Guam Crown-of-Thorns Outbreak Response Plan

December 2017

Overview

The Guam Crown-of-Thorns sea star (COTS) Outbreak Response Plan was developed collaboratively by multiple local and federal agencies, including the Bureau of Statistics and Plans (BSP) and the Guam Coastal Management Program (GCMP), the Guam Department of Agriculture's (GDOAG) Division of Aquatic and Wildlife Resources (DAWR), the Guam Environmental Protection Agency (GEPA), the University of Guam Marine Laboratory (UOGML), the National Oceanic and Atmospheric Association (NOAA), the National Park Service (NPS), Joint Region Marianas (JRM), and the U.S. Fish & Wildlife Service (USFWS).

The COTS Outbreak Response Plan exists to maximize effectiveness of activities conducted by the Guam Coral Reef Response Team and ensure efficient use of resources and human capital by providing a standardized framework for responding to COTS outbreaks. This document, designed as a working draft that will be continuously updated, includes an in-depth description of Guam's early warning system for COTS outbreaks, standard operating procedures for response implementation including detailed assessment and mitigation protocols, and recommendations for post-outbreak management, reef recovery, and restoration approaches. This document is intended for use by coral reef managers and scientists on Guam, but may also be useful to individuals and groups in other locations impacted by COTS outbreaks, especially those who are interested in developing COTS outbreak response plans.

Objectives of the Guam COTS Response Plan:

1. Summarize impacts of past COTS outbreaks on Guam.
2. Provide up-to-date standard operating procedures to be followed before, during, and after COTS outbreaks, including lists of agency assets and necessary supplies and delineation of agency roles.
3. Develop a protocol to monitor extent of COTS outbreaks and provide early warning of potential outbreaks on Guam's reefs.
4. Create a framework for an optimal COTS outbreak response, which would include:
    a. Measurement of spatial extent and severity of COTS outbreaks;
    b. Mitigation (culling) of COTS populations;
    c. Assessment of ecological impacts of COTS outbreaks;
    d. Formation of a plan to mitigate COTS impacts and restore impacted ecosystems; and,
    e. Development of a pathway for communicating findings to decision makers.
5. Involve the community in monitoring the health of Guam's reefs.
6. Communicate with the local media and raise public awareness of impacts of COTS outbreaks on Guam's coral reef ecosystems.

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Acknowledgments:
Among the many documents and papers that were referenced during the development of this plan, several were especially influential, including the *Crown-of-thorns starfish control guidelines, 2nd edition* (Great Barrier Reef Marine Park Authority 2017a), the *COTS primer for American Samoa* (National Park Service 2016), *Hawaii's rapid response contingency plan for events of coral bleaching, disease, or crown-of-thorns starfish outbreaks* (Aeby et al. 2008), and review papers authored by Pratchett et al. (2014, 2017). The Guam Coral Reef Response Team would also like to thank Dr. Ciemon Caballes for his advice and input.

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Acronyms

AIMS = Australian Institute of Marine Science
AMPTO = Australian Association of Marine Park Tourism Operators
BSP = Guam Bureau of Statistics and Plans
CCA = Crustose coralline algae
CNMI = Commonwealth of the Northern Marianas Islands
COTS = Crown-of-thorns sea star (*Acanthaster planci*)
DAWR = Guam Department of Wildlife Resources within the Guam Department of Agriculture
DI = Deionized water
EOR = Eyes of the Reef Marianas
ESA = Endangered Species Act
GBR = Great Barrier Reef
GBRMPA = Great Barrier Reef Marine Park Authority
GCC = Guam Community College
GCMP = Guam Coastal Management Program within the Bureau of Statistics and Plans
GDOAG = Guam Department of Agriculture
GEPA = Guam Environmental Protection Agency
GLTCRMP = Guam Long-term Coral Reef Monitoring Program
JCU = James Cook University
JRM = Joint Region Marianas
LBSP = Land-based sources of pollution
MARAMP = NOAA Mariana Archipelago Reef Assessment and Monitoring Program
NOAA = National Oceanic and Atmospheric Administration
NOS = NOAA National Ocean Service
NPS = National Park Service
PIFSC = NOAA Pacific Islands Fisheries Science Center
SOP = Standard operating procedure
SST = Sea surface temperature
UOG = University of Guam
UOGML = University of Guam Marine Laboratory
USFWS = U.S. Fish & Wildlife Service

Background

COTS biology and ecology

The crown-of-thorns sea star (*Acanthaster* spp.) inhabits tropical and subtropical Pacific reefs and has been recorded across the Indo-Pacific from 32°S to 34°N (Pratchett et al. 2014) (Figure 1). Evidence indicates there are up to five distinct species or clades of *Acanthaster* throughout the entire Indo-Pacific (including the Red Sea and Indian Ocean), but *A. planci* is the only species known to inhabit coral reefs of the Pacific basin (Pratchett et al. 2014). While there have been numerous studies of COTS behaviors, diet, life history, and reproductive strategies, less is known about this sea star's population dynamics and demographic characteristics (Pratchett et al. 2014).

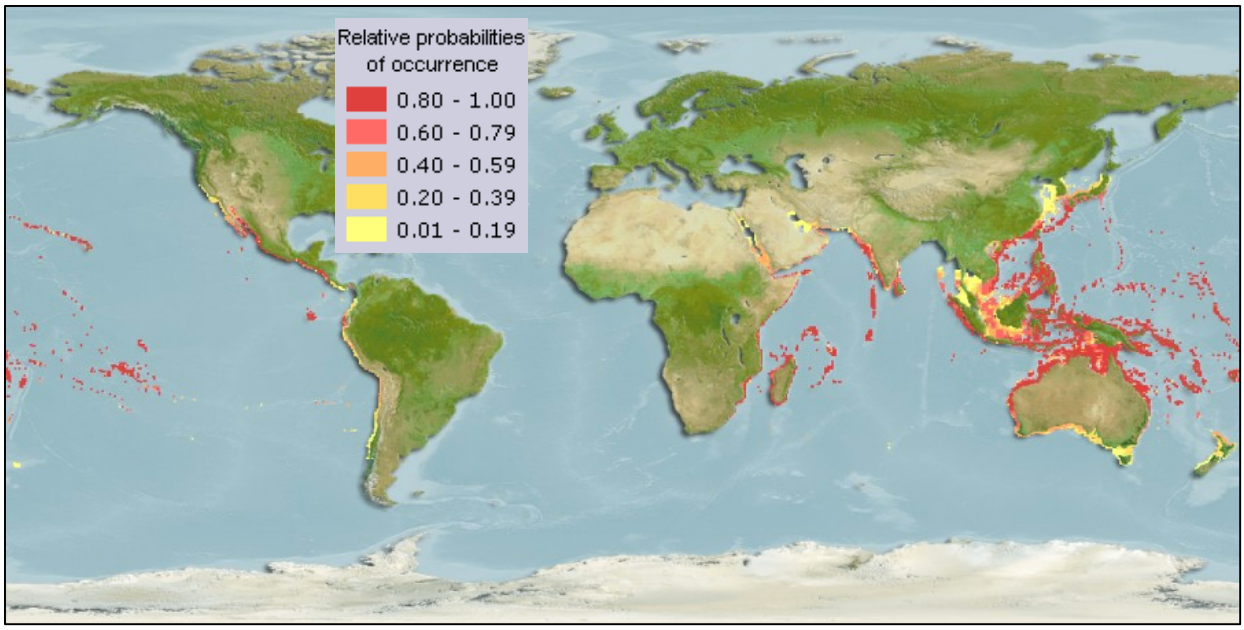


Figure 1. Native distribution map for *A. planci* (AquaMaps 2016, www.aquamaps.org, accessed 01 November 2017)

COTS reach sexual maturity by the age of two years and are incredibly fecund, producing millions of eggs with each spawn; large females (40 cm diameter) may release up to 65 million eggs annually (Birkeland and Lucas 1990). Reproductive success is dependent upon density, as *A. planci* is a gonochoristic broadcast spawner and requires simultaneous spawning of nearby females and males for fertilization to occur (e.g. 90-100% fertilization success occurs with 1 m separation between female and male and 70-100% occurs with 10 m separation, from Benzie et al. 1994). Fertilization rate decreases with distance (and increases with high synchrony), but measurable fertilization can still occur at larger distances (e.g. 5.8% with 100 m separation) (Babcock et al. 1994) (Figure 2). Correlation between COTS reproductive timing and tidal patterns or the lunar cycle has never been detected (Babcock and Mundy 1992).

Seasonal temperature changes are a key trigger for COTS reproduction. Increased temperature is linked to greater rates of gamete production; on warm tropical reefs, spawning is seen to occur when sea surface temperature (SST) surpasses 27°C (Pratchett et al. 2014). Although *A. planci* on most tropical reefs are known to spawn only a few months per year (Pratchett et al. 2014), gravid females have been recorded on Guam during all months of the year (Cheney 1974) (Figure 3). Some evidence suggests that COTS outbreaks may be linked to El Niño events, which impact water temperature across the Pacific basin (Harriott et al. 2003).

The survival rate of *Acanthaster* larvae is considered a key factor in COTS outbreaks, although there is still uncertainty regarding outbreak drivers (Pratchett et al. 2017). COTS larvae feed primarily upon phytoplankton and some studies (e.g. Lucas 1982) have shown that the density of phytoplankton on low-nutrient (oligotrophic) tropical coral reefs is unable to

support the large numbers of larvae produced by COTS spawning, hence their survival is limited by phytoplankton density and thus nutrient availability. Algae blooms resulting from a surge in nutrient-rich runoff following a storm event may provide sufficient phytoplankton concentrations for a COTS outbreak to occur (Birkeland 1982). However, COTS larvae have been successfully produced *ex situ* with low phytoplankton density (Olson 1987) and there is evidence that larvae may be able to acquire energy from bacteria, dissolved organic matter (Olson and Olson 1989), and dissolved free amino acids (Hoegh-Guldberg 1994) in the absence of abundant phytoplankton. COTS larvae are passively transported via ocean currents; larvae may settle after as few as 9-14 days in the plankton, although successful settlement has been recorded at 43 days after fertilization (Pratchett et al. 2017). Self-recruitment is highly variable dependent on hydrological conditions and most COTS larvae will settle within 10 to 100 km of their native reef (Dight et al. 1990, Pratchett et al. 2017).

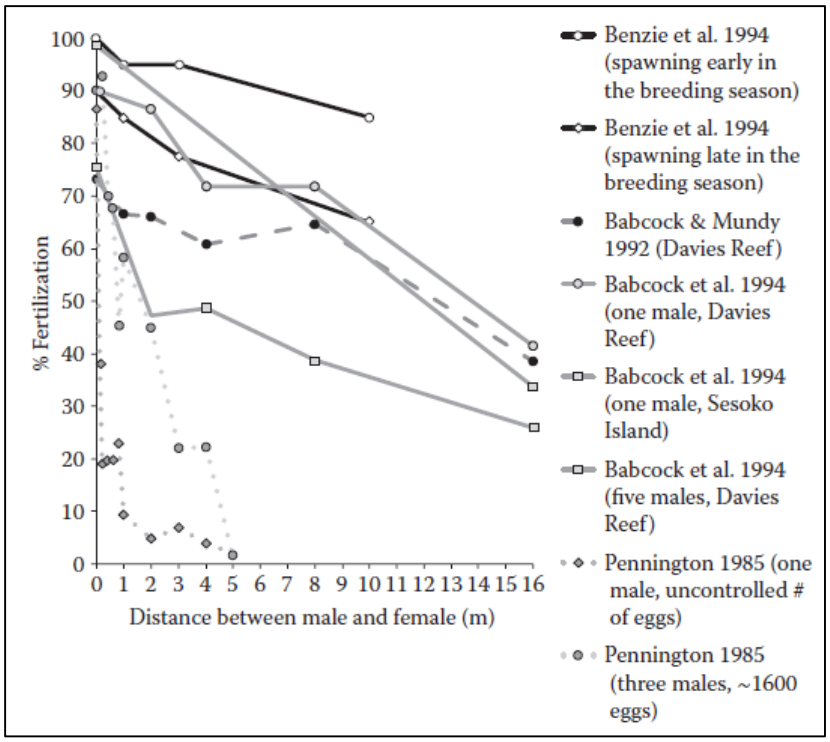


Figure 2. Fertilization rate for female COTS (solid and dashed lines) versus distance from spawning males (From Pratchett et al. 2014)

The extent to which the abundance of COTS predators or competitors influences COTS larvae survival is unknown (Pratchett et al. 2014). Cowan et al. (2017) compiled a list of 80 reef species that prey upon *A. planci* at various stages in the sea star's life cycle and argued that no individual species played an inordinate role in controlling *Acanthaster* abundance. Instead, the predation upon COTS throughout its developmental stages by numerous taxa is likely responsible for regulating COTS populations and moderating outbreaks. The authors concluded that biodiversity loss and declines in predator biomass (e.g. due to overfishing or habitat degradation) could cause increased frequency or intensity of outbreaks, but predator release is unlikely to be the sole catalyst of a COTS outbreak.

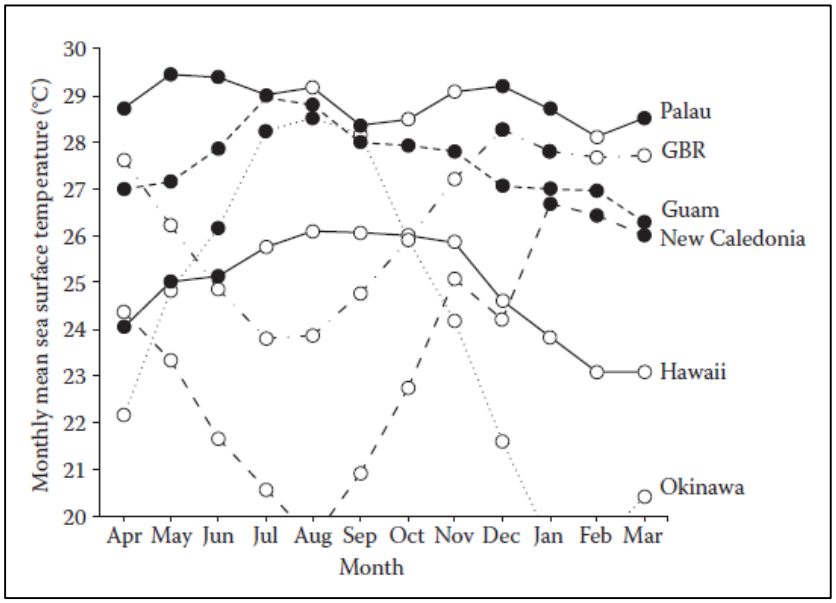


Figure 3. COTS spawning occurrence (solid circles) versus seasonal variation in sea surface temperature (From Pratchett et al. 2014)

Acanthaster larvae contain chemicals that may make them less appealing to potential predators. Some reef fishes that feed on other zooplankton have been seen to avoid consuming COTS larvae (Pratchett et al. 2014). Additionally, these larvae seem adapted to survive fluctuations in salinity (Pratchett et al. 2014). Decreased salinity, which can occur after a storm event with heavy runoff, may actually improve larval survival rates (Birkeland 1982). However, the larvae have a relatively narrow temperature threshold for optimal development (26-30^{o}C) (Pratchett et al. 2014).

Juvenile COTS are herbivorous, feeding upon crustose coralline algae (CCA) for approximately four to six months; at this point, when a COTS is about 1 cm in diameter, its diet shifts to stony corals (Yamaguchi 1974). The sea star grows rapidly, reaching approximately 25 cm in diameter after two more years on the reef and becoming one of the largest, most efficient predators of scleractinian corals (Harriott et al. 2003, Pratchett et al. 2017). An Adult COTS extrudes its stomach over the surface of a coral colony to consume the soft tissue of the coral polyps (Brauer et al. 1970). These sea stars will prey upon most coral species, although they preferentially feed on branching and table corals such as *Acropora* spp. and *Pocillopora* spp. (Kayal et al. 2012, Pratchett et al. 2017). Coral reefs dominated by Acroporids (e.g. many reefs in the western Pacific) are more likely to suffer severe coral mortality due to COTS outbreaks (Pratchett et al. 2017). COTS behavior and feeding preferences vary by location and may shift according to biotic and abiotic conditions, such as coral community composition and water flow. When there is low abundance of branching species, COTS can adapt to feed on less preferred species, such as massive or foliose corals, in addition to consuming algae, sponges, and soft corals (Birkeland and Lucas 1990).

COTS can grow to over one half meter in diameter (Pan et al. 2010) and have a lifespan of up to eight years (Chesher 1969). Adult COTS have few natural predators, although some species will prey upon them, such as Napoleon wrasse (*Cheilinus undulatus*), giant triton snails (*Charonia* spp.), titan triggerfish (*Balistoides viridescens*), starry pufferfish (*Arothron stellatus*), and harlequin shrimp (*Hymenocera picta*) (Harriott et al. 2003, Prakash and Kumar 2013). Adult *Acanthaster* are covered in long, toxic spines and have unpalatable and venomous compounds in their tissues and organs (Cowan et al. 2017). The natural density of COTS in reef habitats is from 6-20 individuals per km^2 (< 1 adult sea star per hectare) (Moran 1990). At these low densities, COTS may enhance coral species richness by consuming fast growing corals and making reef substrate available for slower growing species (Great Barrier Reef Marine Park Authority (GBRMPA) 2017b). COTS move relatively slowly and generally avoid open sandy areas; the sea stars can typically travel < 35 m per day and will generally only move considerable distances when they have consumed desirable coral colonies in the vicinity (Chesher 1969, Pratchett et al. 2017).

A healthy reef system with approximately 40-50% live coral cover may be able to support as many as 20-30 COTS per hectare (Harriott et al. 2003). During outbreaks, however, COTS coral consumption exceeds coral growth rates, resulting in lost coral cover (Australian Institute of Marine Science (AIMS) 2017a). Moran and De'ath (1992) **defined an outbreak as > 15 COTS per hectare**, supported by observations that significant COTS-related coral mortality was only seen on reefs with *Acanthaster* at this density or higher. The Great Barrier Reef Marine Park Authority (GBRMPA) **characterizes an outbreak as > 30 adult COTS per hectare** (Dixon 1996). This plastic threshold for identifying an outbreak poses a challenge to reef managers, particularly in places lacking baseline data on "normal" COTS populations. When an outbreak occurs, COTS predation can cause the loss of 90% of live coral on a reef, with an average adult COTS consuming 5-13 m^2 of live coral per year (Dixon 1996). The stomach of an adult COTS is much larger relative to its body size compared to other sea stars and *Acanthaster* can consume coral tissue 2-5 times faster than other echinoderms of similar diameter (Birkeland 1989).

Stony corals, the favorite prey of adult COTS, provide vital habitat and physical structure for coral reefs and the reef-associated species that depend upon them. Significant loss of live coral cover and reef structural complexity has a direct and almost immediate impact on fishes that rely

upon coral reefs for shelter, food, and settlement habitat (Pratchett et al. 2008, Kayal et al. 2012). Moran (1988) reported significant declines in four reef fish species following COTS outbreaks on Australia's Great Barrier Reef (GBR). The physical structure and coral community composition of the reef moderates important ecological processes and dynamics of reef-associated organisms, including predation, competition, and diversity (Caley and St. John 1996, Munday 2000, Munday 2001). Significant observational and empirical evidence indicates that coral reefs with greater topographic complexity, coral diversity, and higher coral cover are host to more diverse and abundant assemblages of reef-associated organisms, particularly fishes, compared to reefs with low rugosity, coral diversity, and coral cover (e.g. Carpenter et al. 1982, Messmer et al. 2011).

Outbreaks of COTS are one of the most significant causes of coral loss in the Indo-Pacific during the last century, with early outbreaks documented on Japan's reefs in the 1950s and on the GBR in the 1960s, and suspected outbreaks in the 1920s and 1930s in the Philippines (Pratchett et al. 2014, Pratchett et al. 2017). At least 246 COTS outbreaks were recorded in the Indo-West Pacific between 1990 and 2014, which is three times the total number of outbreaks detected before 1990; however, at least some of this increase should be attributed to intensified reef monitoring efforts in recent years. (Pratchett et al. 2014). Although coral reef scientists and managers now seem to be focusing their attention on threats associated with global climate change, such as coral bleaching and the spread of coral diseases, COTS outbreaks are still widespread across Indo-Pacific reefs. Between 1985 and 2012, mean coral cover on the GBR decreased from 28% to 13.8%; 42% of this loss is attributed to COTS predation (De'ath et al. 2012). In some areas with repeated, severe COTS outbreaks, the impacts of *Acanthaster* predation are greater than the cumulative effects of all other coral reef stressors (Pratchett et al. 2014). Fortunately, unlike threats related to climate change, there are specific, direct management actions – e.g. physical COTS removal or culling – that can be undertaken to mitigate COTS outbreak impacts on a local scale, and thus increase the overall resilience of reefs facing climate-related stress (e.g. De'ath et al. 2012, Pratchett et al. 2014, Bostrom-Einarsson and Rivera-Posada 2015).

A healthy coral reef ecosystem can recover from a COTS outbreak in 10-20 years (AIMS 2017b). Many factors influence the recovery of a coral reef following an outbreak, including coral recruitment rates and the impacts of other stressors, such as land-based sources of pollution (LBSP) (Harriott et al. 2003). The recovery process is longer for reefs that are degraded due to climate change and local impacts. These stressed reefs may not be fully recovered before another outbreak develops (AIMS 2017b), particularly if the frequency of outbreak events is indeed increasing due to anthropogenic stressors (e.g. nutrient run-off) that increase the survival rates of COTS larvae.

COTS and other stressors

COTS outbreaks can increase coral reef vulnerability to climate change and local stressors (Hoegh-Guldberg 1999) and decrease the ability of reef systems to recover from other impacts, such as bleaching (Haywood et al. 2016, Pratchett et al. 2017). Reef resilience is negatively affected by declines in coral cover, loss of rugosity, and decreased fish and benthic diversity, all of which can result from COTS outbreaks (Kayal et al. 2012). Climate change could also make some corals more vulnerable to COTS predation. Ocean warming may drive the loss of the symbiotic crustaceans that inhabit certain corals (e.g. *Pocillopora* spp.) and usually protect their host colonies from predation (Glynn 1983, Hoegh-Guldberg 1999).

> "**Resilience** is defined as the ability of a system to maintain key functions and processes in the face of stresses or pressures by either resisting or adapting to change. Resilience consists of two components: **resistance**, which is the ability to absorb or resist impacts, and **recovery**, the ability to recover from them. **Coral reef resilience** refers to building resistance and recovery potential into reef ecosystems by reducing or eliminating stressors (e.g., overfishing, pollution, coastal development). The term '**reef resilience'** refers to coral reefs that are able to bounce back or recover after experiencing caused a stressful event such as bleaching by elevated temperatures."
>
> (Source: http://www.reefresilience.org/about-resilience)

Like corals, COTS populations will likely be affected by climate change and ocean acidification. Ocean warming may increase the rate at which COTS larvae develop (Hoegh-Guldberg and Pearse 1995). Kamya et al. (2014) found that increasing water temperature (to 30°C) and decreasing pH (to pH 7.6 and 7.8) negatively impacted advanced COTS larvae at ten days old, but did not affect larvae in very early stages of development. A subsequent study showed that COTS larvae that consumed CCA grown in acidic conditions (pH 7.6) grew faster than larvae that were fed algae grown at a higher pH. This indicates that ocean acidification may initially enhance the growth of COTS larvae and thus increase the rate of survival to the adult stage (Kamya et al. 2017).

Ocean warming is predicted to increase the occurrence of coral disease outbreaks by increasing pathogen virulence and abundance and heightening coral vulnerability to disease; there is evidence that coral disease outbreaks may be on par with bleaching in terms of coral mortality risk in the near future (Maynard et al. 2015). *Acanthaster planci* could compound this impact by promoting coral diseases. Nugues and Bak (2009) found that coral colonies predated upon by COTS had higher rates of brown band syndrome, indicating that COTS may spread some forms of coral disease. Katz et al. (2014) showed that the pathogenic ciliates responsible for brown band syndrome were more likely to infect coral colonies that had been physically damaged or predated on by COTS compared to healthy colonies.

History of COTS on Guam

Chesher (1969) reported that although *A. planci* were uncommon on Guam's reefs prior to 1967, COTS destroyed more than 90% of coral along 38 km of coast to depths of approximately 65 m between 1967 and 1969. In November 1968, divers removed almost 900 COTS from a 9 hectare area at Double Reef (Chesher 1969). Surveys in April and May 1969 showed greater than 90% coral mortality between Orote Point and Ritidian Point, with live coral found only in shallow areas exposed to strong wave action (Chesher 1969). From 1968-1969, a COTS outbreak at Tanguisson Reef reduced coral

cover to < 1% in two of the three reef zones surveyed (Colgan 1987). At this site, COTS density multiplied from fewer than 0.1 sea stars per hectare to greater than 1,000 per hectare in a one year period, an increase of 10,000% (Chesher 1969). Fortunately, this reef recovered; after 12 years, coral cover and richness at Tanguisson were the same as or greater than at similar reefs before the outbreak (Colgan 1987).

Widespread impacts from COTS outbreaks were recorded on Guam's reefs throughout the early 2000s (Burdick et al. 2008) (Figure 4). In 2006, surveys conducted by the University of Guam Marine Laboratory (UOGML) detected COTS outbreaks and resulting coral mortality around the island; at six of the 17 survey sites, large numbers of COTS were recorded, ranging from about 100 to more than 1,600 COTS per survey (Burdick et al. 2008). At three of the affected sites, COTS densities were estimated at 50-61 sea stars per hectare; at the three remaining sites, densities were estimated at 14-26 sea stars per hectare. In Pago Bay, density exceeded 450 COTS per hectare; at Tanguisson Point, the density was almost 1,500 per hectare (Burdick et al. 2008). Coral species preferred by COTS, such as *Acropora* spp. and *Montipora* spp., were found in very low numbers and COTS had shifted to feeding upon less preferred coral species, including *Goniopora* spp. and massive *Porites* spp. (Burdick et al. 2008).

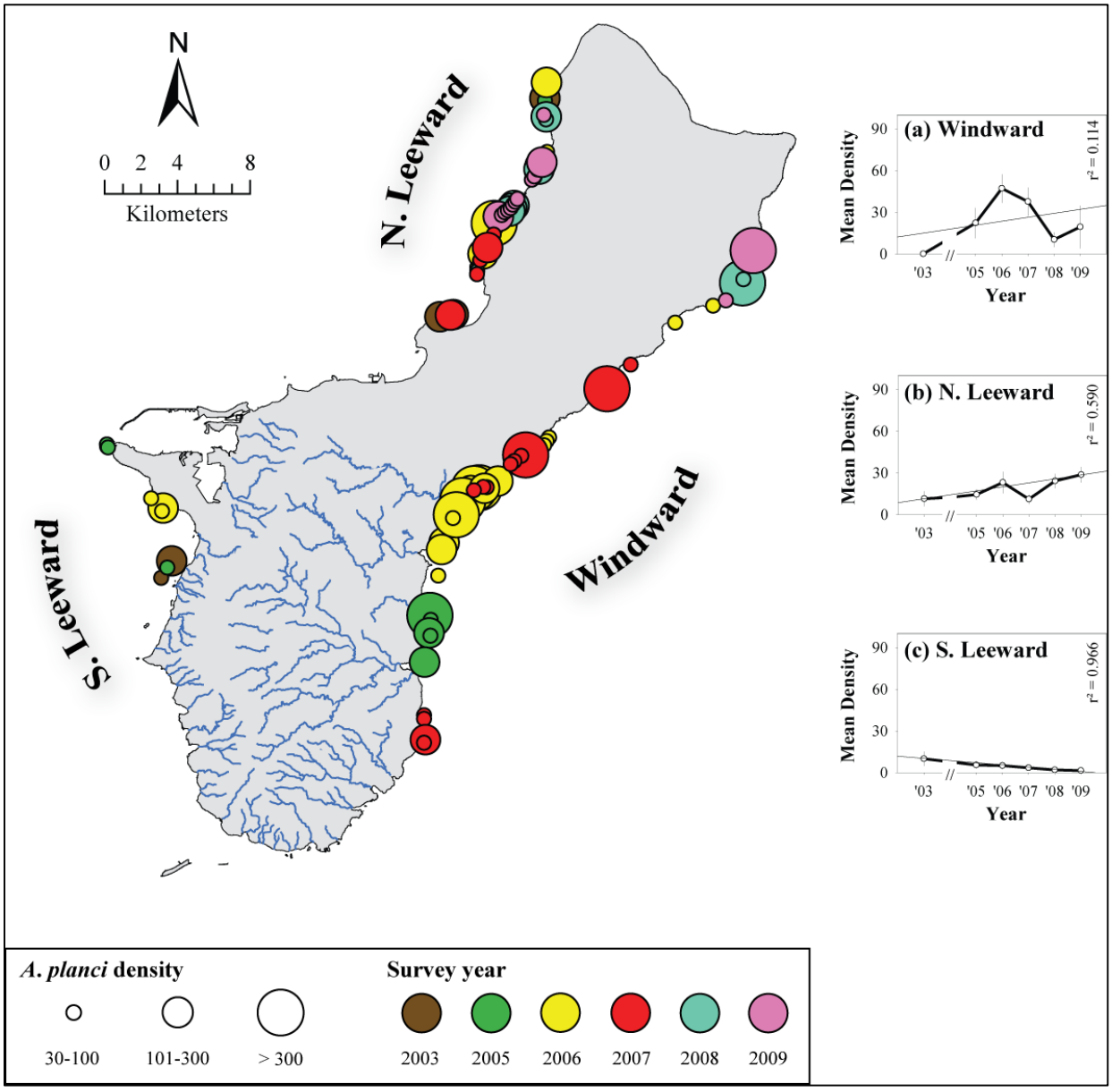


Figure 4. COTS outbreaks on Guam's reefs between 2003 and 2009 (figure prepared by CF Caballes)

Data collected by NOAA have also revealed high COTS abundance and resulting reef degradation. Surveys conducted during NOAA Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP) cruises in 2003, 2005, and 2007 detected COTS outbreaks at many reef sites across Guam, with outbreaks increasing over time (Burdick et al. 2008). During the 2003 MARAMP expedition, 215 *Acanthaster* were observed around Guam. Three of the 20 towed-diver surveys detected 71% of all COTS recorded: 81 individuals were seen in Agat Bay, 43 in Tumon Bay, and 29 between Haputo Point and Urune Point. During remaining surveys, COTS sightings were infrequent (Pacific Islands Fisheries Science Center (PIFSC) 2006a).

Divers on the 2005 MARAMP cruise recorded COTS at 6 of the 11 sites surveyed around Guam. *Acanthaster* numbers were highest between Togcha and Talofofo Bay; 223 COTS were reported here, compared to zero seen in this area in 2003. The highest COTS abundance was seen just outside of Fouha Bay. Large COTS were also recorded near Jinappsan Beach (northeast coast) and along the southern edge of the Piti Bomb Holes Marine Preserve (PIFSC 2006b). In 2007, high COTS abundance was recorded at Fadian (188 individuals) and Aga Point (91 individuals); 30% of the stony corals at Aga Point were reported as 'stressed,' the highest percentage of all survey sites. On average, 3.42 COTS were detected per survey (PIFSC 2007).

During the 2009 MARAMP expedition, an active COTS outbreak was detected south of the Pati Point Marine Preserve at a depth of 24 m. At this site, 10.8% of coral was classified as recently dead. A total of 652 COTS were detected during 22 benthic surveys, an average of almost 30 individuals per survey (National Ocean Service (NOS) 2009). In 2011, MARAMP surveys detected a high proportion of stressed corals (from 20.1-30%) at a survey site along northeastern Guam, which corresponded with an area of high COTS abundance (PIFSC 2011).

Since 2011, no significant COTS outbreaks have been detected on Guam. This may be due to the depletion of preferred prey species, especially *Acropora* spp., caused by both COTS predation and coral bleaching. However, it is possible that some reefs have reached outbreak status without detection and that some reefs have ongoing incipient outbreaks.

Early warning system

Guam's early warning system for COTS outbreaks is designed to detect incipient COTS populations and localized outbreaks before they become widespread. Preventing and managing outbreaks of *A. planci* is considered one of the most effective management interventions to reduce coral loss (Pratchett et al. 2017). Since suspected drivers of COTS outbreaks, such as storm events that cause severe nutrient run-off, do not have immediate effects on adult COTS densities, it is difficult to predict the timing and potential severity of outbreaks. Local observations – including those by community members – will be crucial for identifying potential outbreaks. **The Coordinator of the Guam Coral Reef Response Team is responsible for compiling data relevant to the early warning system (e.g. Eyes of the Reef reports, observations by local scientists) and reporting back to the team and other stakeholders as needed.**

Predicting outbreaks

Although there is an abundance of scientific literature discussing potential factors that cause COTS outbreaks, such as nutrient inputs and overfishing of COTS predators, the exact drivers – and their relative influence – are unknown. There is evidence to support the occurrence of two types of COTS outbreaks (Caballes 2009). Steady, gradual increases in COTS populations composed of multiple age classes are considered primary outbreaks, which can result in explosive population growth (a secondary outbreak) when the highly fecund sea stars begin to reproduce (e.g. Endean 1974, Stump 1996). A primary outbreak will include sea stars of variable sizes and ages, while a secondary outbreak consists primarily of one cohort, evidence of a mass spawning event (Endean 1977) (Figure 5). Distinguishing primary versus secondary COTS outbreaks may be a crucial factor in managing their populations.

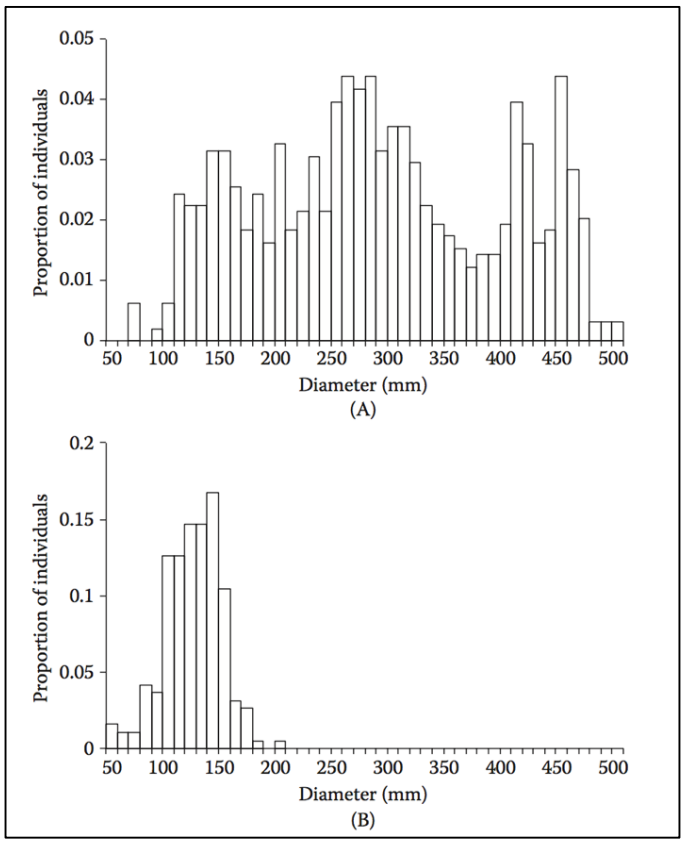


Figure 5. (A) A primary outbreak at Lizard Island, Australia, including sea stars of various sizes; and (B) an outbreak in Suva, Fiji where starfish size varied by less than 150 mm, indicating a secondary outbreak (From Pratchett et al. 2014)

Resource managers and scientists on Guam should commit to tracking potential drivers, such as flooding events and typhoons, to gain a better understanding of what forces cause COTS outbreaks on Guam. Maintaining records of events that could cause future outbreaks may allow the Guam Coral Reef Response Team to work backward if an outbreak does occur and trace its stimulus.

However, given the limited resources and manpower for coral reef management on Guam, the multitude of impacts threatening local reefs, and the uncertainty regarding outbreak drivers, it is unlikely that sustained effort will be dedicated to predicting COTS outbreaks. Alternately, it may be possible to apply findings from other locales where considerable research is being conducted, such as the GBR, to make broad generalizations about when outbreaks could occur around Guam. Scientists at James Cook University (JCU) have determined that anomalously weak currents, which increase local retention of COTS larvae, are a factor in COTS outbreaks (Miller 2015). Researchers believe that outbreaks are caused by a concurrent shift from El Niño to La Niña climate patterns and nutrient pollution. COTS outbreaks occur in approximately 17 year cycles on the GBR (GBRMPA 2017) and JCU's Dr. Jon Brodie predicts that the next widespread COTS outbreak will occur in 2025 (Miller 2015).

Local reef managers and scientists should evaluate reef sites and estimate COTS outbreak risk at a small scale. Site-specific factors influencing COTS outbreak likelihood:

- Presence of incipient COTS populations (density, COTS size)
- Coral community composition: Most reefs around Guam no longer have an abundance of COTS preferred corals
    - *Montipora* spp., *Acropora* spp., *Pocillopora* spp., *Cyphastrea* spp., and *Astreopora* spp. are preferred prey (Figure 6, from Caballes and Schupp, in prep)
- Past occurrence of outbreaks at specific reef sites
- Reef zone: COTS avoid areas with strong wave action and/or strong currents
- Depth: COTS do not typically access reef flats or cross large sandy patches exposed to wave action and/or currents
- Water quality: High nutrient concentration areas, especially if corresponding with potential high concentrations of COTS larvae based on current patterns and locations of known COTS populations

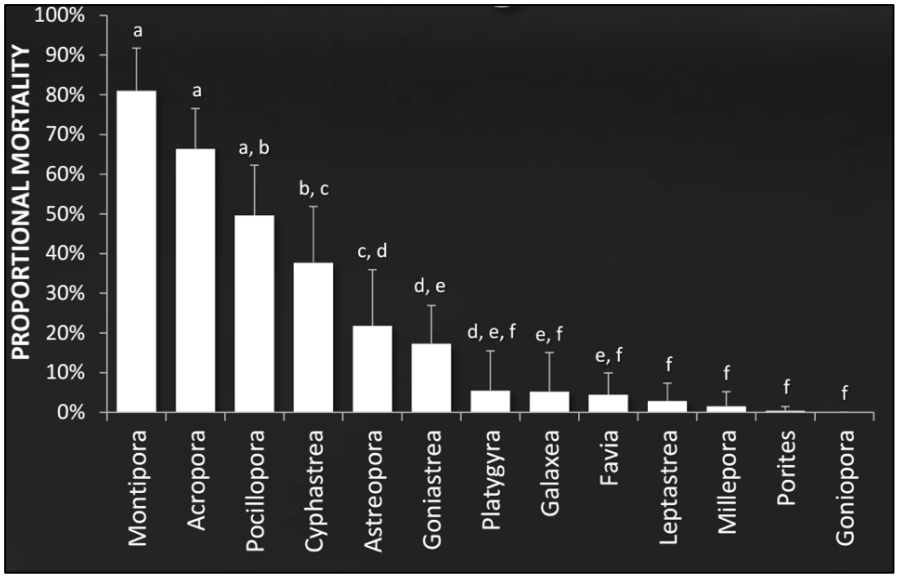


Figure 6. Feeding preferences of COTS on Guam (From Caballes and Schupp, in prep)

Identifying outbreaks

Moran and De'ath (1992) defined an outbreak as a COTS density > 15 individuals per hectare, while the GBRMPA describes an outbreak as the presence of > 30 adult COTS per hectare of coral reef (Dixon 1996). The normal or baseline COTS density will vary across reefs based on coral community composition, habitat structure, bathymetry, and other factors, thus it seems reasonable for the outbreak threshold to vary as well (Caballes 2009). Numerous benchmarks have been used to characterize outbreaks (Table 1). Keesing and Lucas (1992) suggested that reefs with > 20% coral cover could support up to 10-15 COTS per hectare without significant coral loss. According to this model, a reef with 20% pre-

Table 1. Thresholds calculated to signify outbreak-level densities of COTS (From Pratchett et al. 2014)

Minimum threshold	Reference
30–40 starfish per km^2	Clark & Weitzman 2006
14 starfish per 1000 m^2	Endean & Stablum 1975
40 starfish per 20-min swim	Pearson & Endean 1969
100 starfish per 20-min swim or manta tow	Chesher 1969
10 starfish per 1-min spot check	Pearson & Garrett 1978
30–50 starfish in 20 min	Faurea 1989
1 starfish per 24 m^2	Pearson & Endean 1969
100 starfish per hectare	Dana et al.1972
260 starfish per hectare	Glynn 1973
150 feeding scars per 250 m^2	Lison de Loma et al. 2006

outbreak coral cover and *Acanthaster* density of 100 per hectare will experience 50% coral mortality after 13 months; a reef with 50% pre-outbreak coral cover and the same COTS density would see 50% coral mortality after a 33 month period (Keesing and Lucas 1992) (Figure 7).

Site-specific factors to consider when calculating an outbreak threshold:

- COTS density and size (as a proxy for feeding rate) of individuals
- Amount of live coral cover
- Reef size/total area
- Coral recruitment rate
- Coral community characteristics
    - Species richness and evenness
    - Presence of branching vs. massive morphologies
- Ecological and economic value of the site
    - Presence of endangered or ecologically important species

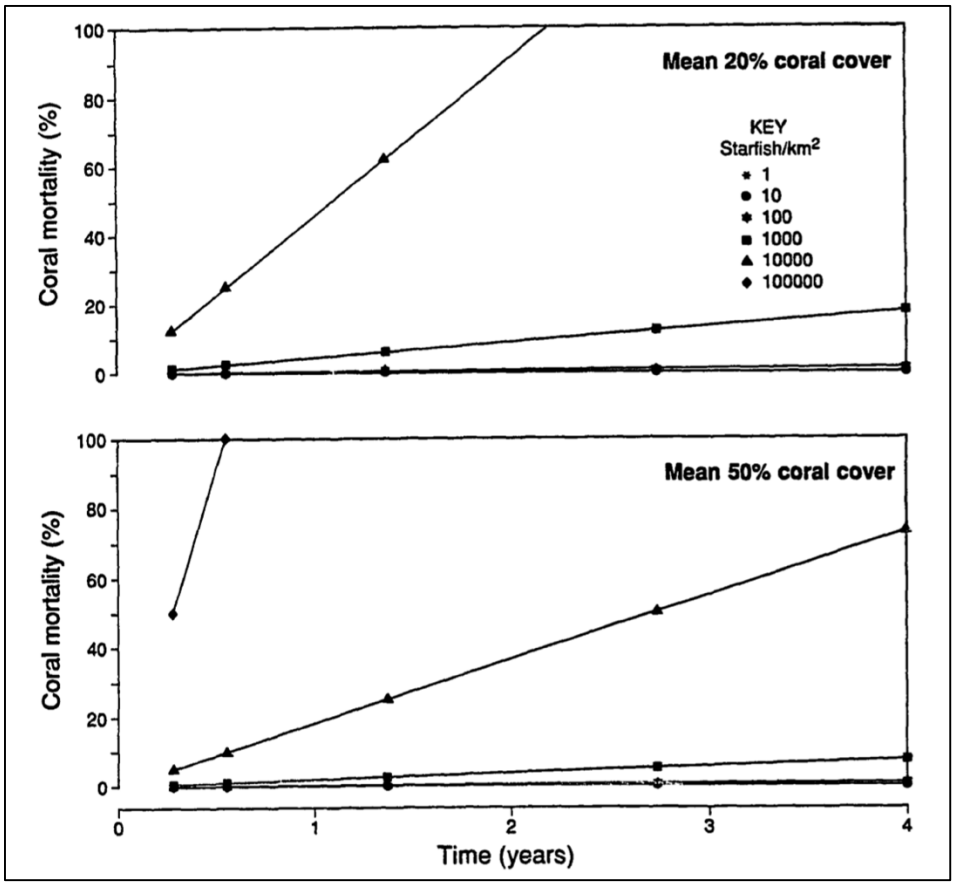


Figure 7. Predicted coral mortality during a four year period at various COTS densities, assuming average consumption of 250 cm^2 of live tissue per COTS per day (From Keesing and Lucas 1992)

COTS outbreaks often start at deeper zones near the base of the reef slope where large quantities of CCA and coral rubble create ideal habitat for *Acanthaster* settlement and provide food (CCA) for juveniles (Kayal et al. 2012). *Acanthaster* are cryptic; therefore it can be challenging to accurately assess abundance (Pratchett et al. 2014). Kayal et al. (2017) found that night-time surveys detected mean COTS densities 27% higher than surveys conducted during daylight hours. Small individuals (< 20 cm diameter) may be especially hard to detect during the day as they feed primarily at night. Populations can be estimated by counting feeding scars rather than recording observations of the animals themselves, then ground-truthing the estimate by counting both feeding scars and COTS individuals in a detailed survey and computing a ratio

(Kayal et al. 2012). Researchers in Moorea, French Polynesia calculated an average of 8.6 ± 1.7 (SE) feeding scars per COTS (Kayal et al. 2012).

Notably, one uncertainty in understanding COTS demographics is whether variation in size among sea stars indicates the presence of multiple age groups, or whether there is significant variation in growth rates within a cohort (Pratchett et al. 2014) (Table 2). The most reliable method to determine the age of *A. planci* is by counting the pigmented growth bands on the longest spines found on the aboral edge (furthest from the mouth) of the sea star's upper arms (Stump and Lucas 1990). These growth bands, which are visible only on mature sea stars (≥ 2 years) are deposited seasonally, thus each pair of band represents one year (Stump 1996).

Table 2. Age-size relationships for COTS in the western Pacific (Adapted from Pratchett et al. 2014, based on data from Yamaguchi 1974, Lucas 1984, Zann et al. 1987, Habe et al. 1989, Stump 1996, and Pan et al. 2010)

COTS size (diameter), mm	Estimated age, years
30-100	1-2
100-250	2-3
250-300	3-4
300-400	4-5
> 380	> 5

Eyes of the Reef reports

Community-based reporting is a vital component of the early warning system. With proper training, engaged participants can significantly increase Guam's capacity to identify and respond to COTS outbreaks. The Eyes of the Reef Marianas (EOR) program was launched in December 2015. EOR Marianas, based on Hawaii's Eyes of the Reef initiative, was established to provide residents of Guam with a mechanism for reporting observed reef impacts. Participants are encouraged to attend a two-hour classroom-based training session, in which they learn how to identify reef impacts (such as COTS outbreaks, coral bleaching, and marine debris) and report these sightings through the online reporting form. However, anyone can report a reef impact through the EOR website. Participants are asked to submit photographs and GPS coordinates with their reports when possible. The EOR online reporting form is available here: http://eormarianas.org/make-a-report

As of December 2017, over 200 participants have completed EOR training. Program staff plan to train additional instructors to lead sessions, create a mobile app for reporting impacts in the field, and develop online tutorials for individuals who are unable to attend a training session or for those who wish to refresh their knowledge. To increase EOR participation, the following groups may be targeted for outreach:

- Divers and snorkelers, accessed via dive companies and tour operators
- Students at the University of Guam (UOG) and Guam Community College (GCC)
- Local high school students and student groups
- Non-profit and community-based organizations
- Military recreation and service group leaders

The EOR model is designed for participants who are already recreational reef users, such as divers, snorkelers, swimmers, boaters, fishers, and stand up paddle boarders. EOR reports may serve as the first indication of a COTS outbreak, as this program has the potential to get many 'eyes on the reef' to alert scientists and managers to possible outbreaks before

they are detected through regular scientific surveys and monitoring activities. **Local NOAA staff and BSP staff will regularly monitor reports submitted through the EOR online reporting form, which is hosted on Google Drive.** Reports should be promptly corroborated through in-water visual verification and the submitter should be contacted. This creates the opportunity to improve the quality of EOR reports by providing feedback to participants and lets them know that their reports are meaningful. On the report form, they can include the number of COTS, approximate size, coral types affected, depth of impacts, location (e.g. dive site, nearby beach), and other information. During training sessions, EOR staff emphasize that participants should not touch any *Acanthaster* or try to remove them from the reef.

Standard operating procedures (SOPs)

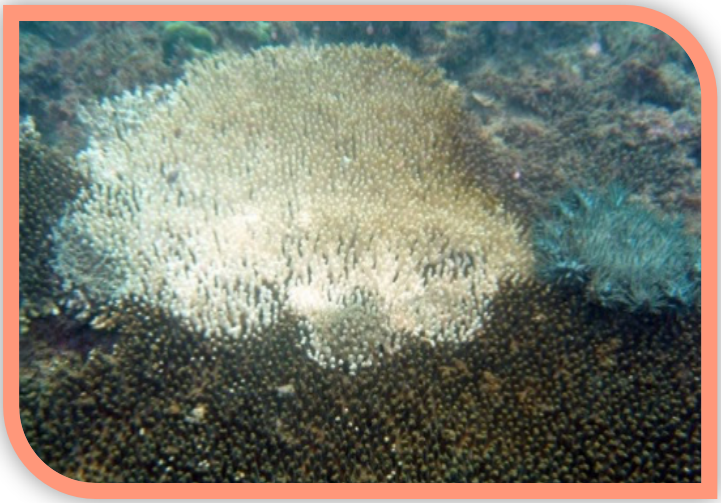
Response initiation triggers

Response initiation is based on specific decision criteria that trigger response activities. Consistent application of the early warning system by tracking and recording potential drivers of future outbreaks, determining probable outbreak risk at local reef sites, and monitoring and verifying EOR reports will allow managers and scientists to employ an appropriate response based on the expected extent and severity of a COTS outbreak before it becomes widespread.

The decision to launch a major COTS response effort is based on the anticipated or known severity of the outbreak. Although specific triggers and their outcomes have been defined within the SOPs, decisions may often be *ad hoc* as outbreak trajectory and resource availability will vary. Response triggers are described below and illustrated in a flow chart (Figure 8).

Factors used to determine the severity of a COTS outbreak:

- Spatial extent (number of reef sites, depth range)
- Number and size of COTS (density)
- Rate of outbreak spread
- Number of coral colonies affected/density of affected colonies
    - Percent coral cover affected
    - Number of coral genera affected
- Ecological and economic value of the site
    - Presence of endangered or ecologically important species



Based on previous studies, an understanding of resource availability, and knowledge of Guam's coral reef dynamics and COTS outbreak history, **the Guam Coral Reef Response Team has determined the following thresholds for COT outbreaks, with each level triggering a set of actions:**

- **Outbreak watch (Level 1):** If a natural resource manager, researcher, or member of the public (e.g. EOR participant) reports an observation of **≥ 2 COTS during a ~30 minute snorkel or dive, this data will be recorded and tracked.**
    - The EOR management team may request that EOR participants revisit this site.
    - If two or more EOR participants or other community members report ≥ 2 COTS at the site during separate visits, a member of the Response Team will visit the site to verify the reports.
- **Outbreak warning (Level 2):** If a natural resource manager, researcher, or member of the public (e.g. EOR participant) reports an observation of **≥ 5 COTS during a ~30 minute snorkel or dive, this triggers broad scale surveys at the site**, which will be conducted using either diver propulsion vehicles (DPVs) or long swims. (Methods are described in the following section.)
    - Opportunistic COTS mitigation may be undertaken during these surveys.
- **Outbreak status (Level 3):** If a member of the Response Team observes **≥ 30 COTS per hectare during a DPV or long swim survey, an outbreak is declared**. Response Team members will check nearby sites for potential outbreaks, prioritize response activities based on available resources and personnel, and develop a plan for outbreak mitigation.

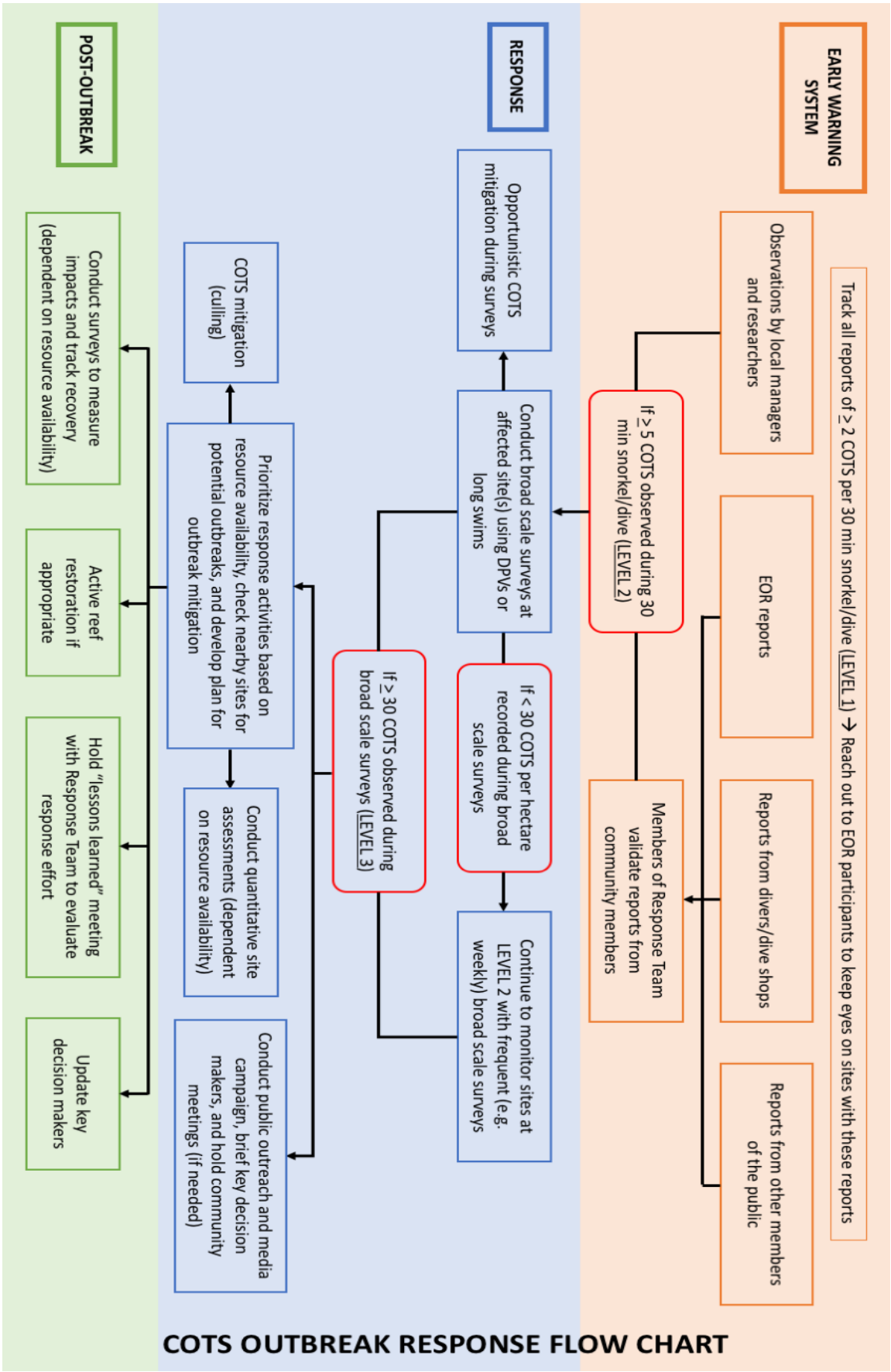


Figure 8. Flow chart for COTS outbreak response

Response personnel

Leadership

COTS outbreak response on Guam will be conducted according to the procedures within this document and input from a core team of local coral experts, including: Dr. Laurie Raymundo (UOGML), Dave Burdick (UOGML), Val Brown (NOAA), and Whitney Hoot (BSP). These individuals serve as the COTS Outbreak Working Group and will meet regularly before and during outbreaks to maximize the effectiveness of Guam's response to COTS and advise on scientific protocols. Whitney Hoot also serves as the Coordinator for the Coral Reef Response Team.

Guam Coral Reef Response Team

The Guam Coral Reef Response Team is responsible for conducting COTS outbreak response activities on Guam. Local entities involved in the response team include BSP, GCMP, DAWR, GEPA, and UOGML. Federal partners include NOAA, NPS, JRM, and USFWS. Broad roles of the local entities are outlined in the MOU signed in March 2016 (Appendix I). Specific tasks are outlined below (Table 3); assignments are expected to change and this table should be updated frequently.

Table 3. Key tasks and roles for COTS outbreak response activities

ONGOING	
Task/Role	**Assigned Personnel/Agency**
Read new publications and reports on COTS; keep Response Team members informed of relevant findings	Response Team Coordinator
Maintain and update lists of agency resources that may be needed during future COTS outbreaks	BSP, GCMP, DAWR, GEPA, UOGML, NOAA, NPS, JRM, USFWS
Acquire and store pre-positioned supplies needed for COTS response	BSP, GCMP, DAWR, GEPA, UOGML, NOAA, NPS, JRM, USFWS
Monitor EOR report responses	NOAA, BSP
PRE-COTS OUTBREAK	
Task/Role	**Assigned Personnel/Agency**
Host EOR trainings and contact current participants to encourage reporting	NOAA, BSP
Check EOR reports and confirm via site survey if report includes observation of high COTS density or predation	COTS Outbreak Working Group
Confirm available resources and personnel for response activities	BSP, GCMP, DAWR, GEPA, UOGML, NOAA, NPS, JRM, USFWS
Renew DAWR permit for ox bile application in marine preserves (annual)	Response Team Coordinator

Reserve sufficient boat time according to anticipated severity and extent of outbreak	DAWR, GEPA, UOGML, NOAA
DURING COTS OUTBREAK	
Task/Role	**Assigned Personnel/Agency**
Assess available data in accordance with decision criteria and determine appropriate level of response based on outbreak severity and extent	COTS Outbreak Working Group; mapping by GCMP
Launch media outreach and public awareness campaign	NOAA, BSP, GEPA
Host community meetings if needed	Response Team Coordinator
Brief key decision makers on outbreak extent, response activities to date, and plans for upcoming response efforts	Response Team Coordinator
Check EOR reports and confirm via site survey if report includes observation of high COTS density or predation	COTS Outbreak Working Group
POST-COTS OUTBREAK	
Task/Role	**Assigned Personnel/Agency**
Assess reef health, coral mortality, community shifts, and recovery following the outbreak	BSP, DAWR, GEPA, UOGML, NOAA, NPS, USFWS; mapping by GCMP
Hold “lessons learned” meeting with the Response Team to evaluate process and results of response activities	Response Team Coordinator
Update key decision makers on impacts of outbreak, outcomes of response activities, and next steps	Response Team Coordinator
Evaluate extent of damage and implement restoration projects if appropriate	COTS Outbreak Working Group; mapping by GCMP

Assessment and mitigation protocols

Guam's COTS outbreak assessment methods involve surveys of varying scales and resource requirements, with the goal of measuring the extent and severity of COTS outbreaks and evaluating the ecological impacts of these outbreaks on coral reef ecosystems. The data collected during the assessments and through post-outbreak recovery monitoring will improve our understanding of the extent, severity, duration, and frequency of *A. planci* outbreaks; the ecological effects of COTS predation, such as impacts on species richness and relative abundance, coral cover, reef structure, and implications for non-coral species (e.g. reef fishes); the rate of reef recovery after COTS outbreaks; and the relationship between other stressors, such as LBSP and coral disease, and COTS outbreaks. We hope to use this information to measure the relative resilience of Guam's reefs and produce data-driven management recommendations for conserving Guam's coral reef resources.

Multiple survey method options are presented for two levels of survey effort: broad-scale surveys (less resource intensive) and quantitative site assessments (more resource intensive). As detailed in this plan, specific decision criteria are required to trigger each level of COTS outbreak response. This section also includes procedures for COTS mitigation (culling) and guidelines for post-outbreak monitoring of reef recovery.

Broad-scale (rapid) surveys

Several methods can be used for broad-scale (rapid) surveys (Table 4), which will provide broad data regarding outbreak severity and potential risk, such as number of sites and genera affected, depth range, and approximate number and size of COTS and/or COTS feeding scars. The manta tow method is a common choice for broad-scale COTS surveys and is used by both AIMS and the GBRMPA, however it is unlikely that this method will be used on Guam due to resource availability. On Guam, broad scale surveys will likely be conducted using either DPVs or long swims. These methods allow the assessment of large areas and minimize the time and resources required for surveying. With each of these methods, it will be important to maintain consistent photographic records and store them in an accessible database (e.g. Response Team Google Drive folder).

Variables to measure at survey sites during broad-scale surveys (when possible):

- Physical conditions: Depth, water temperature, turbidity, nutrient concentrations
- Sources of stress/potential causal factors: Sedimentation, runoff, pollution
- Other coral health indicators: Bleaching, coral disease

Table 4. Methods and respective outputs for broad-scale (rapid) surveys of COTS outbreaks

Method	Description	Data output	Equipment/resources
Eyes of the Reef reports	Community-based early warning system using online form and trained community members	Presence/absence of COTS at reef sites COTS number and size Depth of impacts Number of colonies and genera affected Photographs	EOR network Training materials Report verification
Manta tow surveys	Divers or snorkelers are towed behind a boat with tracks recorded using GPS	Broad spatial extent of outbreak Rapid estimate of COTS number and size Rapid estimate of coral genera impacted	Boat time & fuel Manta tow board Dive equipment Trained divers/ snorkelers GPS Camera

		Rapid estimate of percent coral cover impacted Photographs/video	
DPV (dive scooter) surveys	Divers use scooter to survey large area quickly; may also be used to survey reefs not easily accessible by boat	Broad spatial extent of outbreak Rapid estimate of COTS number and size Rapid estimate of coral genera impacted Rapid estimate of percent coral cover impacted Photographs/video	Scooters Dive equipment Trained divers GPS Camera
Long swims	Divers or snorkelers swim in straight or meandering lines over a specified area	Broad spatial extent of outbreak Rapid estimate of COTS number and size Rapid estimate of coral genera impacted Rapid estimate of percent coral cover impacted Photographs/video	Boat time & fuel Dive equipment Trained divers/ snorkelers GPS Camera

Manta tow survey method

The Australian Long Term Monitoring Program conducted by AIMS uses manta tow surveys to collect data on COTS populations on approximately 100 reefs (Harriott et al. 2003). During the surveys, a diver is towed around the perimeter of the reef (parallel to the reef crest) by a small boat traveling at a slow, consistent speed (~ 4 km per hour) while holding on to a manta tow board (Figure 8) that is attached to the vessel by a 17 m rope (Miller 2009, AIMS 2017c). Every two minutes, the boat stops and the diver records presence and size of COTS and COTS feeding scars and estimates coral cover in the surrounding area (approximately 10 m band including the reef slope starting just below the reef crest). During these surveys, divers are able to see and record COTS that are ~ 15 cm in diameter or larger. The number of COTS observed during each two minute segment of the survey are used to estimate outbreak status. **AIMS defines an incipient outbreak as 0.22 sea stars per two minute tow, the density of COTS at which coral damage is likely to occur. An active outbreak is defined as greater than one sea star per two minute tow, at which density coral damage is almost certain** (Harriott et al. 2003).

Equipment and resources needed for manta tow surveys (Miller et al. 2009):

- Small boat with 15-25 HP outboard and GPS, boat captain, observer, fuel
- Two divers (or snorkelers) able to identify benthic organisms and reef impacts, dive gear
    - If two divers are being towed, one records data while the other takes photos
- Watch or other timing device to track survey segment time
- Safety equipment: Emergency oxygen, first aid kit, etc.
- Communication equipment: Waterproof VHF radio, cell phone, etc.
- Rope harness attached to boat's transom
- Tow rope (17 m long)
- Manta tow board (Figure 9) with pencil(s) attached and clamp for datasheet
- Datasheets (see Appendix II for datasheet used by AIMS) and maps or aerial photographs of the reef sites, printed on underwater paper
- Digital underwater camera(s)

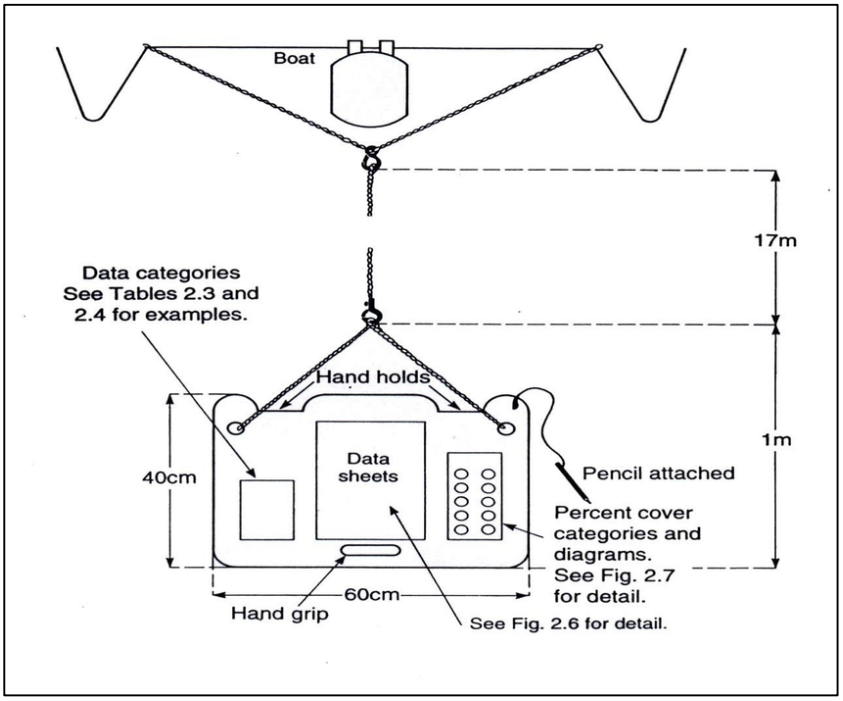


Figure 9. Manta tow board schematic (Welly et al. 2014)

Data to be recorded during each two minute segment of a manta tow survey (Miller et al. 2009):

- Number of COTS
- COTS size, recorded as size class (Note: Manta tows rarely detect COTS < 15 cm diameter):
    - Early juveniles up to one year old (< 5 cm diameter)
    - Juveniles one to two years old (5-15 cm diameter)
    - Sub-adults two to three years old (15-25 cm diameter)
    - Adults three years and older (≥ 25 cm diameter)
- Estimate of percent live coral cover
- Estimate of percent dead coral cover (mortality within previous six months; structure still intact)
- Estimate of soft coral cover
- Number of COTS scars, binned (and coral genera affected, when possible):
    - Absent (0 scars)
    - Present (1-10 scars)
    - Common (> 10 scars)
- Dominant benthic cover (e.g. hard coral, soft coral, sand, rubble)
- Dominant stony coral genus and dominant morphology (e.g. branching, encrusting)
- Other impacts present: Coral bleaching, disease

Recommendations for safety during manta tow surveys (Miller et al. 2009):

- Each diver should conduct no more than 15 two minute tows to prevent fatigue
- Manta tows should not be conducted in swells > 2 m height, when gusts are > 25 knots, or if visibility is < 6 m
- Tow direction and/or speed should be adapted when there are strong currents; abort surveys if the diver becomes fatigued
- Boat captain should maintain a reasonable distance from the reef crest at low tide

Note: AIMS has found that manta tow surveys consistently underestimate COTS density compared to fine-scale assessments of the same reef (Harriott et al. 2003). However, comparisons of manta tow survey data to fine-scale assessments and video footage demonstrate that manta tows are effective in estimating sea star populations and

estimating coral cover with sufficient accuracy to identify and track moderate to severe outbreaks and subsequent recovery (AIMS 2017c).

Further details on AIMS manta tow survey methods can be found in this document (Miller et al. 2009): http://www.aims.gov.au/documents/30301/20e3bf4f-4b3b-4808-ac02-c15c2912c3f2

The National Park Service (NPS) in American Samoa uses towed snorkeler surveys for broad-scale assessment of COTS outbreaks (NPS 2016). During these surveys, two snorkelers are towed behind a small boat moving at ~ 3 knots; the snorkelers scan the reef slope and search for *Acanthaster* and their feeding scars. If the snorkelers observe an area that appears to have an outbreak, they communicate this to the observer on the boat, who records the GPS coordinates (at one point or start and end points, if the outbreak is extensive) and depth of the affected area (NPS 2016). The boat's movement is also recorded using the tracking mode on the GPS unit.

The surveyors will note outbreak severity and convey this to the recorder (NPS 2016):

- Low: A few COTS or feeding scars scattered along reef, but no areas where COTS scars overlap
- Moderate: Patches of numerous COTS scars in one area, with patches of healthy coral over between the patches of feeding scars
- Heavy: Overlapping feeding scars forming a contiguous area of scars without gaps of live coral cover between them

DPV and long swim survey methods

These rapid methods are most likely to be employed by resource managers on Guam after ≥ 5 COTS are detected at one site during a ~30 minute snorkel or dive. During a DPV survey (which can be up to 3 miles long), one diver using the DPV (at speed 3) will record all observations of COTS and feeding scars in a 10 m wide transect. Any DPV operator must be properly trained and certified. The method is the same for long swims, although the recorder can be snorkeling if depth allows. The transect width can be decreased to 5 m if needed due to low visibility and/or high reef rugosity. The recorder will tow a float that is synchronized with the time setting on a dive computer or underwater camera. By taking a photo at the start and end of each transect, the recorder can document the start and end coordinates for the transect. The buddy diver (or snorkeler) may opportunistically mitigate (cull) COTS during the survey as long as both divers remain within a safe distance of each other. (COTS mitigation methods are outlined below.)

Quantitative site assessments

Several methods can be used for quantitative site assessments (Table 5), which will provide fine-scale data regarding benthic composition (e.g. species richness and evenness, percent coral cover, colony size), percent coral cover impacted, COTS predation severity on coral species/genera (including percent of each colony affected), COTS feeding preferences, and COTS population age structure. When possible, these surveys should be conducted using methods consistent with other reef surveys programs around Guam, particularly the Guam Long-term Coral Reef Monitoring Program. The **belt transect method** is a common choice for fine-scale COTS surveys and is used by AIMS.

For quantitative site assessments, specifics of survey methods should be standardized, including:

- Transect length and width
- Number of transects
- Number of sites to survey

These decisions will be based on outbreak severity, spatial extent, habitat type, site accessibility, weather conditions, and resource availability. Potential divers also need to be trained in methods and observations should be calibrated.

Variables to measure at survey sites during quantitative site assessments (when possible):

- Physical conditions: Depth, water temperature, turbidity, nutrient concentrations
- Sources of stress/potential causal factors: Sedimentation, runoff, pollution
- Other coral health indicators: Bleaching, coral disease
- Collect spines from a sub-sample of COTS individuals to infer age structure of COTS population (see methods outlined in Stump and Lucas 1990)

Table 5. Methods and respective outputs for fine-scale quantitative site assessments of COTS outbreaks

Method	Description	Data output	Equipment/resources
Line intercept	Transects are laid haphazardly or end to end within a specified depth; observer records the transect distance at each point when substrate type changes and when level of COTS impact changes	Benthic composition Mean percent coral cover COTS predation severity Percent coral cover impacted Coral genera impacted Photographs/video	Boat time & fuel Dive equipment Trained divers/ snorkelers Transects GPS Camera
Belt transects	Transects are laid along one or more depth contours; one observer counts and identifies coral colonies within the belt while a second observer records COTS and COTS impacts	Coral community composition Coral colony size class structure Density of COTS Percent of colonies impacted Coral genera impacted Photographs/video	Boat time & fuel Dive equipment Trained divers Transect tapes GPS Camera
Photo transects	At beginning and end of each transect, take 360' photo of benthos; then diver swims along transect taking one photo each meter using monopod centered on transect	Benthic composition Mean percent coral cover COTS predation severity Percent coral cover impacted Coral genera impacted Permanent photographic record	Boat time & fuel Dive equipment Trained diver(s) Transects GPS Camera Monopod Photo software for analysis
Video transects	At beginning and end of each transect, take 360' video of benthos; then diver swims slowly along transect at 1 m above benthos while filming the substrate	Benthic composition Mean percent coral cover COTS predation severity Percent coral cover impacted Coral genera impacted Permanent video record	Boat time & fuel Dive equipment Trained diver(s) Transects GPS Camera Video software for analysis

Belt transect survey method

In Australia, AIMS conducts fine-scale surveys using the belt transect method (Harriott et al. 2003). This method is more resource intensive than manta tows, but can detect low density COTS populations, juvenile sea stars, and more detailed information about the coral community. At each reef, divers record COTS along five transects at three sites along the reef (15 transects per reef); sites should be > 250 m apart if possible. Each transect (parallel to reef crest) is 50 m long by 2 m wide, representing 100 m^2 of survey area per transect, 500 m^2 per site, and 1500 m^2 per reef (Miller et al. 2009). The size of each sea star is also recorded to the nearest centimeter or binned into estimated age classes: early juveniles up to one

year old (< 5 cm diameter), juveniles one to two years old (5-15 cm diameter), sub-adults two to three years old (15-25 cm diameter), and adults three years and older (≥ 25 cm diameter) (Miller et al. 2009). With this fine-scale data, **AIMS defines an incipient outbreak as > 30 sub-adult and adult sea stars per hectare. An active outbreak is defined as > 30 adult sea stars per hectare** (Harriott et al. 2003).

Equipment and resources needed for belt transect surveys (Miller et al. 2009):

- Small boat with GPS, boat captain, observer, fuel
- Two divers able to identify benthic organisms and reef impacts, dive gear
    - One diver records data and the other does photo transects
- Safety equipment: Emergency oxygen, first aid kit, etc.
- Communication equipment: Waterproof VHF radio, cell phone, etc.
- Transect tapes (at least 50 m)
- Datasheets (see Appendix III for datasheet used by AIMS) and maps or aerial photographs of the reef sites, printed on underwater paper
- Digital underwater camera(s) and monopod for photo transects

Data to be recorded during each belt transect survey (Miller et al. 2009):

- Number of COTS
- COTS size, to nearest cm or recorded as size class:
    - Early juveniles up to one year old (< 5 cm diameter)
    - Juveniles one to two years old (5-15 cm diameter)
    - Sub-adults two to three years old (15-25 cm diameter)
    - adults three years and older (≥ 25 cm diameter)
- Estimate of percent live coral cover
- Estimate of percent dead coral cover (mortality within previous six months; structure still intact)
- Estimate of soft coral cover
- Number of COTS scars or binned estimate and coral species/genera affected:
    - Absent (0 scars)
    - Present (1-10 scars)
    - Common (> 10 scars)
- Dominant benthic cover (e.g. hard coral, soft coral, sand, rubble)
- Dominant stony coral genus and dominant morphology (e.g. branching, encrusting)
- Other impacts present: Coral bleaching, disease
    - Bleaching extent and severity (refer to Guam Coral Bleaching Response Plan for protocols) and coral species/genera affected
    - Disease extent and severity and coral species/genera affected; type of disease recorded if possible
    - Percent of each colony affected by bleaching and/or disease

Further details on AIMS belt transect survey methods can be found in this document (Miller et al. 2009):
http://www.aims.gov.au/documents/30301/20e3bf4f-4b3b-4808-ac02-c15c2912c3f2

COTS mitigation

Unlike coral bleaching and other climate-related threats, there are direct approaches to mitigating the impacts of COTS on coral reefs at the local level, namely through *Acanthaster* eradication. Early culling approaches from the 1960s included cutting the COTS into pieces, however this is no longer practiced as *Acanthaster* can regenerate from small fragments (Messmer et al. 2013). Contemporary methods include injections of substances like ox bile salts, sodium bisulphate, or household vinegar, which are toxic to COTS. Bile acids induce an allergic reaction in COTS, resulting in necrosis and apoptosis of tissue (Rivera-Posada et al. 2013). Another option is physical removal of COTS from the reef;

however, this must be done with caution due to the risk of damaging corals during extraction and the sea star's venomous spines and potential to spontaneously spawn (and signal other nearby COTS to spawn) if injured. (Note: The ability of COTS to spontaneously spawn is controversial, but precaution is still advisable (Pratchett et al. 2017).) Removing COTS from the reef requires a land-based disposal site for decomposing sea stars.

Crown-of-thorns sea star mitigation on Guam has three goals:

1. Control incipient COTS populations on Guam's reefs to prevent potential outbreaks.
2. If an outbreak occurs, respond rapidly and efficiently to remove COTS and prevent coral cover loss.
3. By reducing the severity and extent of a COTS outbreak, decrease the time needed for reefs to recover from the impact.

Note: Removal or culling of *Acanthaster* from any of Guam's marine preserves requires a permit from DAWR (Appendix IV). This permit is valid for one year and should be kept current to allow mitigation in marine preserves to begin immediately should an outbreak occur.

Ox bile salts

One of the main advantages of ox bile (bile salts) is that it requires only one injection of 10 ml solution per individual, unlike sodium bisulphate which must be applied via 10-25 injections in a sea star's arms and oral disk, requiring up to 60 mL of solution per organism at a concentration of 140 g per L. One 10 mL dose of ox bile at 4 g per L concentration resulted in mortality of 100% of sea stars 24 hours after injection (Rivera-Posada et al. 2013). There has been no evidence of detrimental effects of either sodium bisulphate or ox bile for other reef organisms, including fishes, stony corals, and other echinoderms (Rivera-Posada et al. 2013). Bostrom-Einarsson and Rivera-Posada (2016) found that one 25 mL injection of household vinegar resulted in 100% sea star mortality after 48 hours. Additionally, the authors found no harmful effects of vinegar on other reef organisms. Vinegar is less expensive than ox bile ($0.01 per sea star vs $0.03 AUS), but a greater quantity of solution (20-25 mL vs. 10 mL) is required for each injection. Vinegar was tested in Japan with low success for inducing COTS mortality, although it was highly successful when used on COTS from Papua New Guinea and the GBR. Certain genotypes may be more susceptible to vinegar; researchers on Guam should experiment with vinegar as a control method for local *Acanthaster*.

NPS in American Samoa uses in situ injections of ox bile salts, a slaughterhouse byproduct, for COTS control (NPS 2016). This method was developed by M. Pratchett and J. Rivera-Posada at JCU. In American Samoa, divers using scuba or rebreathers visit reefs where signs of high COTS density were found during surveys. Divers record the duration of the eradication dive (start and end time), number and size of sea stars injected, and average depth per dive. One of the divers tows a surface float with a GPS unit with the tracking feature turned on (NPS 2016). The dive can then be tracked by matching the start and end times with the time and coordinated recorded by the GPS. If COTS are relatively sparse, the diver could record the time of each injection and thus pinpoint the location of each COTS culled.

Injector guns specifically designed for COTS eradication can be ordered from the Australian Association of Marine Park Tourism Operators (AMPTO). These devices are generally preferred to the adapted cattle guns that were previously used to control COTS as they are specifically designed for use underwater and constructed of stainless steel to prevent rust. NJ Philips sells a complete kit for COTS control, which includes a 10 mL metal applicator gun for ox bile, 5 L backpack, transfer tube, spear with needle mount, and spare parts kit. See Appendix V for full specifications. (A different kit with a 20 mL metal applicator is available for sodium bisulphate.)

Kits for ox bile application (10 mL bile salts crown-of-thorns kit, EAM1542) can be ordered through AMPTO here: http://www.ampto.org/services.html

Ox bile salts (Oxoid™ bile salts no. 3) can be purchased from ThermoFisher Scientific. No permit is required to import this chemical into Guam if it is ordered from the United States.
Ox bile powder can be ordered in 250 g quantities here:
https://www.thermofisher.com/order/catalog/product/LP0056J

Additional supplies needed:

- 16 gauge veterinary needles
- Lab balance/scale
- Face masks, rubber gloves, eye protection
- Ziplock bags
- Deionized water
- For measuring COTS: Tongs, meter stick
- Hook with hollow handle for removing COTS from crevices

Guidelines for COTS control procedures and equipment maintenance (NPS 2016, GBRMPA 2017a):

- Ox bile concentration: 10 g per L of deionized (DI) water or freshwater
- Ox bile has a 5 day shelf life in solution
- Wear a face mask, rubber gloves, and eye protection as ox bile powder is very fine and can be an irritant if inhaled, swallowed, or to skin or eyes
- Pre-weigh ox bile powder in desired quantities and store in individual bags; add 1 g extra per bag (e.g. weigh out 11 g to make a solution of 1 L at 10 g ox bile concentration) as some will stick to the bag or inside the backpack
    - Always prepare solutions on land rather than in a moving boat
    - Add red food coloring to the solution so the diver can see that the gun is working when administering injections
- When filling the backpack, leave some space for air so it will float upright when underwater
- Number of injections and location:
    - Ox bile: One injection in middle or base of arm
        - COTS > 40 cm should receive two injections
        - For juveniles, one injection in central disk
    - Vinegar: One injection in base of arm
        - COTS > 40 cm should receive two injections at opposite sides of the body
    - Sodium bisulphate: 10-25 injections across central disk, 3-4 cm apart
        - COTS 25-30 cm need 12-15 injections
        - COTS > 30 cm require up to 25 injections
- Administer each injection in a slow and steady flow, making sure needle does not go all the way through the sea star
- If recording COTS size, measure diameter across the oral disk and from tip to tip of a pair of arms that appear to be of average length for that individual
    - Measure after injection as the sea star will start moving and come out hiding if concealed
- Rinse guns daily with fresh water and once per week, soak and thoroughly clean all components, apply WD-40 to moving parts

Video from the GBRMPA on COTS gun assembly, preparing solutions of ox bile and sodium bisulphate, and injection procedures for each solution: https://www.youtube.com/watch?v=hi3Nns01rLg

Video from the GBRMPA on identifying COTS and feeding scars, effectively administering injections, and recording data on control efforts: https://www.youtube.com/watch?v=ylKylXXgJuc

COTS population control is labor intensive. Divers must be thoroughly trained in finding and culling these cryptic reef organisms. Although ox bile injections seem to be the most effective and efficient control method to date, each individual

sea star must be treated and multiple eradication dives will be required at each dive site, ideally at < 1 week intervals until no new COTS or feeding scars are detected. Ongoing survey dives will be necessary during eradication in order to evaluate success. **It will be important for the Guam Coral Reef Response Team to carefully consider the cost effectiveness of eradication and methodically allocate resources and personnel time for culling efforts** (Figure 10). One option that may be less intensive is opportunistic killing; if divers conducting unrelated surveys are trained in ox bile usage and carry COTS guns while diving, they can inject COTS as they find them. However, this would limit the potential to collect accurate data on COTS populations and outbreaks.

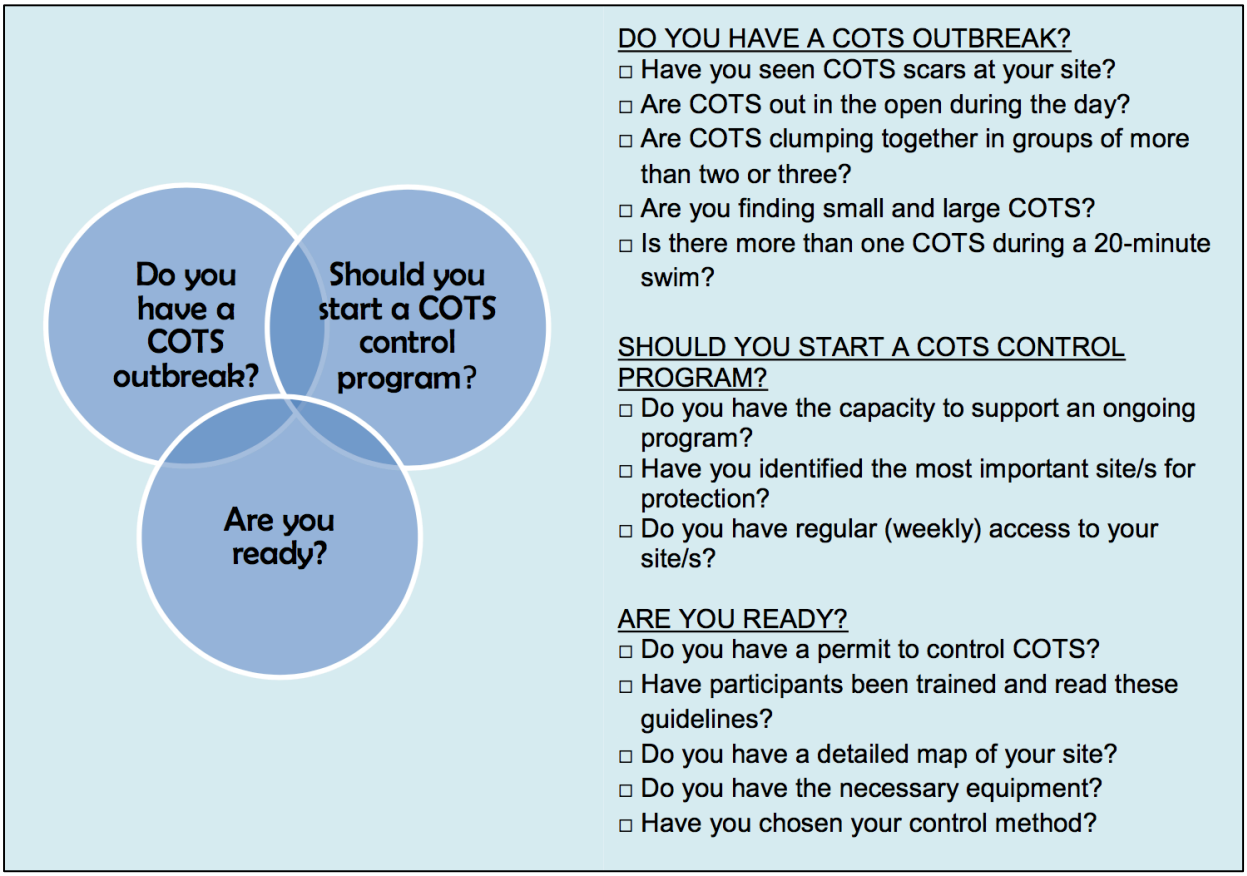


Figure 10. Preparing for COTS control (From GBRMPA 2017a, adapted from Aiello 2006)

Monitoring recovery

A healthy coral reef can recover from a severe COTS outbreak after 10 to 20 years (AIMS 2017b). However, Guam's reefs have faced increasing frequency of coral bleaching events in recent history, including bleaching in 2013, 2014, and 2016. Guam's reefs are also facing local stressors, such as poor water quality due to LBSP and heavy fishing pressure that has greatly reduced fish biomass. Due to the combined impacts of COTS, bleaching, and other threats, many of Guam's reefs now have greatly decreased coral cover, increased algal abundance, and diminished reef fish populations. The confluence of these impacts emphasizes the importance of tracking post-COTS outbreak recovery to improve understanding of the relative resilience of Guam's reef sites.

Given the limited resources available to local coral reef resources managers and scientists, the need for post-outbreak monitoring must be carefully assessed and any monitoring efforts must be cost effective and time efficient. The most realistic option for monitoring after a COTS outbreak may be relying on surveys conducted by the Guam Long-term Coral Reef Monitoring Program. Otherwise, **plans for monitoring will be determined on an ad hoc basis following an outbreak** and considering factors such as the extent and severity of the outbreak, the types of coral affected (e.g. listed species), the ecological and economic value of affected sites, and the availability of resources for monitoring efforts.

Integration with long-term monitoring

The Guam Long-term Coral Reef Monitoring Program (GLTCRMP) involves ongoing data collection on numerous coral reef health variables at several permanent sites along Guam's reefs. The GLTCRMP collects data on water quality, benthic habitats, and biological communities at prioritized coral reef areas around the island. This longitudinal data is vital for determining baseline conditions at a site-level before an impact occurs or to measure change after a management action, such as establishment of a marine preserve or the implementation of watershed improvement projects. The data collected through this program is some of the most statistically rigorous data available on Guam's coral reef ecosystems. Assessments conducted during COTS outbreak response should be designed to augment GLTCRMP surveys to avoid overlap and increase data coverage.

Data collection under the GLTCRMP began in June 2009 at seven sampling stations (2 permanent; 5 non-permanent) in the Tumon Bay MPA, using video transect surveys, coral quadrat surveys, and fish surveys with belt transects and stationary point counts. In 2010, surveys of coral size and condition; benthic cover; and fish and macroinvertebrate communities were conducted at a total of 20 sampling stations (10 permanent; 10 non-permanent) along the outer reef slopes of Tumon Bay and East Agana Bay. The following year, the same surveys were conducted at 23 sampling stations (11 permanent; 12 non-permanent) at Western Shoals in Apra Harbor. In 2012, field biologists with the GLTCRMP surveyed coral size and condition, benthic cover, and fish and macroinvertebrate communities at 20 sampling stations in Piti Bay. The same surveys, with the exception of fish, were also conducted at Tumon Bay (21 sampling stations) and East Agana Bay (10 sampling stations). Reef fish surveys were carried out at five of the stations in Tumon Bay. No GLTCRMP data was collected in 2013.

In 2014, surveys of coral size and condition, benthic cover, and macroinvertebrates were conducted at all ten permanent sampling stations in East Agana Bay, all ten permanent stations within Tumon Bay, and at all ten permanent and two non-permanent stations in Piti Bay. All surveys (except coral quadrat surveys at three permanent sampling stations) were also conducted at 11 newly-established permanent and two non-permanent sampling stations in Achang Bay. Surveys of benthic, fish and, macroinvertebrate communities were conducted at three newly-established sampling stations at Cocos-East. Between October 1, 2015 and March 31, 2016, GLTCRMP staff surveyed 35 long-term monitoring sampling stations (photoquadrats, coral and macroinvertebrate surveys, and rugosity assessments).

Data from GLTCRMP macroinvertebrate belt transect surveys since 2010: https://data.noaa.gov/dataset/dataset/guam-long-term-coral-reef-monitoring-program-macroinvertebrate-belt-transects-since-2010

Data from GLTCRMP coral colony size and condition surveys since 2010: https://data.noaa.gov/dataset/dataset/guam-long-term-coral-reef-monitoring-program-coral-colony-size-and-condition-surveys-since-2010

Report (2012): Comprehensive Long-term Monitoring at Permanent Sites on Guam: 2012 Status Report: https://data.nodc.noaa.gov/coris/library/NOAA/CRCP/other/grants/MonitoringGrants_FY10_Products/NA10NOS4260046_Guam_Monitoring.pdf

Report (2014): Comprehensive Long-term Monitoring at Permanent Sites on Guam: 2014 Status Report: https://data.nodc.noaa.gov/coris/library/NOAA/CRCP/other/grants/NA11NOS4820007/Guam_Reef_Monitoring_FinalRept.pdf

Data management and sharing

When compiling and inputting data from the field, observers should utilize the shared datasheets available on Google Drive. If a spreadsheet is downloaded for entry, it should be re-uploaded after all data is inputted or emailed to the designated data manager.

UOGML may be able to fund a student to create and manage a database that would include data collected during COTS outbreak assessments. Otherwise, the Response Team should examine similar databases of coral reef impact data and find an easily adaptable model. **In the future, the Team should aim to have all data accessible online to registered users.**

The use of citizen scientist-collected data is becoming more commonly accepted and integrated into ecological studies. The value of this data should not be underestimated, given the sheer amount of data that volunteers can collect. With proper training, citizen scientists can collect accurate, reliable data. Survey methods used by citizen scientists should be designed to approach those methods used by experts, allowing usage of citizen science data in academic studies. This is an important opportunity to both increase the amount of available data during a COTS outbreak and enhance community engagement in science and conservation.

Communication and outreach strategy

The communication and outreach strategy is designed to increase awareness of the impacts of COTS outbreaks on Guam's reefs among policy makers, community members, and other stakeholders. An effective communication strategy that incorporates social marketing can alter attitudes and perceptions of the target audiences, ultimately resulting in behavior changes, such as joining the EOR program or reducing personal impacts by avoiding recreation in marine preserves during COTS outbreaks. **The interagency MOU signed in March 2016 states that BSP, GDOAG, GEPA, and UOG will assist with public outreach efforts related to acute reef impacts, including *Acanthaster* outbreaks.** Specific activities associated with this strategy include:

- Developing messaging before outbreaks and disseminating statements during and after outbreaks;
- Hosting community meetings and presenting briefings to agency administrators, legislators, the Governor's office, and other decision makers; and,
- Instigating behavior change to reduce local stressors during COTS outbreaks to increase reef resilience and decrease the cumulative impacts on Guam's coral reef ecosystems.

Press releases and media statements

The provision of concise, informative, and straightforward statements to the media is a key component of COTS outbreak-related outreach. **The public outreach and media campaign will be triggered if an outbreak is detected (≥ 30 COTS per hectare) at one or more reef sites.**

Effective press releases must: be no longer than one page; concisely lay out the information intended for dissemination; include suggested actions for decision makers or specific stakeholder groups; and provide a contact person for enquiries. Press releases must be approved through appropriate channels. The contact person listed in the release should be prepared to participate in interviews for local television, radio, and print media outlets. **The Response Team Coordinator will translate published studies and UOG student research relevant to COTS outbreaks into executive summaries for decision makers and/or press releases for the public.** Another venue for communicating information about COTS outbreaks and response is the quarterly GCMP newsletter, Man, Land, & Sea.

If funding became available, a movie theatre advertisement could be an effective venue for raising awareness of COTS outbreaks and the magnified impacts of threats on stressed coral reefs. An optimal advertisement will focus on actions that individuals can take to reduce their own impacts (e.g. swap sunblock for a rash guard; do not take herbivores).

Communities and decision makers

Community meetings may be required if a severe COTS outbreak occurs. The scheduling of community meetings is generally appropriate when the Response Team is asking for assistance or if there is a COTS removal or mitigation program that involves public participation. Community meetings should be held in the village closest to a reef site that is experiencing a COTS outbreak and hosted at community or recreation centers as arranged through the village's Mayor's Office. The meetings should be scheduled for the early evening, to accommodate working residents, and last

approximately 1-2 hours, although timing may vary depending on attendance and engagement. A brief presentation, provided by a member of the Response Team, should include: 1) an introduction to coral reefs, COTS outbreaks, and other reef threats; 2) a summary of the current outbreak event; 3) a description of how this event may affect the community; 4) actions that can reduce local stressors on Guam's reefs and thus foster reef resilience; and 5) how the community can be involved in response and mitigation. The end of the meeting should consist of a question and answer session.

Briefings to senior management and policy makers should be provided during a severe, widespread COTS outbreak or when the outbreak has the potential to impact ecologically significant or economically important reef sites. Briefings are tailored to the interests and knowledge level of managers and policy makers. Unlike community meetings, they should be held during business hours and kept to a maximum length of one hour.

Key decision makers should be briefed if an outbreak is detected (≥ 30 COTS per hectare) at one or more reef sites. If outbreaks are detected at two or more sites or sites or particular value are at risk, a wider group of decision makers should be briefed, with a topical focus on the importance of decreasing local impacts to bolster reef resilience and increase the ability of the reefs to recover from the outbreak. Decision makers should also be fully briefed following COTS outbreaks, when the extent of the impacts is evident. Post-outbreak briefings should include concrete recommendations for management and policy changes.

Additional outreach activities may include:

- Distribution of posters, factsheets, and other printed materials at community events
- Announcements about COTS outbreak impacts published in the Guam Daily Post, Pacific Daily News, and other local media outlets
- Distribution of printed materials, videos, and other COTS outbreak-related media to the military's morale, welfare, and recreation programs
- Dissemination of materials that encourage voluntary participation in temporary no-take zones, encourage reduced recreational use of stressed reefs, and request limits to off-roading near reefs that are facing stress from COTS predation

Communication strategy evaluation

Surveys may be useful to measure the effects of COTS outbreak-related communication and outreach activities, such as EOR or community meetings. Outreach efforts should use social marketing to instigate behavior changes. This includes increasing awareness of local impacts on coral reefs with the aim of eliminating behaviors that contribute to coral reef stress during COTS outbreaks (e.g. offroading, which contributes to erosion and sedimentation, and thus increases coral stress). The impacts of such campaigns could be quantified through assessments of attitudes, knowledge, and behaviors. Surveys of community members following a COTS outbreak could also be conducted to measure the range and impact of completed media outreach and communications related to COTS impacts.

Recommendations

Recommendations to increase the effectiveness of Guam's response to COTS outbreaks, improve natural resource management efforts, and build the resilience of Guam's coral reef ecosystems include:

Monitoring and data sharing

- Consistently monitor reef sites of high ecological significance and economic value (e.g. key tourism sites) for signs of COTS outbreaks.
- Maintain detailed, descriptive records of all response activities and data collected on COTS outbreaks and potential outbreak drivers. Make these records easily accessible to members of the Coral Reef Response Team and other stakeholders.
- Share data and resources with researchers and reef managers in the Commonwealth of the Northern Mariana Islands (CNMI).

Areas for future research

- Investigate the potential drivers of COTS outbreaks on Guam.
- Execute laboratory experiments to test the effectiveness of ox bile alternatives, such as household vinegar, on Guam's COTS.
- Conduct research that increases understanding of the susceptibility of Guam's corals to the synchronous occurrence of COTS outbreaks and other stressors, such as coral bleaching and coral diseases.
- Quantify spatial and temporal trends in *Acanthaster* density and analyze population structure to increase understanding of outbreak patterns. Examine outbreak occurrence to detect potential cycles and trends.
- Synthesize existing data and collect data as needed in order to quantify the extent of *Acropora* spp. and *Montipora* spp. around Guam and map sites with the greatest proportions of these genera, which are vulnerable to both COTS and bleaching. Use these data to generate a spatial model of these corals on Guam's reefs. This effort will also contribute to the management of *A. globiceps*, an Endangered Species Act (ESA) listed coral species.

Natural resource management

- Purchase and store pre-positioned supplies, including ox bile salts and applicator kits, which will be immediately available if an outbreak occurs.
- Consider the cost-benefit of investing in novel mitigation and removal technologies, such as the "COTSbot" and pheromone lures.
- Hold regular training sessions, including table top exercises and field-based activities, for members of the Guam Coral Reef Response Team and other stakeholders to ensure that response personnel are familiar with assessment and mitigation procedures.
- Implement interagency projects that reduce local stressors to Guam's reefs, such as LBSP, recreational misuse, and heavy fishing pressure, which will improve the health of local coral reef ecosystems and support reef resilience.
- Conduct "lessons learned" meetings with all personnel involved in response activities following each response. Continuously update the COTS outbreak response plan to reflect new scientific findings and improve the efficiency of the early warning system, SOPs, and assessment and mitigation protocols. The COTS outbreak plan should be updated every two years with consensus from all active members of the Guam Coral Reef Response Team.
- Establish an interagency GovGuam scientific diver program and dive board to ensure dive reciprocity among agencies and increase efficiency of response activities.
- Develop adaptive management plans and a long-term strategy to conserve coral cover and biodiversity on Guam's coral reefs.

- Increase public awareness of the value of Guam's coral reef ecosystems and coral reef impacts, while fostering sustained participation in outreach programs, including EOR.
- Investigate COTS mitigation/removal as an alternative livelihood option for local residents who currently engage in scuba spear fishing.

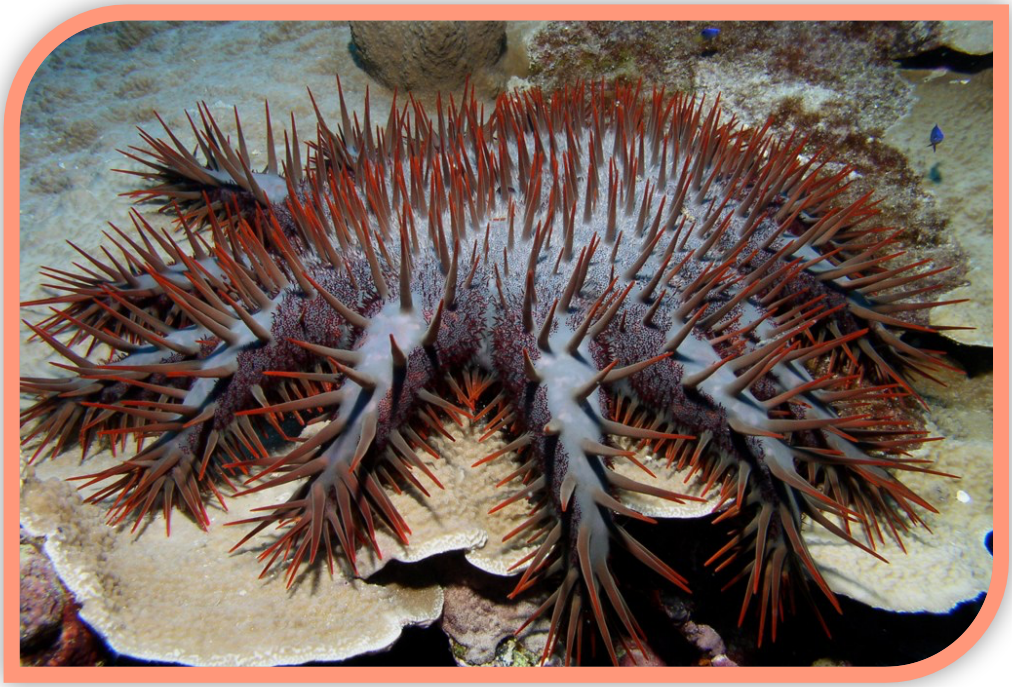
Reef recovery and restoration

- Continue development of Guam's coral nursery. If a severe COTS outbreak threatens ecologically important or listed species, it may be necessary to transplant some of these corals to the nursery for rearing and propagation. When appropriate, transplant colonies from the nursery to reefs that have been denuded by COTS.
- Develop methods and build capacity to scale up restoration efforts on Guam. This may include adding additional nursery sites and devising techniques to increase production of corals for outplanting such as sexual propagation and micro-fragmenting.
- Train community members in restoration techniques.

Funding for COTS outbreak response

In the past, funding for response activities on Guam has been largely opportunistic, as most grant-makers are unwilling to support activities that are contingent upon the uncertain occurrence of an event. Planning for COTS outbreak response in advance is challenging, given that the drivers of outbreaks are still poorly understood and agency resources, personnel, and leadership are often in flux.

The largest expenditure for COTS outbreak response on Guam is vessel time. Personnel availability is also a limiting resource. It may be possible to include funding for COTS outbreak response in grant proposals if the activities are framed as training or capacity building. The funds will be used to support response activities if a COTS outbreak occurs during a given grant cycle, but if an outbreak does not occur, the money will be spent on training opportunities for the Guam Coral Reef Response Team and other stakeholders in order to build capacity to respond to future events.



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Appendices

APPENDIX I: Interagency MOU for the Guam Coral Reef Response Team (2016)

GUAM CORAL REEF RESPONSE TEAM

MEMORANDUM OF UNDERSTANDING
AMONG THE BUREAU OF STATISTICS AND PLANS, THE DEPARTMENT OF AGRICULTURE, THE GUAM ENVIRONMENTAL PROTECTION AGENCY, AND THE UNIVERSITY OF GUAM

FOR ACTIVITIES OF THE GUAM CORAL REEF RESPONSE TEAM WITHIN THE CORAL REEF INITIATIVE

The Bureau of Statistics and Plans (BSP), the Department of Agriculture (DOAG), the Guam Environmental Protection Agency (GEPA), and the University of Guam (UOG) enter into this Memorandum of Understanding (MOU) for the purpose of formalizing the activities to be carried out by the Guam Coral Reef Response Team. This MOU is based on the following statements of purpose and delineation of responsibilities. The term of this MOU will become effective once signed and remain in effect indefinitely from the date of signature.

The Coral Reef Response Team will be responsible for responding to acute coral reef impacts such as bleaching events, coral disease outbreaks, invasive species, vessel groundings, oil spills, and outbreaks of nuisance species such as *Acanthaster planci*, the crown of thorns starfish, on Guam, as part of the Guam Coral Reef Initiative (CRI). Members of the Coral Reef Response Team will include representatives from BSP, DOAG, GEPA, and UOG. When needed, the Coral Reef Response Team will consult and cooperate with US federal partner agencies, such as the National Oceanic and Atmospheric Administration (NOAA), Department of Defense (DoD), US Coast Guard, US Fish & Wildlife Service (USFWS), and the National Park Service (NPS).

RESPONSIBILITIES

The Bureau of Statistics and Plans (BSP) agrees to:

1. Coordinate the meetings and activities of the Coral Reef Response Team from 2016 to 2017.
2. Host at least one training, workshop, or exercise per year in 2016 and 2017 for members of the Coral Reef Response Team.
3. Provide Standard Operating Procedures to guide the activities of the Coral Reef Response Team.
4. Finalize the Guam Reef Resilience Strategy, which will include the reef impact Standard Operating Procedures and management recommendations.
5. Provide at least one representative to the Coral Reef Response Team from the Guam Coastal Management Program (GCMP). The representative will attend all meetings, provide guidance and technical assistance, and serve in a leadership capacity if needed.
6. Assist with public outreach, collection of data on coral reef ecosystem health, and documentation of response activities.

The Department of Agriculture (DOAG) agrees to:

1. Provide at least one representative to the Coral Reef Response Team. The representative will participate in response activities; attend all meetings, trainings, and workshops; provide guidance and technical assistance; and serve in a leadership capacity if needed.
2. Contribute input on Standard Operating Procedures (SOPs) for responding to acute impacts.
3. Contribute feedback on draft Guam Reef Resilience Strategy during 2016 to 2017.
4. Assist with public outreach, collection of data on coral reef ecosystem health, and documentation of response activities, including, when possible, provision of access to collect data before and after bleaching events during aerial surveys conducted by DOAG Division of Aquatic and Wildlife Resources (DAWR).

The Guam Environmental Protection Agency (EPA) agrees to:

1. Provide at least one representative to the Coral Reef Response Team. The representative will participate in response activities; attend all meetings, trainings, and workshops; provide guidance and technical assistance; and serve in a leadership capacity if needed.
2. Contribute input on Standard Operating Procedures (SOPs) for responding to acute impacts.
3. Contribute feedback on draft Guam Reef Resilience Strategy during 2016 to 2017.
4. Assist with public outreach, collection of data on coral reef ecosystem health, and documentation of response activities.

The University of Guam (UOG) agrees to:

1. Provide at least one representative to the Coral Reef Response Team from the UOG Marine Laboratory. The representative will participate in response activities; attend all meetings, trainings, and workshops; provide guidance and technical assistance; and serve in a leadership capacity if needed.
2. Contribute input on Standard Operating Procedures (SOPs) for responding to acute impacts.
3. Contribute feedback on draft Guam Reef Resilience Strategy during 2016 to 2017.
4. Assist with public outreach, collection of data on coral reef ecosystem health, and documentation of response activities.

ALTERATION OF TERMS OR ENTIRE AGREEMENT

The body of this MOU expresses the understanding of the signatories concerning all matters covered and shall constitute a total agreement. No alteration of this MOU, whether by written or verbal understanding of the signatories or the members of the Coral Reef Response Team, shall be valid unless made in the form of a written amendment to this MOU, which is formally approved and executed by the participating agencies.

AMENDMENTS

In the event that one or more participating agencies wish to amend the terms of this MOU, all participating agencies will comply with the terms of this MOU until such time as the amendment is agreed upon and approved in writing by all signatories.

CONCURRED:

William ~~M.~~ Castro, Director, Bureau of Statistics and Plans — Date: MAR 0 3 2016

Mathew L.G. Sablan, Director, Department of Agriculture — Date: 3/4/16

Eric Palacios, Administrator, Guam Environmental Protection Agency — Date: 03/04/16

for Dr. Terry J. Donaldson, Director, UOG Marine Laboratory — Date: 3/4/2016

Dr. Robert A. Underwood, President, University of Guam — Date: 3/8/2016

APPENDIX II: AIMS manta tow survey datasheet

MANTA TOW SURVEY

AUSTRALIAN INSTITUTE OF MARINE SCIENCE
Long-term Monitoring Program

Reef name:..... Sample ID:..... Collector:.....

Time:..... Date:..... Wind:..... Cloud:..... Sea:..... Tide:.....

Tow No.	Coral Cover			Vis.	COT				Remarks
	Live	Dead	Soft		No.	Size	Scars		
1									
2									
3									
4									
5									
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APPENDIX III: AIMS belt transect survey datasheet

FIXED SCUBA SEARCH SURVEY

Long-term Monitoring Program
Australian Institute of Marine Science

Reef: **Site:** **Date:** **Time:** **Observer:**

Transect 1		Transect 2		Transect 3		Transect 4		Transect 5	
Scar	Genus/form	Scar	Genus/form	Scar	Genus/form	Scar	Genus/form	Scar	Genus/form
								COTS J	
COTS J		COTS J		COTS J		COTS J		COTS A	
COTS A		COTS A		COTS A		COTS A		COTS B	
COTS B		COTS B		COTS B		COTS B		COTS C	
COTS C		COTS C		COTS C		COTS C		Bleaching	
Bleaching		Bleaching		Bleaching		Bleaching			

Bleaching recorded as a percentage of the total hard coral cover: 0=absent, 0+ = individual colonies, -1= 1-5%, +1= 6-10%, 2=11-30%, 3=31-50%, 4 =51-75%, 5=76-100%

COTS: **J** < 5cm, **A** = 6-15cm, **B** = 15-25cm, **C** > 25cm — COTS Scar: **COTS** — Drupella: **Drup(#)** — Bleaching: see above — Unknown: **UN**

White Syndrome: **WS** — Skeletal Eroding Band: **SEB** — Brown Band: **BrB** — Black Band: **BBD** — Atrementous necrosis: **AN**

Porites Pinking: **PP** — Hyperplasia: **HYP** — Neoplasia: **NEO** — Coralline Orange: **CLOD** — Coralline Pink: **CLAP**

APPENDIX IV: DAWR permit for marine preserve special request

DEPARTMENT OF AGRICULTURE
DIVISION OF AQUATIC AND WILDLIFE RESOURCES (DAWR)
MPA APPLICATION SPECIAL REQUEST

(Section 63123 of Title 5, Guam Code Annotated GCA)
(Use additional sheets if needed)

1. Applicant: _____
2. Representative: _____
3. Address: _____
4. Telephone: Residence_____Work_____
5. Project name (Attach project proposal): _____

_____

6. Project purpose: _____

_____

7. Location of project:_____
8. What will be collected (List common and species name)?_____

_____

9. Quantity:_____
10. Are there areas outside the preserve where organism can be collected (List areas)?

_____

_____

11. Why can't organisms be collected in those areas outside the preserve?_____

_____

_____

_____

1 of 2

12. Describe methodology (Include equipment, etc.):_____

_____

_____

_____

13. Describe general area and marine organisms at or near project site?_____

_____

_____

14. Dates on which the project will begin and end:_____

15. Describe any impacts, if any:_____

_____

_____

16. Mitigation:_____

_____

_____

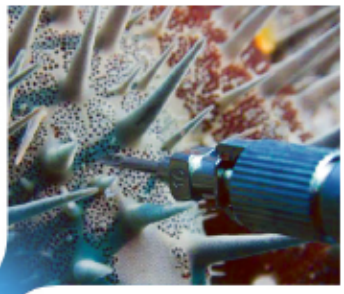
Representative's
Signature:_____ Date:_____

Applicant
Signature:_____ Date:_____

2 of 2

APPENDIX V: Specifications for ox bile applicator kit

CROWN-OF-THORNS
10ml Bile Salts Applicator



Order Code: EAM1542

10ml Bile Salts Applicator
- Purpose designed for use with Bile Salts application.
- Robust metal construction.

5 Litre Backpack
- Robust, ergonomic design.
- Large size handle for ease of portability.
- Large handle area allow lanyard to be secured for use under water.
- Supplied with storage cap.
- Supplied with robust metal spigot allowing easy connection of transfer tube between Backpack and Applicator.
- Suitable for both Bile Salts and Sodium Bisulphate Applicators.

Transfer Tube
- Specially designed to ensure good flow of product in under water conditions.

Spare Parts Kits
- Supplied kit has additional valves, springs and needle nut.

Bile Salts
- Available from New Zealand Pharmaceuticals with AQIS Permit.

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AMPTO
Association of Marine Park Tourism Operators

BILE SALTS AVAILABLE THROUGH NZP WITH AQIS PERMIT
Contact Rhys McKinlay **Email** market@nzp.co.nz **Skype** nzpharm07
Phone +64 6 952 3829 **Fax** +64 6 952 3802 **Web** nzp.co.nz

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