale. Success in these tasks would result in ecological and economic benefits as the current outbreak moves south towards the Whitsunday Islands. Coupled with targeted studies of thresholds and triggers of outbreaks in the initiation box, these regional-scale tools are likely to let us structure management there to prevent future outbreaks.

Management of the current outbreak (a secondary outbreak) requires a regional-scale decision support tool, underpinned by a model of the spread and growth of both CoTS (3.1.3) and coral (3.5.2) populations across networks of reefs. This regional model must be integrated with the site and local model of the previous section as well as data on regional scale specific management capacity and constraints.

The regional-scale decision support tool will enable the delimitation of outbreak and build-up zones (3.2.4), the identification of reefs to minimise coral loss in the outbreak zone (3.3.1), reefs likely to receive high CoTS larval settlement from the outbreak zone (3.4.1) and reefs likely to be important to the recovery following the outbreak (3.5.3). The site and local-scale model developed as part of 1.2.4 would then be used to identify how to distribute effort at those reefs, CPUE stopping rules to minimise coral loss (3.3.2), to minimise CoTS larval spread (3.4.2), and to decide when to redeploy divers at outbreak sites (3.3.3).

The same underlying regional model (3.1.3) can be used to structure management actions in the initiation box, with some additional refinement to include primary outbreak dynamics (4.3.1) and long term management considerations in the initiation box (4.3.2).

Ideally, these models would be based on field measurement of larval dispersal, settlement and recruitment (3.2.1) which might be achieved through a range of new technologies (3.1.2, 3.2.3, 3.5.1). Because existing data provide proxies for many of these parameters they are accorded lower initial priority.

### 3) Developing new control technologies

The development of alternative control methods, either to replace or to complement manual control must be a priority (6.1.1 – 6.1.4). Options to be explored include attractants and repellents to improve or complement the performance of manual control (1.5.1), an assessment of the potential for the use of natural predators as biocontrol agents (5.6.1, 6.1.1), including possible predator species and zoning to protect predators. Finally, the potential for silver bullets such as biocontrol or other new technologies should be reviewed (6.1.1) and assessed (6.1.3) given recent advancements in the field. Because of the sensitivities here it is imperative that this includes careful consideration of the risks, the potential for public acceptance, and the legal context in designing a path forward.

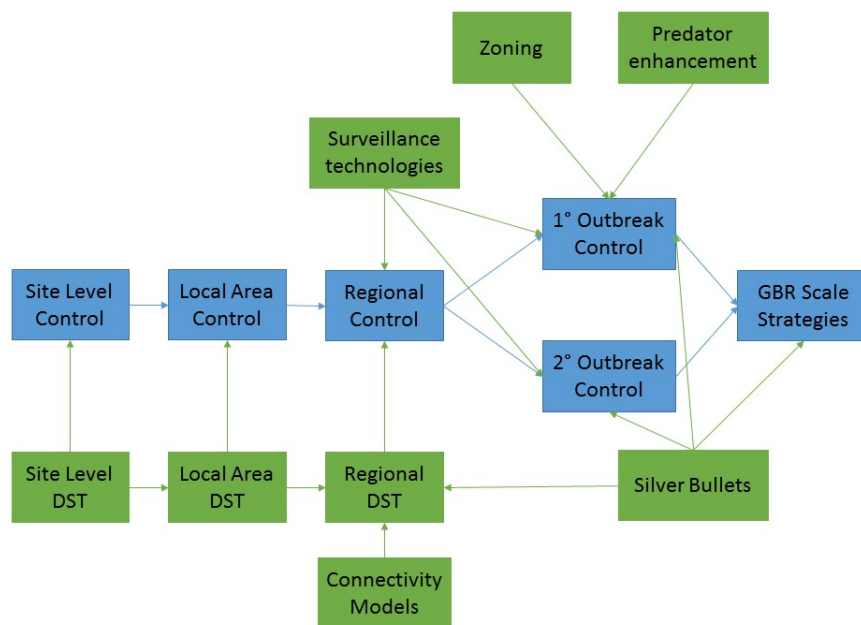
### 4) Developing a CoTS Working Group

Research to date has been conducted in cycles of collaboration and independence between researchers, and between researchers and managers. It is vital to coordinate research efforts between on-water and policy managers and researchers from different institutions investigating different questions at different scales in order to achieve direct and efficient outcomes for management. This is also vital if we hope to present a coherent, actionable

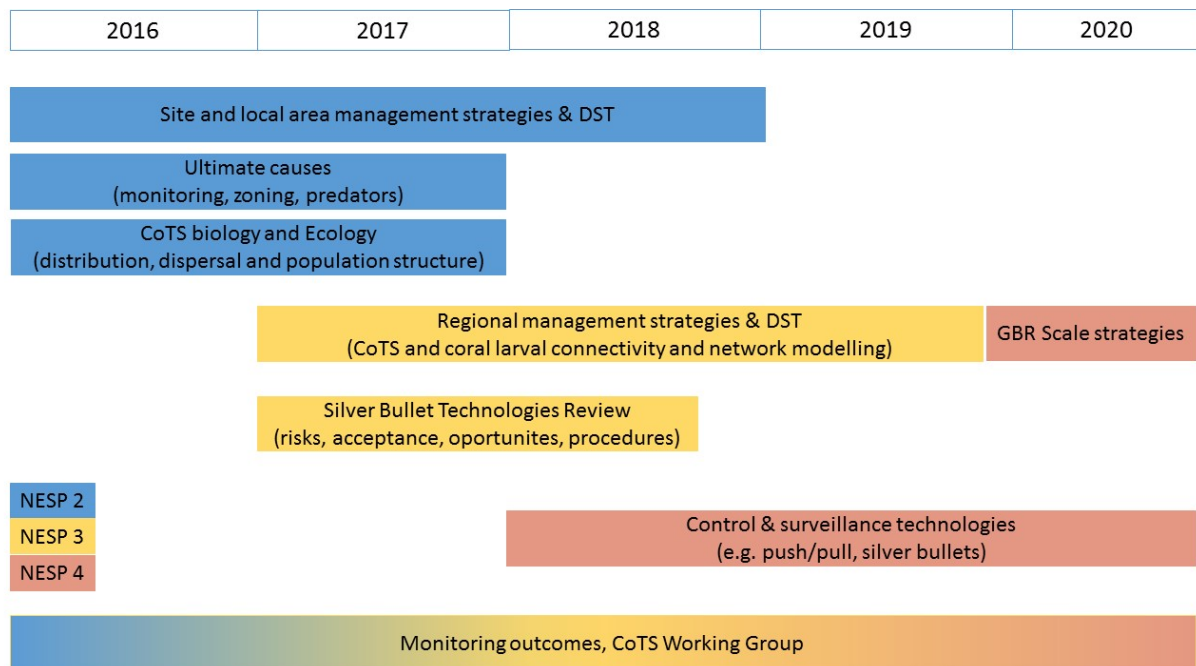
plan for CoTS management to policy makers to ensure consistent and sufficient funding to address the ecological scale of the CoTS problem (4.1.1).

We suggest that this should be facilitated by regular workshops amongst CoTS managers and researchers to review knowledge and directions, as well as the creation of a data integration and sharing platform. Identifying and accessing necessary data to inform the development of management has been, and remains an issue for CoTS management and research. Data sharing agreements and infrastructure are a high priority and should be implemented as part of a collaborative IPM network.

The consideration of implementation provided above suggests that improvements to management are likely to proceed as follows: first, improved control of sites and local areas to optimise current management programs and protect important assets; second, attempting to modify spread of the existing secondary outbreak at regional scales; third, employing these regional-scale tools and learnings to prevent future primary outbreaks; and fourth, GBR-scale strategies. Staging the research in this manner permits relevant research being conducted under other programs, e.g. the Accelerate Program work on connectivity, to be completed and those results and researchers to be incorporated into the NESP program at a sensible point in its progress. Further, the lack of clear options for non-manual control options suggests that investment needs to be made in identifying potential options and, where appropriate, exploring their development. This research would be run concurrently to the decision support research. How the research links to management and linkages among research topics is summarised in **Figure 2** while **Figure 3** provides a guide to the relevant timeframes and Appendix 1 provides a detailed breakdown of tasks and timing.



**Figure 2:** Relationships between management objectives (blue boxes) and the research components identified in this strategy (green boxes). **The arrows indicate how different objectives and research products contribute to each other**



**Figure 3:** Timing of the main research components within the NESP timeframes. The nature of the NESP 4 project would be determined by the outcomes of research in the NESP2 and NESP 3.

In summary, the research strategy prioritises the research according to scheduling and the scale of investment recommended into four stages:

1. Optimisation of control at sites and local areas – these represent the basic units of management. Success at other scales requires success at these scales.
2. Optimisation of control at regional and larger scales – influencing the trajectory of outbreaks and coral health requires successful strategies implemented at regional scales.
3. Addressing ultimate causes – While we must manage current outbreaks, we need to build the knowledge and management expertise now that will one day prevent future outbreaks.
4. Developing new control technologies – There are limits to the gains that can be obtained from current control technologies and new options must be explored.

This provides a logical sequence of work that ensures that each piece of work provides the groundwork for the subsequent research steps and ensures that on-water management is benefiting and improving based on the research throughout the research program rather than waiting for a benefit at the end of the research.

## **4. RECOMMENDATIONS AND CONCLUSION**

Based on the workshop and review we make the following prioritised recommendations for NESP TWQ Hub investment, scored by their urgency, in terms of NESP funding round (NESP2, NESP3, NESP4, and their importance to that funding round (A – very important, B – important, C – desirable):

1. (NESP2/A) Development of site and local scale Decision Support Tools, including necessary ecological data collection and model development
2. (NESP2/A) Implementation, testing and refinement of site and local scale management using the site and local scale Decision Support Tools
3. (NESP2/B) Preliminary development of the knowledge and data necessary to inform a regional-scale Decision Support Tool
4. (NESP2/B) Review of the role of predators as an approach to control and progress surveillance technologies to a decision point.
5. (NESP2/C) Establishment of a CoTS Working Group
6. (NESP3/A) Development, testing and refinement of regional-scale Decision Support Tools, including data collection and development of CoTS and coral population models, current network connectivity models, and integration of management models
7. (NESP3/A) Implementation of the regional-scale Decision Support Tools to minimize the spread of the current outbreak
8. (NESP3/B) Preliminary development of surveillance and monitoring technologies for the initiation box
9. (NESP3/C) Research into new technologies providing options for non-manual control
10. (NESP4/A) Completion of surveillance and monitoring technologies for the initiation box
11. (NESP4/A) Implementation, testing and refinement of the regional-scale Decision Support Tools to prevent future outbreaks in the initiation box
12. (NESP4/A) Development of new control and surveillance technologies

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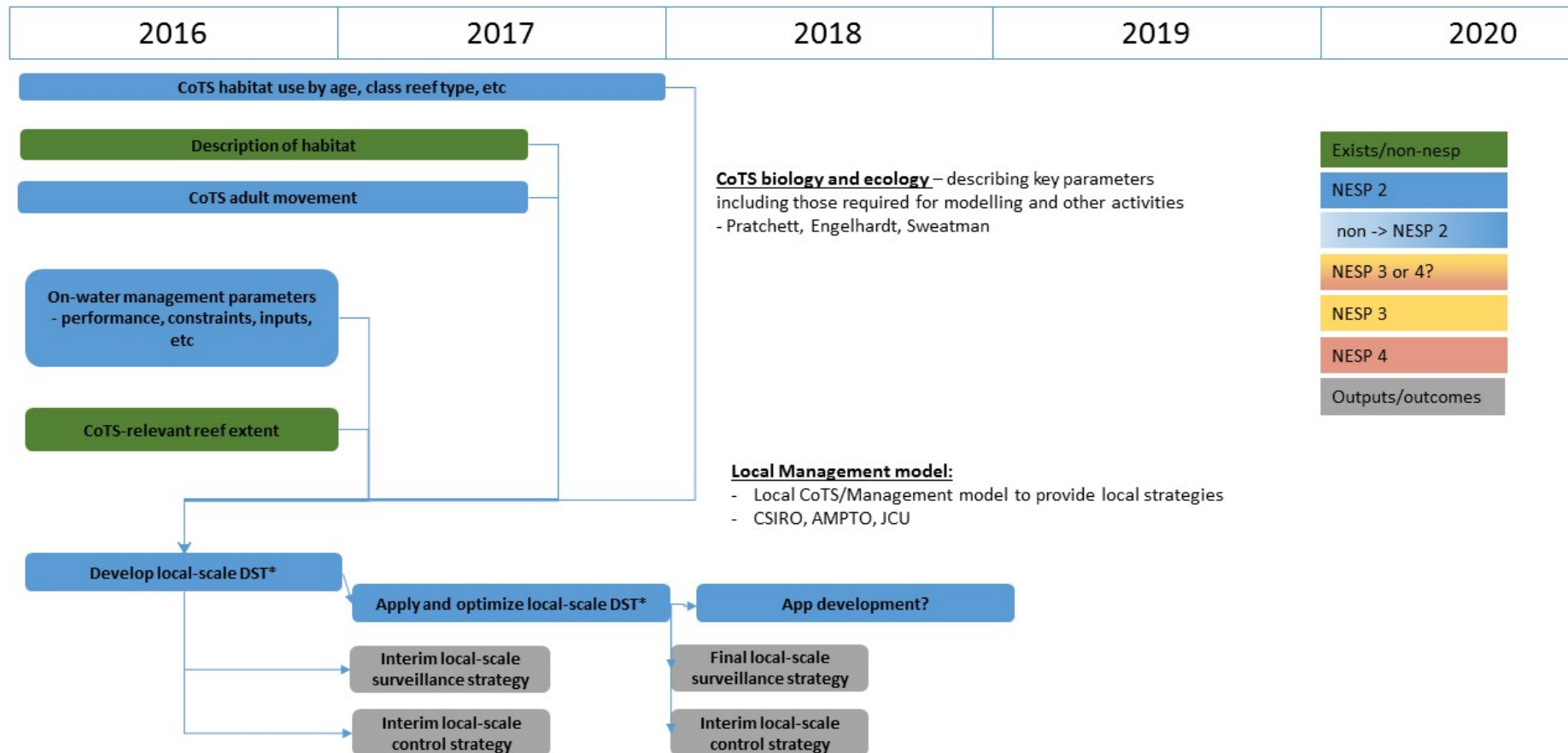
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## **APPENDIX 1 – GRAPHICAL REPRESENTATION OF THE RESEARCH STRATEGY**

The following diagrams outline the details of a research strategy derived from discussions that took place during and after the NESP 1 Crown-of-Thorns Starfish Workshop that was held at JCU Townsville on the 1<sup>st</sup> and 2<sup>nd</sup> of September 2015.

## A1.1 Site and local area control

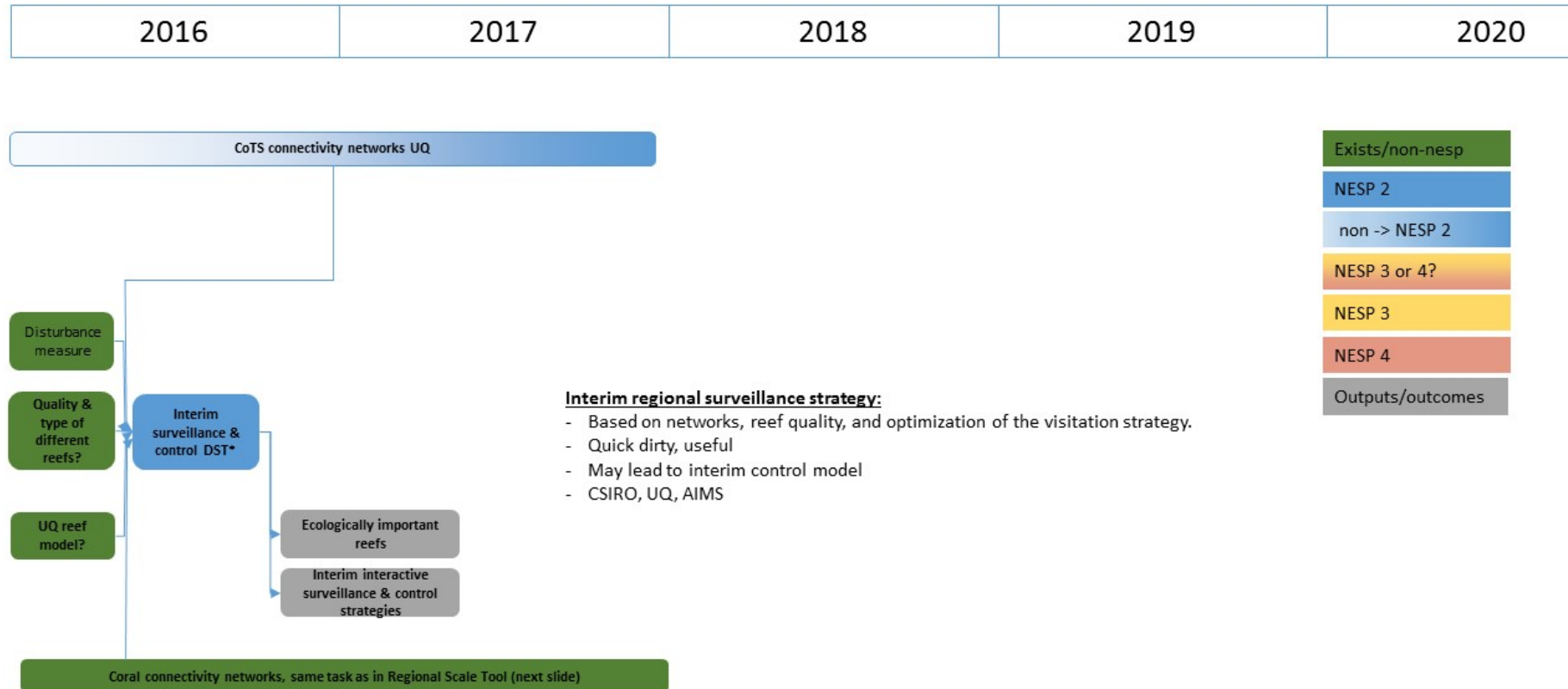
**Figure 4:** Identified research tasks and their timing required to achieve objectives for CoTS control at sites and in local areas, e.g. at a reef or reef complex.



\* Decision Support Tool

## A1.2 Connectivity modelling (primarily funded by Accelerate)

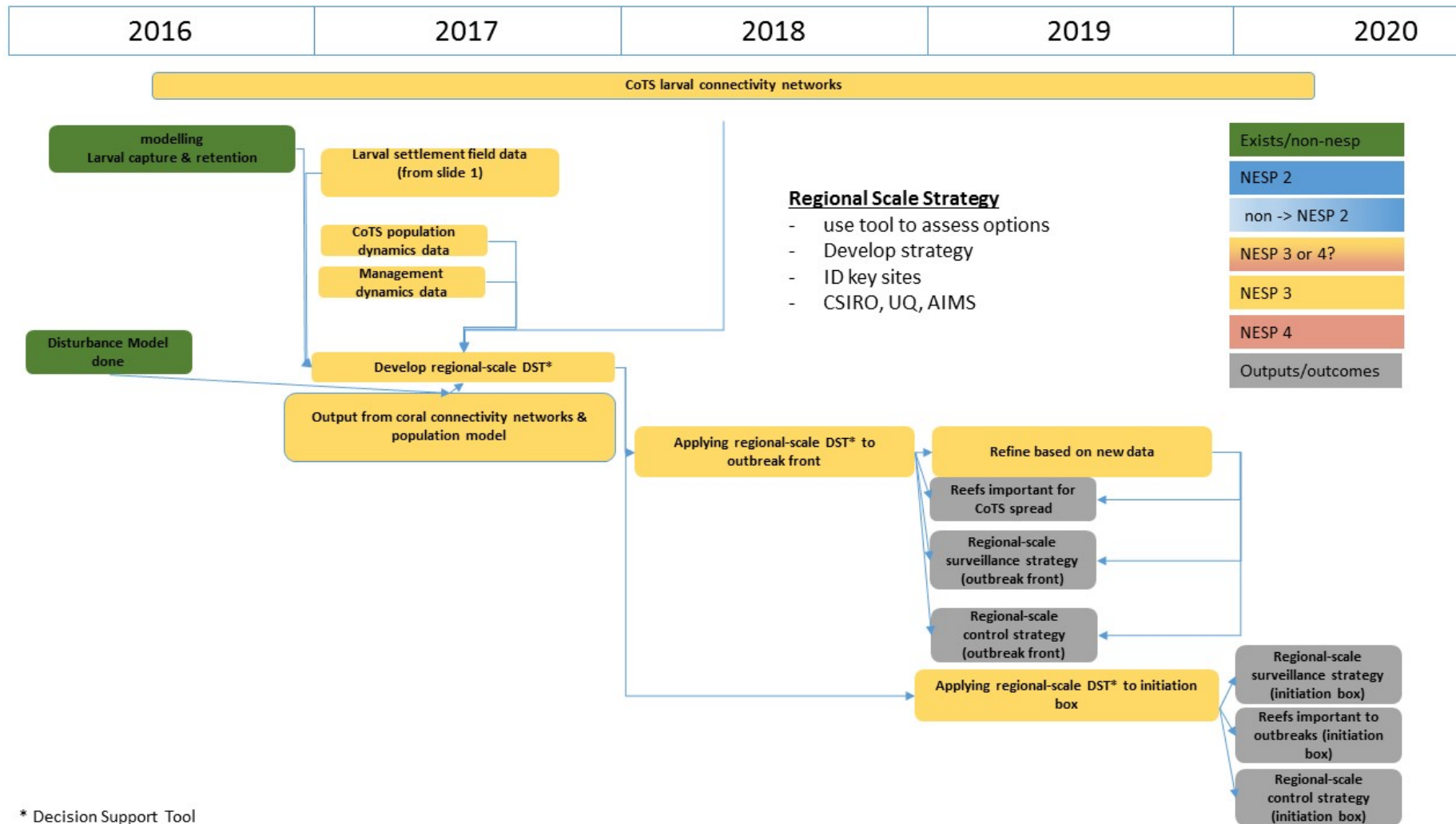
**Figure 5:** Identified research tasks and their timing required to achieve connectivity objectives for CoTS control at sites and in local areas and to provide the basis for the Regional Scale Control models.



\* Decision Support Tool

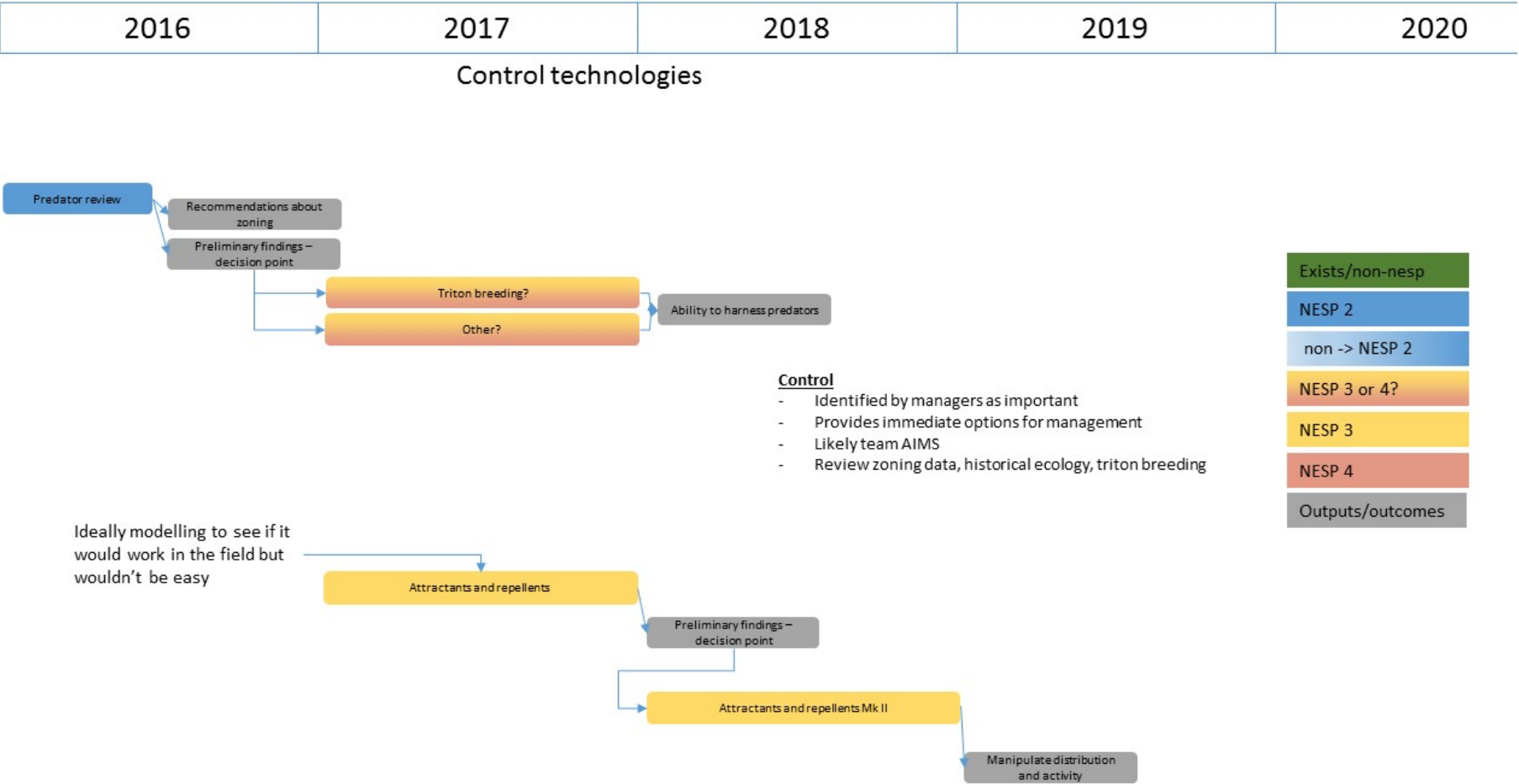
## A1.3 Regional scale control

**Figure 6:** Identified research tasks and their timing required to achieve objectives for CoTS control at regional scales.



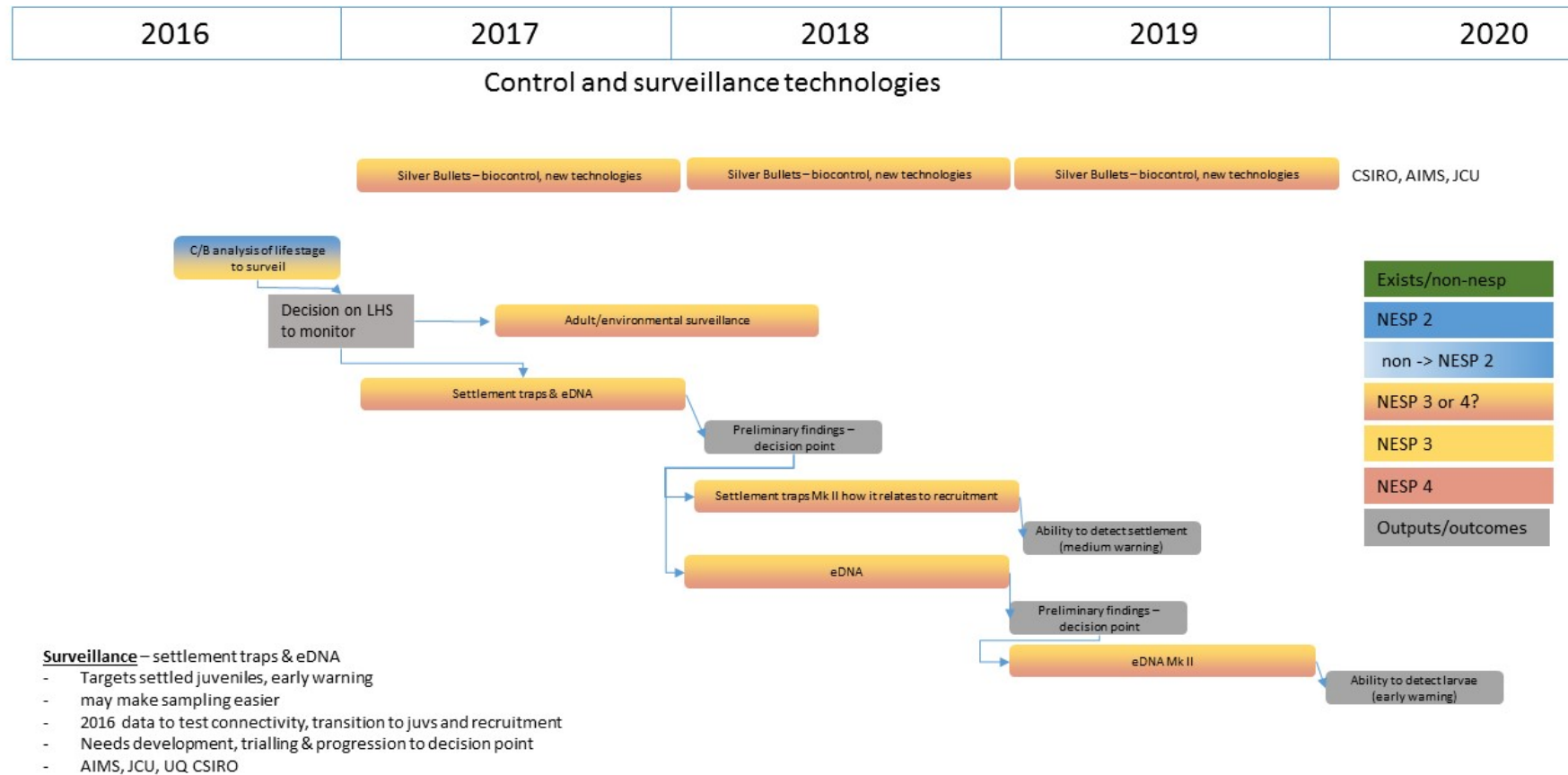
A1.4 Development of control technologies

Figure 7: Identified research tasks and their timing required to achieve objectives for CoTS control technologies



## A1.5 Control and surveillance technologies

**Figure 8:** Identified research tasks and their timing required to achieve objectives for CoTS control and surveillance technologies



## APPENDIX 2 – WORKSHOP DISCUSSION NOTES

1<sup>st</sup> and 2<sup>nd</sup> September 2015, James Cook University, Townsville

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## **A2.1 Foreword**

This report summarises the outcomes of a Workshop held in Townsville, Australia on 1 and 2 September, 2015. The Workshop was funded by the Tropical Water Quality Hub of the National Environmental Science Programme. The goal of the Workshop was to bring together Australian researchers on Crown of Thorns Starfish (CoTS) to identify a set of Research Priorities that could underpin CoTS management and research strategies and help inform future NESP research investments. Participants were asked to focus on management and research strategies that could fill key knowledge gaps and contribute to on-water management of CoTS by NESP's end-user stakeholders.

Participants included representatives from the Department of the Environment (DotE), the Great Barrier Reef Marine Park Authority (GBRMPA), the Association of Marine Park Tourism Operators (AMPTO), the Tropical Water Quality Hub (TWQ) of the National Environmental Science Program (NESP), the Reef & Rainforest Research Centre (RRRC), the Commonwealth Scientific and Industrial Research Organisation (CSIRO), the Australian Institute of Marine Science (AIMS), James Cook University (JCU), the University of Queensland, the University of Sydney and the University of Melbourne. For a full list of participants see Appendix A.

The following notes were collected during discussions held throughout the workshop. In this report they have been summarised, combined and collected into subject areas and sub-areas to aid readability. Where possible they have been modified only slightly from the original verbatim conversations. A brief summary and the research needs for the next five years have been prepended to the start of each section where it is appropriate to make the key messages accessible.

## **A2.2 NESP TWQ Hub priorities and aspirations (Damien Burrows)**

1. Summarised the purpose, structure and resourcing of the NESP Hub
2. TWQ Hub has \$26m for research over six years, \$1.8m on the first round of short term (6 month) projects. Anticipating annual funding calls for longer term (3 year) projects to spend the remaining \$24M.
3. NESP is very much an end user driven process – more so than MTSRF / NERP. Accompanying the funding is a list of priorities, funded research must be focused on these. Most priorities will probably only have one project allocated against them – some may have two
4. The idea of the workshops funded in the current projects, like the CoTS workshop, is to clearly identified priority areas for research and, ideally, research projects that will fill those needs
5. Proposals must support on-ground works, research must be directly applicable to on-ground works.
6. End users, including Indigenous, must be involved from the very beginning
7. Other annual calls probably won't have quite as much money – maybe around the \$5m mark
8. In terms of CoTS - to support the on-ground management program
9. Question from the room:
10. FK - Will NESP support Ph.D. students?
11. DB – Proposals get shortlisted by scientific committee, then goes to steering committee (entirely end-users) and they make the final decisions on everything
12. DB – The Hub has a proposal for a top-up scheme, but it hasn't gone to the Steering Committee yet, so no guarantee
13. This project has a direct path to the Reef Trust Project (management project) – the NESP work needs to be delivering research information into that- development of an Integrated Pest Management methodology – needs to be demonstrably more effective - \$7m over three years

## A2.3 GBRMPA's priorities and aspirations (Roger Beeden)

1. The managers in the room have a mandate that is quite different from the researchers. We are charged with looking after the health of the GBR for future generations. We have a desperate need to maintain the assets. The issue is not really about CoTS – it's all about coral - CoTS are important because they give us the best chance of managing coral and reef health
2. What can we do right now?
  - a. Integrated Pest Management – a set of strategies that we can put together
  - b. Which reefs are most important to recolonise corals downstream to foster recovery
3. Surveillance is important because it can help understand us understand what we can do, when and why. Surveillance must be conducted across a range of scales, from site through to the GBR. That said broadscale surveillance is particularly important in that it let's us know about overall patterns in an appropriate time period. Existing monitoring is awesome, but it was designed for other purposes and is too slow and cumbersome for the CoTS task.
4. To be a bit more specific:
  - a. We need a collective vision of what we can do, what we should do now, etc.
  - b. We need to arrive at a coherent set of management strategies. IPM is the way.
  - c. We need more research but that research needs to be focused on the management
5. Three key things we need to do:
  - a. Work out where they are, how to predict where they are
  - b. Work out management options
  - c. Go out and kill them
6. We need to balance off the research we can get up and running to manage the risk of outbreaks vs optimising the control methods we have right now
7. Key questions
  - a. What's our approach?
    - i. Strategic and tactical options for addressing Coral Reef resilience
  - b. What are the drivers of outbreaks?
  - c. What are the spatial dimensions?
    - i. Connectivity at the whole of reef scale
    - ii. What do we need to do to protect individual reefs?
    - iii. What are the targets for coral cover to know whether we should do something anyway?
  - d. What can management get out of this research? Lots and managers have demonstrated that they will apply research as soon as it is available.
  - e. What do we need to know as managers?
    - i. I'd argue that we do know a lot of what we need to, and it's really about balancing between different scales etc.
8. Response from the room:
  - a. SU - If you think you know what you need to know – I'd disagree with that – because you're currently taking out a lot of CoTS, but not necessarily having the best population level impact

- i. RB – I agree with that – we can definitely do better – the devil is in the managing across scales
- b. PD - A once large effort is now pulled back to 21 reefs – 15 that were economically important, 6 that were important to the spread of the current infestation, you can't control with current resources. What can be done with current resources.
- c. KA – I'm getting slightly uncomfortable here – there's a lot of legacy in this room – listening to what Roger's just said, trying to gauge the feeling in the room – I'm on the same page as Roger, but also the same page as the researchers – we have a problem – we have one little bucket of money – we have one boat – we're talking how we can best reconcile our different objectives – I think the objective of the room should be about problem solving – it should not be about carving up a small bucket of money for researchers to go off and write papers – we've been doing this for thirty years – to solve this problem what do we really need – to what extent is this problem solvable with today's technology, the brains in the room, the collaborating institutions – compared to Yellowstone fire issue (\$120m for something 1/6 the size of the GBR) we have the equivalent of one "fire truck" on the reef . Why hasn't the Minister got the navy out
  - i. RB Several of us have suggested something like that – the reality is that the message the Minister and high level decision makers are receiving about CoTS is very confused about whether protection / control can be achieved. We need to have a collective viewpoint on that so that we can communicate it to people like the Minister – no politician is going to commit to a non-coherent message.
  - ii. SM – we have approached the Navy – their budget constraints mean they can't, although they'd be happy to volunteer on weekends to get their dive times up

## A2.4 AMPTO's goals and aspirations (Steve Moon)

1. The track record over past 2.5 years: i) 1300 days at sea, ii) 5000 dives, iii) 3800 Reef Health Impact surveys, iv) 370,000 CoTS killed, v) 125 divers trained, 60 currently involved. It costs \$2M a year to run a vessel.
2. Two vessels are involved, Venus and Hero. One is currently seconded to surveillance only – Sep – Nov 2015 – the peak period where we want to see what's going on
3. In this season Venus will survey From Lizard to Port Douglas, QPWS are going to concentrate their surveys from Flora to Bramble, Hero will be working control in the middle.
4. Resources are being cut: QPWS down from 40 days to 30 days a year, AMPTO had a visitation rate of every 6 weeks, new cuts will mean return rates of over 3 months
5. AMPTO's project's primary outcomes - Protection of tourism sites / high value reefs to GBRMPA. Lizard Island To Whitsundays is split into 10 sections – 4 of those contain high value sites
6. Improvement of tactical control and containment on a broader scale is required but that can't be done on current funding
7. We're using a similar methodology to QPWS for the surveys
8. Implementing on-water management:
  - a. A big reef has many dive sites, each defined by a polygon.
  - b. In each dive there is a process; anchoring, dropping in, assessment, control diving...
  - c. Even when there are no CoTS, the whole process must be done, takes time
  - d. Surveillance could seriously improve this
9. Training and education were a focus but likely to be sacrificed again due to funding cuts
10. Arlington is major problem. 70k removed, 27k in one 9 day period. Suspected to be the feeder for many of the tourism reefs
11. Surveillance at the GBR vs Surveillance at the Reef Scale. Resources mean there is tension here
12. What's happening out there right now? The front of the current outbreak has moved south of Innisfail, there has been a second build up North of the front, culled a couple of thousand <25cm – that area didn't have that activity six months ago, they won't be able to get back there for three months
13. Question from the room – T – the interaction between site return time and the stopping rule for how much you spend at a site – do you use these stopping rules?
  - a. Seems to be more funding / scheduling / logistic based

## A2.5 Group discussion about management goals

1. The overarching long term goal is to maintain coral cover in the face of threats, especially CoTS, bleaching and cyclones. This can be achieved by reducing CoTS populations and impacts and by maximising the potential for recovery of coral on the GBR
2. Management goals are likely to be different at different times during the outbreak cycle and at different spatial scales and locations:
  - a. Ultimate causes – e.g. reversing nutrient release or predator release
  - b. Prevent an outbreak, by monitoring and controlling pre-outbreak populations in the initiation box to reduce densities below outbreak thresholds
  - c. Minimise regional impacts during an outbreak, by managing priority highly connected reefs to minimise the spread of CoTS larvae and maximise the spread of coral larvae
  - d. Protect assets at the scale of individual reefs, by optimally distributing surveillance and control actions to most effectively control ecological populations
3. The focus of the NESP CoTS research program is likely to be the latter three.
4. Costs and benefits are a vital part of the conversation, because it is cheaper to manage CoTS proactively and intensively in a small number of locations than reactively, with management effort dispersed across whole regions
  - a. Vital to coherently communicate costs and benefits to funders and decision makers
  - b. Need a way of valuing direct and indirect benefits, both economic and ecological
  - c. It's important to invest in CoTS because it's the big lever we have to improve reef health (compared to bleaching of cyclones etc.)
  - d. However, fixing CoTS will not fix everything – can't manage reef resilience just by considering CoTS
  - e. Bipartisan support for CoTS management

## A2.6 Management scenario 1: Asset protection during an outbreak

### *Summary of discussion – how do you minimise impacts and facilitate reef resilience?*

At the scale of managing an outbreaking population at an individual reef, the spatial and temporal scale of management needs to be informed by the locations and habitats over which individuals are distributed, the rate at which individuals move, and the rate and cause of the manageable population recovery following management actions. At the moment, our knowledge of each of these three key pieces of information is incomplete: there is evidence that CoTS can move between reefs currently controlled as separate management units; although we have information on the maximum speed with which CoTS can move, we do not know how far they move in practice, and although we know that CoTS populations can recover within six weeks of management, we do not know with certainty why or where this recovering population is coming from. Current management actions are protecting coral cover on key reefs, but it is very resource intensive, and becomes unsustainable if funding is reduced. Ecologically informed management of local sites could improve this.

### *Summary – research needs over the next five years*

1. Model-based decision support tool to optimise the strategic split of management resources between surveillance and control to achieve the best possible population-level control, rather than the most individuals removed
2. Model-based decision support tool for selection of sub-reef scale dive and control sites to most effectively achieve population-level control of impacts at key asset sites
3. Improve our understanding of how CoTS move and use reef habitat, including average movement rates and the use of non-managed habitat (such as adjacent deep water) by focussed experimental studies
4. Improve our understanding of whether CoTS populations are being controlled effectively by analysing AMPTO's control data of the size distribution of removed CoTS over time.
5. Use models to investigate thresholds in coral cover and CoTS population viability – can we create a “fire break” by reducing coral cover to <14% so that CoTS population can't establish, and still have coral recover rapidly once the threat is passed?

### *Detailed discussion notes – The spatial scale of management*

1. The key scale depends on the type of asset (e.g. tourism or ecological), the scale of protection needed (e.g. individual tourism dive sites, ecologically important coral communities, entire reef), and the level of ecological connectedness to other sites (e.g. Green Island seems connected to Arlington from the perspective of CoTS movement capacity)
2. Should we aim to control whole reefs or sub-sections of reefs? The aspiration is to manage entire reefs but the reality is that management actions take place at sub-reef dive sites following a whole-reef survey to identify significant aggregations
3. The scale of reefs and reef complexes as mapped on charts and management units reflects bathymetry rather than CoTS movement capacity – e.g. CoTS can move over a ‘bridge’ between Green Island and Arlington, so unmanaged outbreaks on Arlington are likely to continually reinfest managed areas on Green Island
4. How do you choose the assets?
  - a. Based on their connectivity, whether they are super-seeders, etc.

- b. We do not currently have a mud-map of the most important assets in different parts of the reef – could be useful, although there could be a lot more to it (see
- 5. What is the strategy for choosing the sites that are our ecological assets during an active outbreak?
  - a. Something about CoTS: current density, habitat suitability, capacity for downstream spread
  - b. Maximise coral recruitment from those reefs

*Detailed discussion notes – The management goal*

1. Tourism sites you might want coral cover to average 40% because that generates the best economic outcome
2. At an ecologically important site, 20% coral cover might be sufficient in a biological sense

*Detailed discussion notes – The temporal scale of management*

1. Current management actions have been revisiting sites and finding new adult CoTS in areas from which all visible adult CoTS were removed six weeks earlier
2. Understanding the scale of management actions is vital to interpreting recovery of CoTS population following management, because they could be:
  - a. Immigrants from outside the management zone on the current reef, which will depend on how the management zone was defined and how fast individuals move
  - b. Immigrants from other reefs that are connected in terms of CoTS movement capacity to the current control reef
  - c. Immigrants from deep water (management actions only operate to 15 m)
  - d. detectable-size adults that were missed during previous control actions
  - e. they could be small (undetectable-sized) adults that became detectable since the last visit, perhaps because they grew rapidly once the large and easily detected adults were removed
3. The optimal management response will be different depending on where those new individuals are coming from
4. We need to consider how fast CoTS move and reinfest control area vs the return time of management actions.
  - a. Budget cuts have led to return time more than doubling from six weeks to over three months.
  - b. Do we need to manage larger areas if the return time increases?
  - c. CoTS can move up to 30m an hour, which is 720m a day, or many kilometres between management trips, easily enough to move anywhere on most reefs
    - i. CoTS can move that fast, but that does not mean they do move that far – we need to know more about how they move and use habitat

*Detailed discussion notes – The effectiveness of management*

1. Real world example: Moore Reef (just south of Arlington) is a high value tourism reef, with a lot of operators visiting every day and running their own control programs. On the other hand, operators are only on site a few hours each day, and only occasionally have spare staff for control actions. AMPTO have visited on a six weekly schedule since 2013 and got 800 – 1000 CoTS per visit. It's only a modest sized

asset, with long term relatively intense management, but at the current level of investment although coral cover remains high, they're not seeing a long term improvement in the number of CoTS – it's at a chronic disease stage, where management is working but the investment will need to be maintained

- a. One vessel can cover roughly 20 medium-sized reefs in a year, with a 6 week revisitation schedule, which is just enough to maintain coral cover / the impact of CoTS, but not make significant progress towards long term control
  - b. We don't know whether management efforts are making a population level difference – if we are removing 50% of individuals, are we just releasing the other 50% from competitive pressure? On the other hand, while coral cover is high, we're protecting the capacity of the reef to reseed.
2. **Research question: Are CoTS populations being controlled effectively if they recover within six weeks? One preliminary answer could be found by analysing AMPTO's control data of the size distribution of removed CoTS over time to figure out whether the population is being controlled effectively, whether reinfestation is small adults being competitively released following control of large adults, whether large individuals are moving into control areas from outside, and at what rate? We could also look for differences in the size distribution between newly managed sites and sites that have been revisited multiple times.**
3. Can we design experiments to answer these questions piggybacked on AMPTO control trips?
- a. Difficult at the moment because AMPTO operating with much reduced budget
  - b. Scientists are welcome along on the trips – there are vacant bunks – but management staff cannot be diverted to research

#### *Detailed discussion notes – Thresholds for management*

1. What are the ecological thresholds to CoTS population and coral cover? There have been studies showing that at coral cover of around 14% CoTS populations struggle. There have been suggestions that coral can recover from cover rates as low as 10%. If we can more accurately determine both those numbers, we may be able to reduce coral cover below 14% on key reefs to prevent CoTS establishing without having to prevent them entirely.
  - a. This is a question of the biology of CoTS, the biology of coral, but also the rate at which CoTS populations react to reduced coral cover.
  - b. At individual locations where coral cover has dropped to 15% we have not seen a reduction in juvenile recruitment
  - c. Logically, as we let this go further and further at larger and larger scales, we must reach a point where recruitment is affected
2. **Research gap: Can we let coral cover run down to 15% to control CoTS populations, and will the reef recover effectively once the CoTS population collapses? Are any of the reefs damaged by Cyclone Yasi suitable to test this theory as the outbreak front passes South of Innisfail?**
3. Monitoring – a lot of on-water monitoring is focussed on how many CoTS we're removing, and that is fairly accurate – but how good is the data on coral cover?
  - a. Do we need to invest to improve our monitoring of coral cover to really answer this question?
  - b. At the moment, we don't monitor until we see CoTS or scars – is this too late?

- 4. Research gap: a lot of the questions that are coming up repeatedly could be answered by a project that can go and look at all the data that is currently being collected (CoTS population size distribution, coral cover) (Strong support from GBRMPA)**

## A2.7 Management scenario 2: Minimisation of regional impacts during an outbreak

*(Modifying the spread of CoTS and coral larvae)*

*Summary of discussion – how do you minimise impacts and facilitate reef resilience?*

The goal of CoTS management is ultimately to maintain the health and resilience of the GBR, a key part of which is coral cover and diversity. Factors that limit the spread of CoTS larvae can reduce the short term impact of an outbreak, and factors that promote the spread of coral larvae can improve the rate of recovery of coral following an outbreak. Both are likely to be important to minimise regional impacts once an outbreak has begun. At the moment, our ability to select key reefs is limited by the lack of: biological factors in connectivity models, connectivity models for key coral species, knowledge of coral cover and diversity at individual reefs, and how exposed reefs are to disturbance.

**To do this effectively, we need a decision tool to determine a subset of priority reefs in / in front of the current outbreak front at which to focus management, based on:**

1. Reef connectedness in terms of coral and in terms of CoTS
2. Quality of the reefs in terms of species diversity, age structure and quantity
3. Population models for coral and for CoTS
4. How exposed each reef is to disturbance / other drivers of reef health
5. Further questions:
  - a. Is current flow connectivity sufficient, or do we need other assessments of connectivity?
  - b. How can we optimise surveillance in terms of logistic constraints as well as ecological importance?
  - c. How often does this optimisation need to be revisited – annually?
  - d. Does the optimisation change for different time horizons? Is the appropriate temporal scale a whole outbreak cycle?
  - e. Do Green Zones have a role to play beyond affecting quality?

*Summary – research needs over the next five years*

1. Understand what types of connectivity are important
  - a. Coral, CoTS, difference between current connectivity and genetic connectivity
2. Map or collate information on the quality of the reefs in terms of species diversity, age structure and quantity
  - a. Do we have this already?
3. Population model: for coral, perhaps for CoTS
  - a. We need to know where high quality reefs and high density of CoTS are now to know how they might move on the connectivity network
4. How exposed each reef is to disturbance / other drivers?
  - a. Do we have any information on this?
5. Develop a decision tool to set priority reefs using these three bodies of information
6. Develop a model to optimise surveillance for targeted reefs

*Detailed discussion notes – how to select sites*

1. Do we want to design a strategy that assumes a change in the resource base (e.g. Optimising the number of boats), or do we assume it's going to stay at the current levels (e.g. Doing the best we can with a single boat)?
  - a. We could look at more investment, but we should so with the goal of expressing the benefits of increased investment as a simple, coherent message – if we can come up with a technique to do it, and a way of communicating that, we are more likely to generate more funding for these outcomes
  - b. Reef Trust is being set up to source alternative revenues – corporate sponsors, philanthropy, green trusts. They are currently coming up with an Investment Prospectus, and CoTS is one of the most saleable parcels – for instance, we know that \$2m gets us a new boat – can we offer sponsors naming rights to the boat?
2. What's the spatial correspondence of high value tourism sites and super spreader reefs?
3. Need some form of surveillance to find out where these aggregations are occurring?

*Detailed discussion notes - connectivity and prioritisation*

1. Selecting reefs should not be just a ranking based on the qualities of individual reefs - it's about selecting packages of reefs, because if you protect one reef that might affect the priority of the reef next to it, or other similar reefs.
  - a. For instance, if you choose which three reefs you'd protect with a given level of funding, would you select those same three reefs plus two more if your funding was increased so you could manage five reefs overall, or would you select five different reefs? How bad is the optimisation if you get your level of funding slightly wrong?
2. Configuration of priority sites may be sensitive to the time horizon over which you're doing the optimization – if it's over the current outbreak you may choose one suite of reefs, but if it's over fifty or a hundred years, you might choose a different set

*Detailed discussion notes - ecologically important connectivity*

1. There's an implicit assumption that protecting key reefs will save us in the long term – but we don't actually know if it's better to have 40% cover on 3 reefs, or 20% cover on all reefs.
2. Are we protecting coral abundance, species diversity, age structure? Could be any or all
3. Connectivity work tells you whether CoTS on a given reef have the capacity to reach other reefs, but we don't currently know the quality of coral cover at all the reefs, and the connectivity models do not consider it
  - a. We have a tool to tell us how connected each reef – we need to confirm it
  - b. We have some tools that will give us some information about coral cover, but possibly not at fine enough spatial and temporal detail – maybe factor in green zones?
  - c. We need a way to identify reefs that are least prone to disturbance – including water quality
  - d. Can we use those three tools to identify key reefs, and focus on them for surveillance etc.

4. Does reef structure (i.e. large, complex reef vs small, simple reef) affect CoTS and / or coral persistence? For instance, would large, complex reefs have more refugia for either CoTS or corals following major disturbance? Would they have higher self-recruitment? Would they be harder to manage?
5. Reefs with high *Acropora* cover recover more rapidly – should we protect reefs with high *Acropora* because they're likely to bounce back more quickly?
  - a. Alternatively, should be protecting the areas that have slow-growing coral, because if they get damaged they'll take longer to recover?
6. Most corals have very different dispersal times to CoTS, so reefs that are important in terms of their connectivity for corals may not be connected for CoTS
  - a. Corals may have different spawning times than each other, and than CoTS
7. There may be some reefs that are connected for both coral and CoTS – what does that mean?
8. Is there a difference between species composition that is good for coral and that is good for CoTS – i.e. a reef covered in *Acropora* may be ideal habitat for CoTS, with the potential to support a massive outbreak population that could seed the infestation further South – but if it only has *Acropora* maybe it's not so great biologically?
9. Research goal: Might need connectivity layers for “corals”, as a group, and perhaps key species, and connectivity layers for CoTS
10. Other factors affecting reef prioritisation: Green zones, water quality? Logistics (travelling salesman)
11. Are there any data that we could use, in hindsight, to identify reefs with outbreaks and correlate with disturbance (cyclones, southerly winds, non-green zones?)

## **A2.8 Management scenario 3: Preventing an outbreak in the initiation box**

### *Summary of discussion – how do you prevent an outbreak in the initiation box?*

In the long run, the most effective way of minimising the impacts of CoTS outbreaks on the health of the GBR will be to prevent outbreaks beginning in the initiation box. This has not been possible in the past because research and management funding have been cut or diverted to other reef causes as CoTS populations declined or moved south. Although significant questions remain about the relative importance of various ecological processes that may drive CoTS outbreaks in the initiation box, we can and should use the understanding, knowledge, and data we currently have and continue to collect during management and research activities to structure management while designing research that will fill the gaps we need to control CoTS outbreaks in the long term.

Since the 1960s, CoTS outbreaks have occurred every 15 – 17 years in the initiation box, and without going into the details we can broadly structure our biological understanding and management response around three broad phases each lasting roughly 5 years. For the first five years following an outbreak coral is recovering from such a low level that they cannot support significant CoTS populations, and management should focus on monitoring coral recovery with surveys every couple of years. For the second five years, coral cover has reached a point where it can support small densities of juvenile and adult CoTS, so management activities should focus on monitoring CoTS populations and aggregations, at least annually. During the final five years, CoTS populations have established across the initiation box and begun to build towards populations capable of sustaining an outbreak when triggered, so management should focus on removing individuals within the initiation zone to keep populations below densities likely to trigger outbreaks, at sub-annual scales.

### *Summary – research needs over the next five years*

1. A unifying model of outbreaking populations in the initiation box explaining how the range of potential triggers accumulate to increase the chance of an outbreak, to integrate and underpin smaller-scale research and a compelling narrative for the benefit-cost trade-off of effective management of the initiation box to secure long-term funding
2. A data repository and efficient methods of analysing it as new data is added to bring together the diverse data and research conducted independently on CoTS in general and the initiation box specifically, to help structure management plan as effectively as possible
3. Focussed field research leveraged off management activities to collect data about outbreak triggers, such as larval production, transfer and settling, nutrients, currents and self recruitment, and biophysical conditions

### *Detailed discussion notes – location and available data*

1. Location - do we know the key locations within the initiation box? Are they related to connectivity? Habitat suitability? Water quality? Population accumulation?
2. Weekly data coming in from tourism operators. During the last outbreak, tourism operators were detecting CoTS downstream before the outbreak in the initiation box was detected by LTMP

3. If the outbreak begins in the Lizard Island area, there's nothing you'll get from tourism operators or Eye on the Reef, so we might need to supplement that with extra surveys in the Northern part of the Initiation Box
4. Can we back-cast connectivity model to infer location of primary outbreaks from our known secondary outbreaks:
  - a. Combination of a series of complex larval processes including current connectivity, but also nutrient plumes, length of larval survivability

*Detailed discussion notes - triggers*

1. We need to validate the triggers, need to have good monitoring of potential triggers, need to have good CoTS surveys, need to marry them together
  - a. Role for new techniques, e.g. eDNA, juvenile detection
2. Understanding triggers would give us options for early-warning systems
3. Can studying secondary outbreaks help inform the triggers of a primary outbreak:
  - a. If we have to wait for the next primary outbreak, then we'll still have some knowledge gaps about what the triggers are when the next outbreak hits
  - b. If we could study secondary outbreaks
  - c. Can't infer anything about causes on primary reefs in terms of gradual population build before outbreak
  - d. Can you infer something about population dynamics throughout the outbreaks? Not the dynamics of an outbreaking population
  - e. Can you infer something about the minimum level of coral and the minimum level of self-recruitment lead to a primary outbreak? (Can't answer this from secondary outbreaks)
4. **Research goal: Need a coherent framework that explains how the range of potential triggers accumulate to increase the chance of an outbreak so that we can get funding and resources on the water before the outbreak establishes**

*Detailed discussion notes – population accumulation*

1. Do we have the tools to understand the gradual build up of populations as a pre-condition for outbreaks? We would need to describe: gradual population accumulation, self-recruitment, coral cover and increased nutrient availability
2. Settlement location vs recruitment location – importance of Halimeda beds?
3. In the intermediate period between likely outbreak, can we come up with an experimental design around monitoring juvenile build-up, stratified by retention rate
4. Multi-pronged research program to test whether any of the following techniques can detect small changes in CoTS density: larval tows, settlement traps, fine scale surveys
5. Outbreaks occur on 15 – 17 year cycles, and although there are some disagreements about the likely importance of specific triggers and drivers of an outbreak, we know that the ability of populations to build on individual reefs in the initiation box will be limited by coral cover, which in turn needs to rebound before CoTS population can rebuild
6. Crudely: block it up in 5 year periods:
  - a. First 5 years after a known outbreak – coral recovering from very low levels
  - b. Next 5 year period where coral is sufficient for CoTS population to start ratcheting up from low levels

- c. Next 5 year period where the potential for exponential outbreak growth of CoTS population
- 7. Eva has looked at the data and they back up the broad concept
  - a. In the Northern reefs you see it takes 4 - 5 years for coral to recover, then you start to see peaks in the CoTS populations on individual reefs, which you do not see in the same ways on Southern reefs – these could be the sign that CoTS populations are building to a point that could outbreak
- 8. If we're talking about 50 reefs, we might currently have the resources, because:
  - a. First 5 years: monitor coral cover – probably don't need to be going to every reef every year
  - b. Next 5 years: monitor coral cover + larvae + CoTS population variability – need intensive monitoring at this point, but possibly not a lot of control
  - c. Next 5 years: CoTS populations – faster monitoring (of adults) and intensive control
- 9. Time between first detection at Lizard Island is 14 years, the last outbreak is inferred to have begun around 2007 – 2009 – so for the next outbreak we'd need to be looking from 2021
- 10. We had an understanding of these dynamics before the last outbreak – so what were the impediments that prevented this process?
  - a. Funding had been cut, so intensive monitoring of the initiation box was not possible
  - b. We need to construct a clear narrative that links the management process we're proposing to the ecological processes – if we can do that, we're more likely to get funding to have this monitoring in place for the next outbreak
  - c. Can we use, for instance, a quantitative model to clearly link strategic investment to improved average coral cover, to help communicate this narrative to funders?

*Detailed discussion notes – monitoring the initiation box*

- 1. We need a way to integrate what we're talking about in terms of scientific monitoring north of Port Douglas with the twelve “anchor points” provided by tourism operators as part of the Eye on the Reef
- 2. Are we trying to survey lots of reefs with the resources we've got, or are we going to search a small number of reefs that we are confident are the individual reefs where outbreaks begin?
  - a. We may not have the resources to do intensive small scale surveys across all reefs, but we do not yet have the knowledge of key reefs to limit our surveys to just a few reefs ... so how do we choose where along the spectrum we work, how long do we have to spend learning about key reefs before we can have sufficient confidence?
  - b. Could use hierarchical surveillance; if broad surveys or other information indicate a risk we ramp up the monitoring, try to go to the LTMP sites for consistency
- 3. When did increased CoTS numbers start showing up in the LTMP as a result of the current outbreak? Although we had information from Eye on the Reef, it wasn't integrated with LTMP – maybe we need to improve the integration of data from all sources

4. **Research question: Can we look at the LTMP data from 2009 with 20/20 hindsight to understand whether we could have detected a problem?**
5. During the last outbreak, one significant problem was the lag between first indications of an outbreak and the availability of resources to delve into surveillance further and to begin implementing control. Of the ideas we've discussed, intensive surveys of the initiation box is the only one that would let us deal with the lag phase using current techniques
6. Intensive monitoring of 60 reefs in the initiation box during a 2 – 3 year window based on an indicator: coral cover, feeding scars, gradual build up in population recorded by LTMP?
  - a. After an outbreak you probably have 5 years on those reefs where you don't need intensive monitoring
  - b. Peter Doherty suspects that control to reduce densities on those 60 reefs in the initiation box during the 2002 – 2005 period might have avoided the current outbreak (first detected 2009, maybe began 2007?)
  - c. This mechanism has some support, but we're not 100% sure, so we need to be careful of putting all our eggs in this one basket
  - d. We need focussed intensive monitoring because neither of the current broad-scale survey techniques (RIS or LTMP) will detect sub-adults
7. No regrets outcome of intensive monitoring of the initiation box:
  - a. Best case scenario: we hit building populations prior to outbreak sufficiently hard we avoid outbreak entirely
  - b. Worst case scenario: we know exactly when outbreak begins and can bring massive resources to bear as soon as adult population booms on primary reef - also have excellent data on outbreak so we can iteratively refine the strategy before the next outbreak
  - c. Down sides: it would likely be expensive in the context of what is spent on monitoring right now – but it would be cheap compared to what is spent on control right now, so if it can avoid the next outbreak, the benefit will outweigh the cost

*Detailed discussion notes – nutrient flows*

1. Can we use nutrient flows to help structure surveillance? Would need to monitor flood plumes from the Wet Tropics and Burdekin to see where they go and what their nutrient concentrations are. eReefs can help, but we would also need in situ monitoring to get idea of nutrient concentrations – for instance, modelling suggests fresh water from Burdekin reaches the initiation box, but do the nutrients actually reach the whole way? We would also need to understand the different forms of nutrient in Burdekin vs Wet Tropics plumes (Burdekin much larger N load, but perhaps in less bio-available form)
2. Larvae have good survivability even with very low nutrient availability – so you don't need a massive plume of nutrients to hit the initiation box – only a small bit would need to reach the Initiation Box to have a large effect. Also, settled recruits are the actionable part of the problem, rather than larvae in the water column, because currents are so variable and at that point we don't know where they'll settle.
3. It's not necessarily just nutrients flowing from river systems, either - after massive disturbance you could have a trigger on the reef itself (algal bloom), so in situ monitoring is important

4. Nutrients link into the coral bleaching story – if high nutrients exacerbate coral bleaching as well as CoTS, then it delivers directly into the reef resilience argument
5. There are other factors to consider correlated with weather but not casually related to nutrient flow: ENSO mediated residence time, reduced salinity due to flood events
6. Surveillance of triggers and CoTS population tied into the coarse 5-year timing of outbreak dynamics
7. Use existing Eye on Reef, augment with targeted surveillance
8. Use that to refine surveillance and control efforts
  - a. One key step to this working is to have strong collaborations, including centralised data collation, coordinated data collection in overlapping areas where possible
  - b. eAtlas could be the platform for that
    - i. but that is focussed on production quality data
    - ii. where do we put experimental data

*Detailed discussion notes – practical considerations*

1. There's some prospect of snuffing out an outbreak very early on – hit all reefs in the initiation box hard, but if it's leaks out, you switch to thinking about asset protection
2. Would you ever seriously countenance targeting reefs to limit dispersal, or once the outbreak begins, is it just too far gone?
3. A key question is whether the outbreak is still one cohort, or whether it is already multiple cohorts
4. One thing we've established this morning is that the investment we've currently got is sufficient, but only just, to maintain coral in the current management region. This suggests this is worthwhile, but that we can't afford to redirect resources out of the region to manage other areas
5. **Research goal: Use a model(?) or some other technique to demonstrate how the management effort in this region has been effective, but requires at least the current level of resourcing to achieve that outcome. Then use the same approach to show what would be required in the reef system further South to control the effect before / by the time the outbreak reaches the Whitsundays, to underpin a coherent argument for sufficient funding to protect those regions.**
6. Real-world example: AMPTO have run a selection matrix developed by GBRMPA to determine which tourism reefs should be managed, and used that to focus their management down from ~354 sites (multiple sites per reef, used to extend up to Lizard Is) to 170 sites (still almost all the reefs within the zone, but the zone has been constrained further south than Lizard Island)
7. **Research goal: How do we optimise surveillance across GBR scale / the regional scale / the reef scale – for instance, last time surveillance outstripped the control effort – we knew where the CoTS were but, often, by the time the control boats got there the CoTS had moved. How do line up the various monitoring tools that we have to give us a picture at the GBR scale, the regional scale, and down to the individual reef scale?**

*Detailed discussion notes – whiteboard notes*

1. It's in the box somewhere
  - a. Monitoring to pin it down (will vary)
2. Recognising triggers – early warning system

- a. Nutrients / disturbance / cyclones
  - b. Larval settlement
  - c. Coral cover
  - d. Eye on the reef / QPWS / LTMP / RIMRAP
  - e. Focused surveys
  - f. Use 1 – 5 to ID preferred strategy (what to monitor, how, trade offs between ??? and warning)
- 3. Triggers
  - a. CoTS Data / thresholds
  - b. Coral cover
- 4. Target
  - a. Surveillance
    - i. Extent
    - ii. Severity
  - b. Control

## A2.9 Management technique 1: Surveillance technologies

1. Manta-tow
2. Sniffer – developing genetic tools, eDNA approaches
  - a. Detect a larval settlement event by putting out settlement cages, then use genetic probe to figure out the prevalence of CoTS in the plankton samples, or manual plankton count can get us down to taxon
  - b. There is a ship of opportunity already travelling across region recording Temperature, CO<sub>2</sub> – could we get a Continuous Plankton Recorder running on it?
    - i. Morgan or Sven are already collaborating with AMPTO to get samples. Hard to take genetic plankton samples on moving ships because although they can be collected using plankton net by hand the ships need to stop
  - c. Larva in the water column is useful from the perspective of connectivity, but it doesn't necessarily tell you where it's going to settle.
3. Settlement collectors (bioballs) integrate what's in the water column over the sampling period - you don't have to worry about being out there on the day the larvae are passing by
  - a. Plankton netting is point sampling (in time), so good for research, but does it scale up for tactical management? Recruitment collectors can scale up to time scales useful for management.
4. Management contribution of detecting larvae:
  - a. Early warning: if you get large numbers of larval settlement, then you probably need to be planning to distribute management resources to those reefs 18 – 24 months later ... and on the flip-side, if you have almost no larval recruitment, you would know that you didn't need to invest so many resources in that location two years later
  - b. Understanding where you are in the management process: Managers would love to know whether or not the places they're currently managing are receiving new recruits that will keep the problem running year after year, to facilitate planning
5. We don't know how many CoTS are at depth? That's a key question.
6. We don't know exactly when they're becoming reproductive vs when they're becoming detectable – for instance, the smallest recorded mature individuals are 100mm for male, 140mm for female, and individuals are generally only becoming detectable around 140mm. This is a major issue for effective population control.
7. Manta-tows are a proven technology for detecting adults - they show good correlation with the number of CoTS that end up removed during control activities, but that is partly because they only detect the medium-sized adults and larger that are being controlled. Are they detecting enough of the age-profile of the population to lead to population control? We would need 10 times the resources to cover the entire reef.
8. Can we use connectivity modelling to target surveillance more efficiently?
  - a. Then use 30 days of QPWS effort to survey high priority reefs
  - b. Then use manta-tows on the areas where high densities are found
9. How do surveillance techniques and control techniques scale as density gets lower?

- a. We're good at detecting high densities, and we can control high densities efficiently, but we don't know how well our approaches work as densities drop off
- 10. Mike's attractant / repellent work
  - a. Can we use repellent at bottle necks in the connectivity network to make control efforts more effective?
  - b. Can we use it at the lower end of age/size structure to augment poor detectability? With a bit more proof-of-principle this year, could the question about juvenile attractants / repellents be pitched as a NESP second year project?
- 11. Smart technology on the horizon:
  - a. CoTSBot - can we augment manta-tows with machine vision techniques?
  - b. Can we use citizen science to augment formal surveys, e.g. Navy divers wanting to get their dives up?
- 12. Surveillance program might cost \$350k/year to run as it did in the past – that is a small proportion of a control program with an overall budget of \$7m over 3 years
- 13. Does protecting key individual reefs actually make a population-level difference to CoTS spread / damage / resilience of the reef over the time scale of a full outbreak?
- 14. Do you choose your set of reefs throughout an outbreak, do you change it through time as connectivity changes / larger outbreak continues?
  - a. Has to be dynamic – at least annual review of where we're at in the outbreak, what disturbances we're facing, what current connectivity is doing
- 15. Are our current surveillance techniques missing ecologically important parts of the population? Is there a significant proportion of the population being missed? What about CoTS below maximum survey depth?
  - a. Never been an aggregation recorded at, for instance, 50m
  - b. Don't know anything about 15 – 30m depth
  - c. Is it really important? Probably important at the scale of an individual site.
  - d. If it is true, would it change anything? All we can do is manage to 15 m, so we'd just keep doing what we're currently doing
    - i. If they are at depth in significant numbers, it will have implications for revisitation rate, and the aspiration for management
  - e. There have been surveys at really deep reefs, but not so much at the intermediate depths 15 – 30m?
  - f. Slug diver in the bottom of the channel between Batt and Tongue Reef (28m) told them there were lots of CoTS at the bottom of the channel, by the time AMPTO got there they'd come up the walls onto the higher reef
  - g. Difficult to do full surveillance at these depths, but we might need to do some prospective surveys to figure out if it's likely to be a problem at all
  - h. Could use tow cameras, or could engage with commercial divers working at those depths for other reasons
  - i. Coupled deep water surveys with surveys in normal shallower reefs to look at correlation
  - j. Could eDNA be used to look at where they're settling as a function of depth? A function of coral species? Is it a priority? Method of finding juveniles early to have time to plan future management actions and secure funding, or in future perhaps use attractants to control juvenile phase

## A2.10 Management technique 2: Control technologies

1. One-shot bile salts
  - a. Already available, proven
2. One shot Vinegar? Not for widespread use.
  - a. To use vinegar as an effective control medium you'd have to carry twice as much on the boat because you can't break down vinegar to a powder to be reconstituted at sea
  - b. Might be useful for smaller tourism operators, although they can use bile salts if they get licensed
3. CoTSBot – difficult to see them being rolled out on an industrial scale in a way that's comparable to the current human program – certainly not on the time scale of NESP
4. Mike Hall's attractants and repellents - how might we utilise those in a control program, and what are the research gaps we'd need to fill to operationalise it?
  - a. Attractants could draw out CoTS from coral protection, enhance predation of juveniles
  - b. Attractants could increase congregation of CoTS to increase efficiency of management, but we'd still need to physically cull animals once aggregated
  - c. Attractants could engage a vital part of the age structure currently not amenable to management (juveniles / small adults)
  - d. Another approach they're trying is de-syncing spawning using chemical / pheromone cues – but it's very early days, high tech, high intervention, high risk strategy
  - e. **Research questions: What kind of road bumps on the way, in terms of getting the technique operational / costs / practicalities? We don't yet know the trigger concentrations, or how long it takes for them to respond?**
  - f. Might be easier to operationalise the repellent than the attractant because attractants based on CoTS pheromones might be overwhelmed by the natural distribution of pheromones in the water when CoTS are in relatively high densities, whereas a repellent based on the chemical signal from a triton is likely to be viable at low densities because triton are so rare – could embed it in slow-release blocks around high value sites
    - i. The lesson from the vertebrate world is that repellents based on predator pheromones is only a temporary measure, because animals learn
  - g. Non-target impacts: Other starfish and sea cucumbers might be repelled by triton repellent
  - h. Looks promising, but still quite a few questions to be answered before it can be operationalised – might warrant further investigation
5. Disease dynamics
  - a. Microbiomes and viromes
  - b. What is controlling the disease susceptibility and a pathogen to understand vulnerability?
  - c. (Side note: target specificity – bait in CoTS-specific trap, CoTS-specific bait)
  - d. What is the path / timeline to application? Probably not in the next couple of years

- e. The research is not high risk initially, but as it went along, you'd have to look at communications / public education etc.
- f. Look at reefs where CoTS populations are collapsing to see whether specific pathogens are contributing
- g. How can we leverage these natural disease processes?
- h. Morgan: Lack of preferred corals increases susceptibility to disease
- 6. Encourage natural predator populations to limit peak densities
  - a. e.g. Increasing density of tritons on key reefs
- 7. Green Zone / Blue Zone
  - a. Some studies have found a difference in CoTS effects between Green and Blue Zones, but we don't know the mechanism yet – Blue Zones may have increased disease susceptibility because of reduced habitat quality, which may be direct or indirect, e.g. coral damage from fishing boat anchors.
  - b. It's possible direct trophic interaction, but that's controversial. The measured rates of predation inside and outside Green Zones on egg, larvae, juveniles and adults show no evidence of different rates of damage
  - c. It's attractive to think that if you reinstate predators, they may be able to limit CoTS densities to below threshold levels in self-sustaining way – but the fact that we get outbreaks in Green Zones suggests that this isn't a silver bullet.
- 8. Tritons
  - a. How to get enough - are tritons available anywhere else in the world?
  - b. Mike has summarized all the information that is available on the reef, but is unlikely to publish it – can we get someone to write it up to inform this subject for everyone
  - c. AMPTO have been recording triton sightings for Mike – lucky if they get one or two a trip – six months before they found any at all
  - d. What steps would we need to put in place to actually use tritons: access to sufficient tritons, run experiments (e.g. put 100 on one reef, 0 on another) – problem: no one has managed to get the larval to settle yet
- 9. Fish predators:
  - a. For adult CoTS, we can't underestimate the importance of fish species. When Morgan tethered CoTS with a camera trap in summer, every single one was taken by fish by midnight, but when CoTS were tethered in winter none were taken
  - b. We could find the complete target list of things that might predate CoTS and figure out if any of them are higher within Green Zones than elsewhere?
  - c. We know almost nothing about the predation on eggs, larvae, settling larvae, juveniles, other than that there is a phenomenal potential for predation of settling larvae (anything can eat them, can lose all larvae in a single night)
  - d. 20 years of LTMP fish counts – coral trout go up in Green Zones, but no evidence of trophic cascades in other species
  - e. Could we use eDNA technique on stomach contents of potential predatory fish for a quick method to identify natural predators?
- 10. Invertebrates
  - a. Shrimps
  - b. Molluscs have nematodes that consume gonads – is there anything similar for CoTS?
  - c. There was an idea to import a castrating parasite from Japan, but it never happened (Side note: Would need to be species-specific)

## A2.11 Integration

1. Management goals:
  - a. Overarching goal about long term reef resilience
  - b. How do we deal with a site?
  - c. How do we deal with an existing outbreak?
  - d. How do we prevent an outbreak?
  - e. Ultimate causes – haven't talked about this, because it seemed beyond the scope of this discussion
2. We talked about surveillance, we talked about how you kill CoTS, we talked about how you manage an incipient primary outbreak in the initiation box
3. Goal:
  - a. Do we just aim to promote coral recovery?
  - b. Is it realistic to aim to reduce spread in any meaningful way? Can we act early enough, across enough of the reef, do our techniques let us manage an ecologically meaningful portion of the population?
4. How do you manage to facilitate reef resilience and recovery?
  - a. Reef connectedness: in terms of coral, perhaps in terms of CoTS
  - b. Quality of the reefs in terms of species diversity, age structure and quantity
  - c. Population model: for coral, perhaps for CoTS
  - d. How exposed each reef is to disturbance / other drivers
  - e. Develop a decision tool to set priority reefs using these three bodies of information, then optimise surveillance for them
  - f. Further questions:
    - i. Is current flow connectivity sufficient, or do we need other assessments of connectivity?
    - ii. How can we optimise surveillance in terms of logistic constraints as well as ecological importance?
    - iii. How often does this optimisation need to be revisited – annually?
    - iv. Does the optimisation change for different time horizons? Is the appropriate temporal scale a whole outbreak cycle?
    - v. Do Green Zones have a role to play beyond affecting quality?
5. **Research needs over next 5 years (NESP period)**
  - a. **Understand what types of connectivity are important - coral, CoTS, difference between current connectivity and genetic connectivity**
  - b. **Map or collate information on the quality of the reefs in terms of species diversity, age structure and quantity - do we have this already?**
  - c. **Population model: for coral and CoTS - we need to know where high quality reefs and high density of CoTS are to calculate movement on the connectivity network**
  - d. **How exposed each reef is to disturbance / other drivers - do we have any information on this?**
  - e. **Develop a decision tool to set priority reefs using these three bodies of information**
  - f. **Develop a model to optimise surveillance for targeted reefs**
6. In the initiation box structure monitoring and control program with reference to coarse five-year-periods understanding of outbreak dynamics

- a. First 5 years: monitor coral cover – probably don't need to be going to every reef every year
  - b. Next 5 years: monitor coral cover + larvae + CoTS population variability + nutrients – need intensive monitoring at this point, but possibly not a lot of control
  - c. Next 5 years: CoTS populations – faster monitoring (of adults) and intensive control
  - d. Best case scenario we hit building populations prior to outbreak sufficiently hard we avoid outbreak entirely, worst case scenario – we know exactly when outbreak begins and can bring massive resources to bear as soon as adult population booms on primary reef - also have excellent data on how to iteratively refine this strategy for the next outbreak
  - e. **Research need over the next 5 years: we're just moving into the second five year period now, so need to begin implementing currently available monitoring methodologies such as coral surveys and CoTS population surveys in Northern initiation box to augment Eye on the Reef, and need to start testing new monitoring methodologies: larval detection, population variability, nutrients**
7. In practice, we manage CoTS at individual sites:
- a. Turn up at a pre-selected reef
  - b. Implement surveillance, delimit where CoTS are right now
  - c. Choose control sites at sub-reef scale
  - d. Get underwater and kill CoTS up to some threshold of either resourcing / CPUE / residual density
  - e. Revisit based on external funding
8. We could refine and improve each of these steps by integrating our understanding of:
- a. Where the CoTS are, habitat use, proportion of population deeper than 15m
  - b. How far and fast they can move, how far they actually move
  - c. How fast the manageable population can change – recovery time, where do they recover from, uncontrolled individuals in the management region, or movement from outside the management region?
  - d. How fast and effectively we can kill CoTS vs density using current techniques? Future techniques?
  - e. **Research need over the next 5 years: integrate our understanding of these complex interacting processes with a local-scale CoTS model, to:**
    - i. **Prioritise surveillance when we arrive at a reef**
    - ii. **Prioritise sub-reef management units within the reef, based on current population distribution and likely movement capacity relative to key assets**
    - iii. **Optimise our return times based on an ecological understanding of the population**

## A2.12 Management and research priorities

### *Are the three scales we identified reasonable?*

1. We need to optimise on-water control activities at the local site scale to help improve management actions right now
2. Once we've done that, can we get together a research strategy to help deal with the outbreak as it reaches the Whitsundays – minimise impacts and maximise coral recovery
3. Then we have a slightly longer timeline to deal with preventing an incipient outbreak in the initiation box

### *Dealing with the current outbreak*

1. We think the front is offshore Innisfail, but outbreak still extant up North
2. With the current outbreak structure, by the time the outbreak reaches the Whitsundays, we'll still have issues up here and won't be able to redirect resources down South
3. Important that that message comes clearly out of this workshop to make this argument to funders – we agree that we will need more resources to protect the Whitsundays while maintaining effort around Cairns. We have the framework in place to ensure we know best how to invest those resources
4. We know that the next areas to be hit do not fit within AMPTO's current contract – the outputs of this workshop will give us a plan and a document that maximise our chances of convincing funders that it is more efficient to get in before the outbreak moves into the Whitsundays
5. Arguing the case for some time for a second vessel – the current vessel is fully committed just to maintain the AMPTO tourism sites and 6 extra reefs, we'd need a second vessel to protect recovery of other reefs south at the outbreak front.
  - a. Mid-shelf reefs in the Cairns – Mackay region only just showing coral recovery following Cyclone Yasi, and CoTS have only recently been detected on some of those reefs
6. Need to be developing the overall perspective on how you manage the entire outbreak process at the same time as developing the techniques to improve individual site management, because the overall perspective will be vital for generating the funding we need to do the job (GBRMPA perspective)

### *Is there anything we've completely left out so far?*

1. How do we refine stopping rules for stopping an incipient outbreak (as opposed to just removing adults at a site)
2. Effective delimitation of larval stage

### *How does NESP fit with other CoTS research?*

1. Accelerate
  - a. Focussed on identifying plausible bounds, but speculative with big uncertainties
  - b. No potential for data collection
  - c. Big uncertainty around density dependence in the stock-recruitment relationship, detectability
2. Potential sources of funding: NESP, Reef Trust, Philanthropic funds, ARC Linkage

*How do we want to operate as a group into the future?*

1. Are we a working group that we keep operating into the future so that we can be responsive to what we learn and so that we can modify things as we learn?
  - a. A representative from our group could be part of GBRMPA Research Steering Group
  - b. Do we put in a proposal to NESP that we keep a working group running
  - c. How do we respond to the short-term goal of NESP proposals, and how do we come up with longer term plans / respond to other opportunities
2. Do we put in a combined proposal from the group? Strong support from GBRMPA
3. Current project team could pull together a first pass at the prioritisation, then distribute and receive feedback via email, timeline:
  - a. Core group prepare Workshop report, distribute next week (by Friday 11th)?
  - b. Video conference the week after to discuss projects (by Friday 18th)
  - c. Submissions due Monday 28th
4. Need a clear progression of research needs over the three years of NESP funding rounds
  - a. First Round (3 years + potential 2 year extension) – need some immediate tactical advice + coherent overview of the system to show that we understand the system, and have a plan, to justify a second boat and generate more funding
  - b. Second Round (3 years + potential 1 year extension) - ???
  - c. Third Round (3 years) – maybe more blue-sky, speculative
5. Other areas in the Hub that may have some overlap (e.g. Water quality) – some component of the TWQ Hub has a priority around identifying thresholds in terms of long term monitoring – it's really quite open with no preferential area at the moment and certainly room for a connection to CoTS – how do we facilitate connections with those other areas?
6. The ongoing working group should also provide a framework and a home for sharing CoTS data in general
  - a. Can we extend the eAtlas infrastructure to provide a non-production quality repository?
  - b. Set up an agreement that everybody in the group tables their data, but also put agreements in place so that no one would publish from other peoples' data until agreed
  - c. eAtlas will be refunded via the NESP to provide continued support
  - d. Can we get support to import legacy data from previous studies?
  - e. First step: Need to do an audit of exactly what is out there
7. Working group
  - a. Can be used to develop NESP proposals
  - b. Can be used as an advisory group for informing a management strategy for the upcoming Whitsundays issue
  - c. Can be used to make sure everyone is singing from the same song sheet

## APPENDIX 3 – WORKSHOP PARTICIPANTS

### Day 1: September 1, 2015

1. Roger Beeden (GBRMPA)
2. Jen Dryden (GBRMPA)
3. Steve Moon (AMPTO)
4. Anne Clarke (RRRC)
5. Peter Chase (DotE)
6. John Keesing (CSIRO)
7. Maria Byrne (USyd)
8. Morgan Pratchett (JCU)
9. Ainslie Archer (AIMS)
10. Ken Anthony (AIMS)
11. Damien Burrows (NESP)
12. Frederieke Kroon (AIMS)
13. Sven Uthicke (AIMS)
14. Lone Hoj (AIMS)
15. Russ Babcock (CSIRO)
16. Karlo Hock (UQ)
17. Terry Walshe (UMelb)
18. Eva Plaganyi (CSIRO)
19. Peter Doherty (AIMS)
20. David Westcott (CSIRO)
21. Cameron Fletcher (CSIRO)

### Day 2: September 2, 2015

1. Roger Beeden (GBRMPA)
2. Jen Dryden (GBRMPA)
3. Steve Moon (AMPTO)
4. Anne Clarke (RRRC)
5. Peter Mumby (UQ)
6. John Keesing (CSIRO)
7. Maria Byrne (USyd)
8. Morgan Pratchett (JCU)
9. Ainslie Archer (AIMS)
10. Ken Anthony (AIMS)
11. Damien Burrows (NESP)
12. Frederieke Kroon (AIMS)
13. Sven Uthicke (AIMS)
14. Lone Hoj (AIMS)
15. Russ Babcock (CSIRO)
16. Karlo Hock (UQ)
17. Terry Walshe (UMelb)
18. Eva Plaganyi (CSIRO)
19. Peter Doherty (AIMS)
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