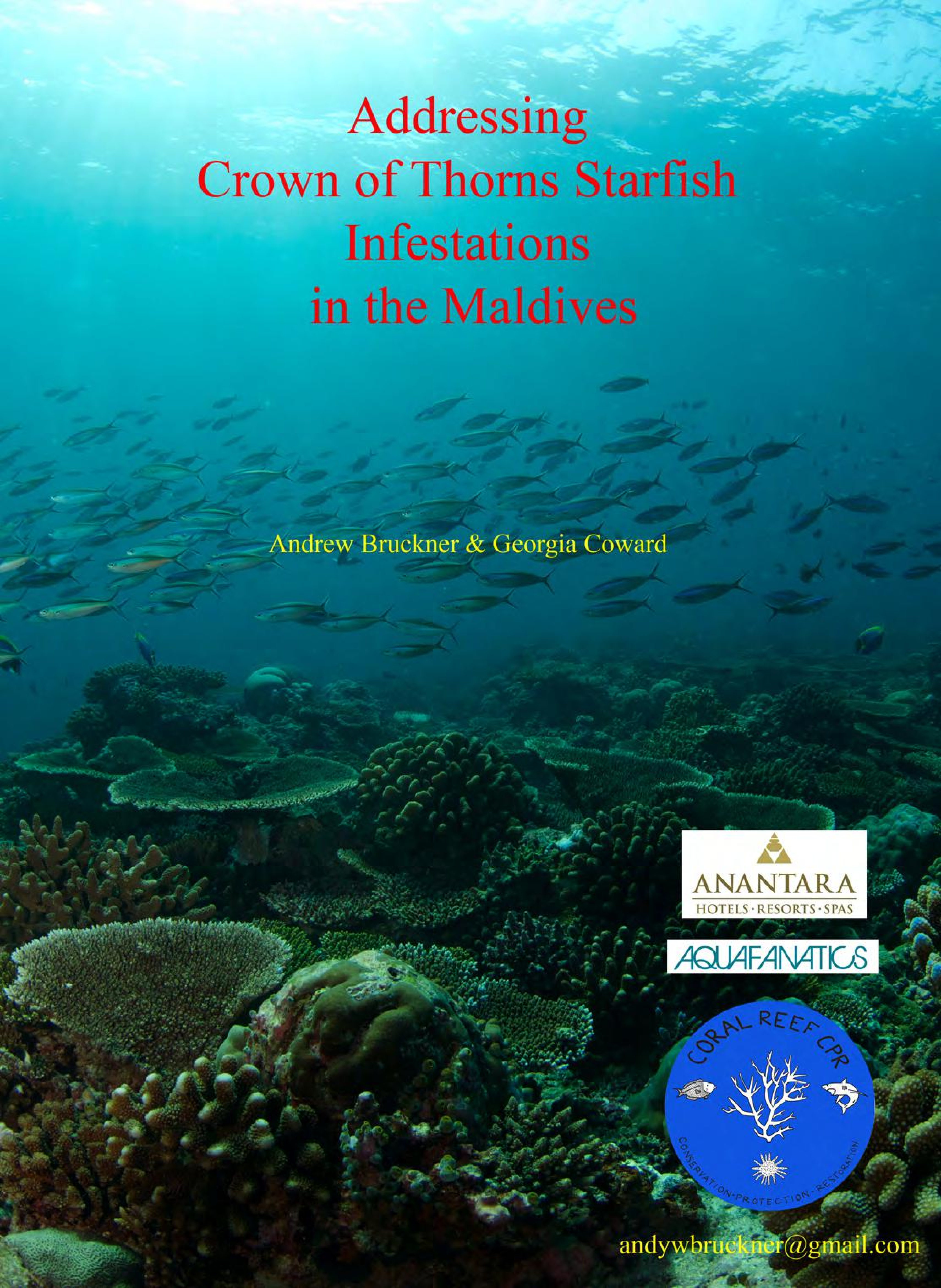

Addressing Crown of Thorns Starfish Infestations in the Maldives

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ANANTARA
HOTELS · RESORTS · SPAS

AQUAFANATICS

CORAL REEF CPR
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Front cover: Reef scene at Veli Reef, South Malé, Maldives. Photo by Joao Monteiro.

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All photographs used within this guide are credited to Stefan Andrews, Anderson Mayfield, Georgia Coward and João Monteiro.

Fig. 1. Shallow reef near Anantara Resorts, South Malé

Preface

This guide is intended to assist dive operators, marine biologists, government agencies and non-government organizations in the Maldives in identifying possible options to address crown of thorns (COTS) infestations. A summary of the biology and ecology of COTS is presented to provide general knowledge on the behavior of these animals and factors that may be responsible for population explosions. We hope this will help increase public awareness about these corallivores, their impacts and steps that can be taken to minimize coral losses. This may also be useful in identifying causes and linkages of population explosions in the Maldives, thereby facilitating the development of methodology to reduce factors responsible for unnatural changes in starfish abundances.

We have compiled all accessible information on previous and current outbreaks of COTS, as well as efforts undertaken to reduce impacts from these voracious corallivores. We realize this is an incomplete summary and will update the document once more information is available. A section on different approaches to cull starfish populations is included, with a summary of the different chemicals currently used to kill starfish, and the advantages and drawbacks of each of these. In addition, sources for COTS equipment collection/injection supplies and chemicals are provided. A brief discussion of COTS first aid is also provided. We have also compiled a list of all the currently available literature on COTS. This list is likely to continue to grow as scientists obtain new information on these starfish and as studies using these techniques develop.

It is important to recognize that any effort to reduce impacts from COTS requires a sustained, long-term commitment. COTS can, and have devastated entire reef tracts. These reefs can recover, but the time for recovery depends on the severity of an outbreak, how much and what types of corals they ate, the condition of the reef system, and the availability of healthy coral populations that are upstream and can provide the coral larvae necessary to rehabilitate the reef. The COTS will also disappear naturally from a site, but this may take years and the damage can be quite severe, with compounding impacts to associated reef fish. There are times, however, when a removal or culling effort is not feasible, practical or necessary and careful assessment and monitoring is needed to determine the costs and benefits of a potential intervention.

The first step in an effective program to address COTS is information sharing. It is imperative that local divers, marine biologists, dive centers, fishermen and other stakeholders report any unusual occurrences, including the sudden appearance of large white areas of denuded coral and high numbers of COTS (as well as other disturbances). Further information on the spatial extent, time of appearance, duration, and unusual environmental conditions just before or during the present observations will help determine whether additional efforts are necessary to combat the crisis. Considerable planning should be undertaken before implementing a clean-up activity. Following the removal and/or killing of COTS on an affected reef, further monitoring is necessary to identify animals that were missed and whether secondary outbreaks occur.

Data sharing and publicity are a key step in a successful COTS eradication program as this can help mobilize additional resources and individuals, and also further raise awareness about the issue.

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Summary

Crown of thorns starfish, *Acanthaster planci* (COTS) have undergone a dramatic population explosion in the Maldives since 2013, beginning on North Malé Atoll near Reethi Rah and spreading to distant atolls. The starfish have already caused widespread devastation to a number of affected house reefs, and their range continues to expand. Their impacts are likely to be more extensive, severe and longer lasting than any previous COTS outbreaks in the Maldives as the current infestation is being compounded by impacts from temperature-related stressors associated with a two-year El Niño event. The current event is the third COTS outbreak in recent times, with previous documented infestations in the 1970s in North Malé (Vahibinfaru and Ari Fesdu), and between 1988-1991 on North Malé Atoll, Ari Atoll and South Malé Atoll.

Resorts, dive centers and marine biologists have taken rapid action to control the spread of the starfish through direct removals and injections of a variety of poisons. While some of these efforts have been effective, the starfish continue to expand their range, and they have reappeared in treated areas. Further, there is insufficient capacity and man power to effectively control the starfish at the current scale of infestation, and the fear of injuries has hampered other efforts.

Due to the value of coral reefs to the Maldives and its residents, and the precarious state of these reefs as a result of other severe and ongoing threats, large scale efforts to eradicate COTS are critical. These should be combined with additional scientific studies on the biology, ecology, and impacts of the starfish. Control efforts for COTS are feasible in the Maldives because of the structure and distribution of coral reefs. Their success will increase if these control efforts are undertaken as soon as possible after the starfish invade a new reef system. Once an eradication effort has been conducted, the impacted reef must be monitored regularly to ensure that the starfish do not re-invade the reef again.

This document presents a summary of the biology and ecology of COTS, including their life history, short and long term impacts, and patterns of recovery. Specific information on the Maldives and current and past COTS occurrences are summarized. Detailed information on options for starfish control, including removal efforts and effectiveness of different injection methods and chemicals are provided. A short summary of human health risks attributed to COTS injuries and options for treatment are also presented.

Background

The Maldives

The Republic of Maldives is an island nation in the Indian Ocean located approximately 600 kilometers southwest of India and 750 kilometers southwest of Sri Lanka, and directly north of the Chagos Archipelago. The Maldives consists of twenty-six atolls that form a double chain in the central portion and a single chain in the north and south. The islands are oriented north to south, encompassing a distance of 864 kilometers long (7° 06'N to 00°45'S), and 130 kilometers wide (72° 33' E to 73° 47' E), and located atop a vast submarine mountain range (the Chagos-Maldives-Laccadive Ridge). The atolls are made up of 1,192 islands and numerous sand cays and faros spread over an area of roughly 90,000 square kilometers, making the country one of the world's most geographically dispersed countries. The Maldives is the lowest country in the world, with maximum height of only 2.4 meters and an average height of 1.5 meters above sea level. In addition, over 80% of land is less than one meter above mean sea level, heightening vulnerability to floods and storms (Woodroffe 2008).

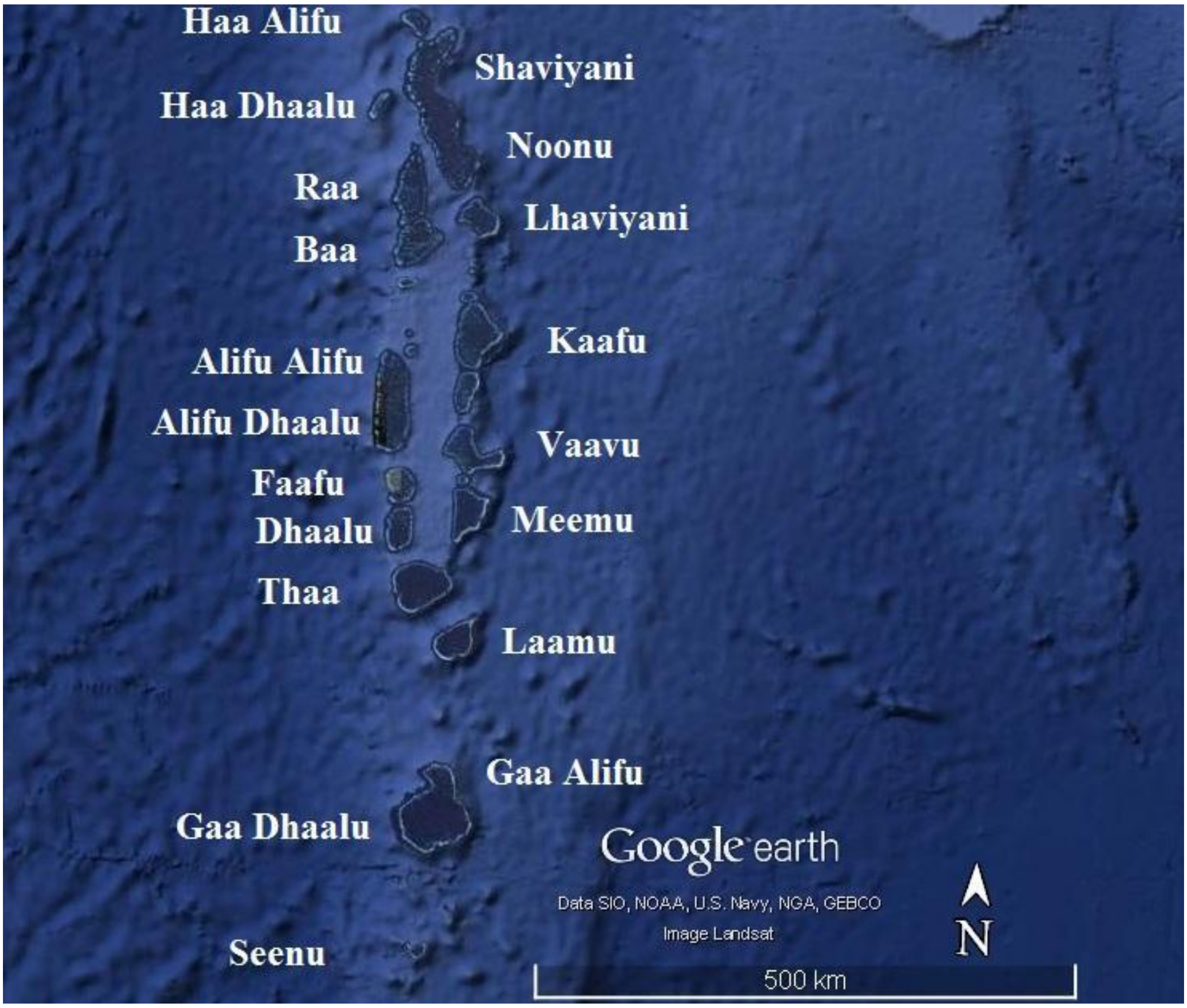


Fig. 2. The atolls of the Maldives

Importance of coral reefs to the Maldives

The 320,000+ inhabitants of the Maldives are highly dependent on their coral reefs for numerous economic goods and services. Among these, reefs provide Maldivians with their main source of protein, employment from fishing and revenue from tourism. Reef-based tourism is the predominant source of economy and employment, contributing 30% to national GDP (Moser 2013). In 2013, 1,125,000 tourists visited the Maldives and Malé continued to attract the majority with 41.3% total resort bed capacity (Ministry of Tourism, Arts and Culture 2012; World Bank 2016). Export fisheries for food, including pelagic tuna (reliant on bait fish harvested on the reefs) and reef-based fisheries, provide another 5-15% of the GDP (Moser 2013). Reef organisms are also harvested for luxury food items including sharks (banned in 2009), sea cucumbers and giant clams (also banned due to overexploitation), along with ornamental species for aquaria and grouper for the live reef food fish trade. Harvest of reef organisms (fish, lobsters) to support the tourist sectors has also increased dramatically over the last two decades (Naseer FAO Profile). Healthy coral reefs also provide the building blocks of these islands, buffering them from monsoon waves and tsunami, building islands and maintaining land areas above sea level. Further, approximately 209 scleractinian coral species provide critical habitat used as nursery areas, resting grounds and feeding areas for more than 2,000 species of reef fishes (Solandt and Hammer 2012). This rich diversity includes internationally threatened populations of whale sharks (Rowat 2007) and manta rays (Kitchen-Wheeler 2010). The country supports the seventh largest reef system in the world, with 2,041 distinct reefs and over 8,900 square kilometers of reef habitat spread over the 9° latitude.

Threats to coral reefs

Coral reefs are undergoing a worldwide crisis due to a host of natural and human-induced stressors, and they are being lost at an alarming rate. Unsustainable and destructive fishing practices, pollution and runoff, and coastal development other human stressors are compounding impacts from natural disturbances and climate change. In the Maldives, some of the most egregious anthropogenic impacts include:

1) Pollution from human waste, petrochemicals and rubbish;
2) Increased sedimentation;
3) Extraction of sand, rubble and coral rock;
4) Overexploitation;
6) Habitat alteration from coastal development, dredging and channelization; and
7) Habitat destruction from anchors (MRC 2009).

Widespread losses of coral have been associated with coral disease outbreaks, mass bleaching events, and recent population explosions of the crown of thorns starfish (COTS, *Acanthaster planci*). Outbreaks of COTS are now recognized as one of the most significant threat to coral reefs throughout the Indo-Pacific region, including the Maldives. If outbreaks of these starfish are not controlled quickly, they will continue to spread and kill coral. Severe outbreaks of COTS are capable of destroying an entire reef system in a matter of weeks, and their impacts can worsen the effects of other disturbances, especially temperature perturbations associated with El Niño and climate change. Typically, reefs damaged by COTS require a decade or more to recover, but in extreme cases they may fail to rebound.

Species protection and reef conservation

A number of marine species are now fully protected in the Maldives, including dolphins, whales, whale shark, turtles, triton shells, Napoleon wrasse, black coral and giant clams. Coral mining is now highly regulated and licensed, and prohibited on island House Reefs, atoll rim reefs and bait fish reefs. While lobster harvest is legal, berried females and undersized (<25 cm) lobsters are protected. Fisheries Law of the Maldives also prohibits the use of dynamite, guns, and chemicals to collect fish and SCUBA gear for sea cucumbers and lobsters. The Maldives has 35 marine protected areas, designated between 1995 and 2011 (Jiminez et al. 2012), along with *de facto* reserves (house reefs) that protect approximately 4.3% of the total reef habitat.

Recent changes to Maldivian coral reefs

Coral reefs in the Maldives were considered to be in excellent condition prior to 1998, with a total live coral cover on seven different atolls ranging from 28% to 58%. Reefs were badly degraded due to bleaching associated with the 1998 El Niño event as a result of abnormally high sea water temperatures. By the end of the El Niño event, live cover of stony corals had fallen between 0% and 5%, with mortality rates of 80-95%. As observed in other countries, mortality varied among taxa, with branching corals (especially acroporids) suffering the most extensive losses and certain massive corals such as *Porites* and faviid corals surviving better. Recovery of reefs was initially slow, with approximately 10% live coral cover documented on surveyed reefs by 2002 (Rajasuriya et al. 2004). Assessments of eight atolls in December 2004, following the tsunami, also revealed low coral cover ranging from 4-12% (Commonwealth of Australia 2005).

A National Coral Reef Monitoring Program, using Reef Check methodology, has provided coral reef data for one northern, one southern and three central atolls. Surveys undertaken on these sites in 2009 identified hard coral cover ranging from 7.5% to 59.4%, with four sites having over 50% live cover (MRC 2009). In many of these locations, prominent recovery of reefs has been observed since the 2004 surveys, while recovery was delayed in other locations. Factors preventing recovery include increasing anthropogenic influences, coral disease outbreaks, predation by coral eating snails (*Drupella*), and echinoderms (*Culcita*), phase shifts to algae and corallimorphs, and other stressors.

Fig. 3. Coral eating snails, *Drupella cornus* (left), *Culcita* starfish (middle) and coral disease (white syndrome).

In 2013, a population explosion of COTs was documented on North Malé Atoll (near Reethi Rah), reversing the trend of recovery. Alarmingly, COTS progressively spread to surrounding atolls during 2015, and their populations continue to expand. Over the last year they have caused widespread losses of corals in at least four other atolls, and new outbreaks are recorded on almost a monthly basis. Outbreaks of COTS in the Maldives were first observed in the 1970s in North Malé (Vahibinfaru and Ari Fesdu), but they quickly subsided. A second outbreak was reported in 1988 in the vicinity of Reethi Rah and by 1991 they had spread to Ari Atoll and South Malé Atoll. Hundreds of reefs were devastated by these outbreaks. It is quite interesting and alarming to note a similar pattern of spread during the present outbreak, nearly 25 years later.

New threats from coral bleaching occurred in 2015, and again in 2016, due to what is predicted to be the most severe El Niño on record (NOAA 2015). Of most concern, concurrent COTS outbreaks could seriously exacerbate losses associated with a mass bleaching event.

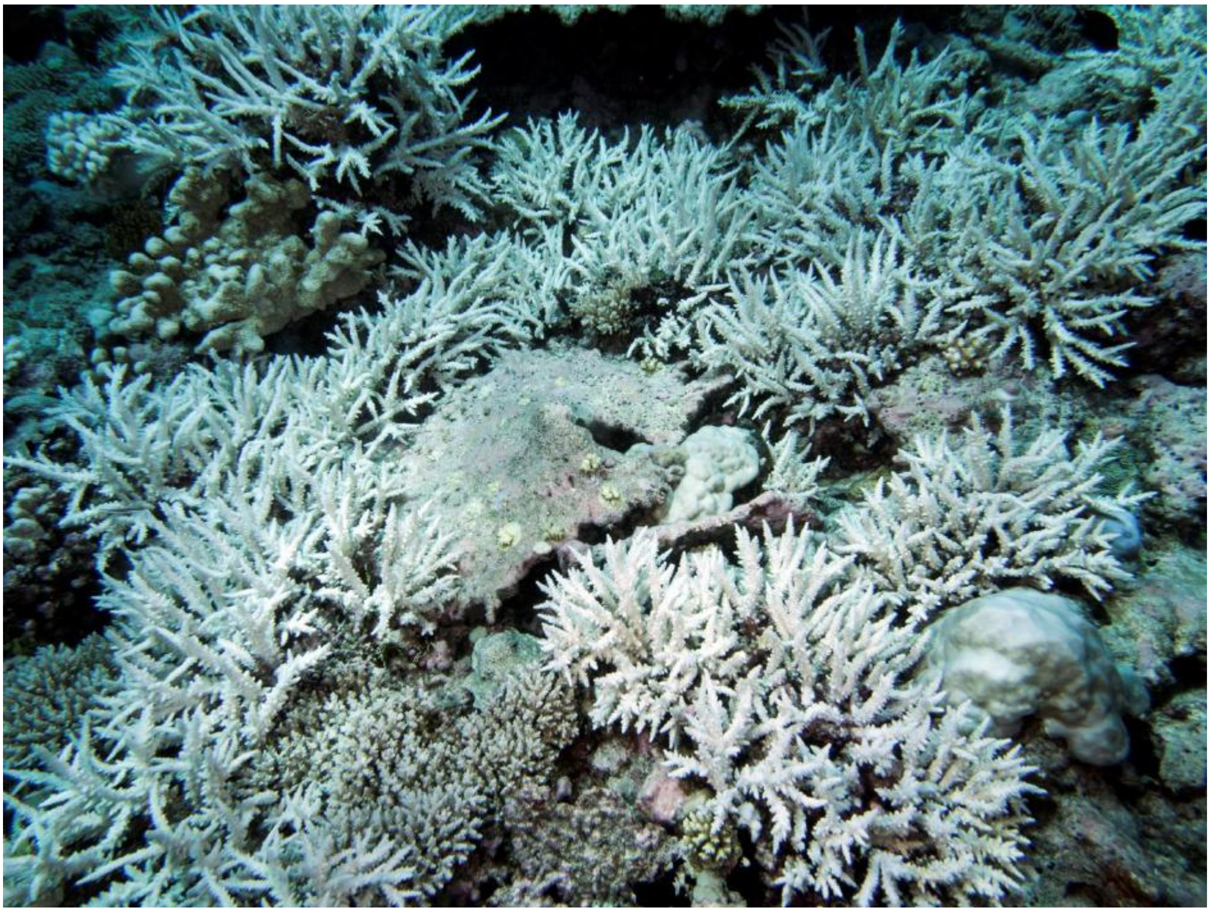


Fig. 4. Bleached *Acropora* during the 2015 El Niño event

Crown of thorns starfish
Acanthaster planci

Acanthaster planci are echinoderms in the family of *Acanthasteridae*, class *Asteroidea* (starfishes). They are a normal inhabitant of coral reefs found throughout the Indian Ocean, Pacific Ocean and Red Sea. The starfish are multi-armed (14-22 arms), with a central disc and mouth located on the underside of the disc. Their aboral surface (top) is covered with 3-5 cm long, venomous spines, while their oral surface has rows of tube feet with suckers extending down each arm. Like other echinoderms, a large part of their body is filled with fluid (water vascular system) which operates hydraulically to expand and retract their tube feet and aid in movement. Adults can achieve sizes of 80 cm.

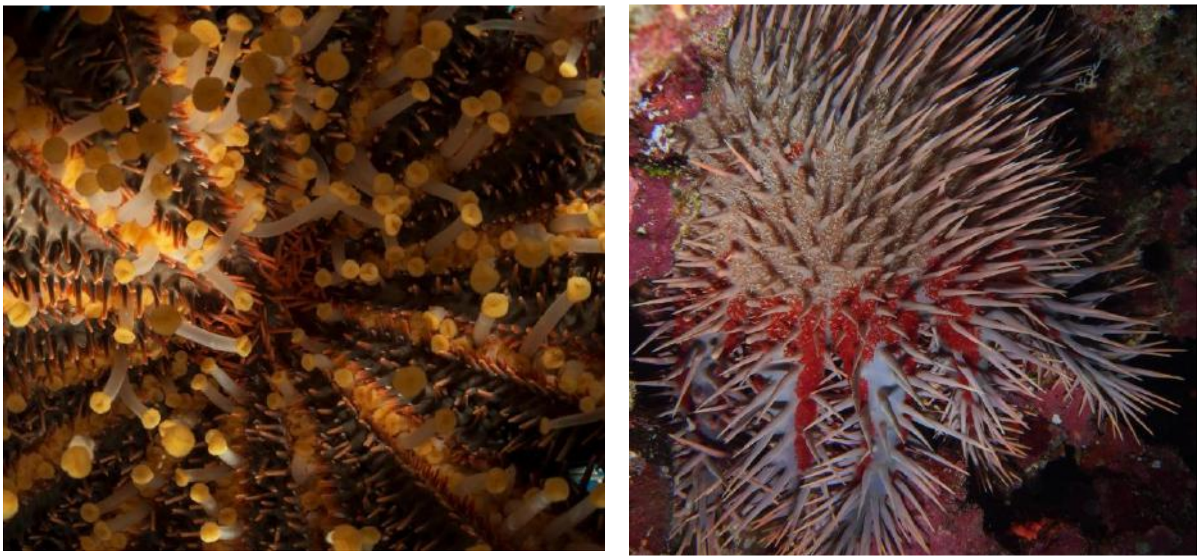


Fig. 5. Underside (oral surface) of a crown of thorns starfish showing the tube feet (left) and the top (aboral surface) of a COTS showing the spines.

COTS are the most influential corallivore in the Pacific, and are responsible for shifts in species assemblages and near-complete elimination of all reef-building corals during outbreaks (Birkeland 1989). They are vulnerable to predation as they slowly feed on coral but have few documented predators. In addition to their razor-sharp spines, their soft tissue (including the outer surface of the spines) contains chemical substances that are toxic called saponins, as well as surfactant and detergent-like compounds. Nevertheless, they serve as a key food source for certain species of gastropod molluscs (e.g. *Charonia* and *Cassis*), fish (e.g. species of wrasse, triggerfish, pufferfish and filefish), certain polychaetes, harlequin shrimp and crabs, and certain coral symbionts (*Tetralia* and *Trapezia* crabs) deter starfish from feeding on coral. Provided the ecosystem is intact, and water quality is high, COTS densities are usually kept low. Typical densities range from <1 to 5 starfish per hectare.

Fig. 6. The Trapezia crab protects *Pocillopora* colonies from COTS predation.

Fig. 7. *Trapezia* crab attacking a starfish.

Fig. 8. Trumpet triton *Charonia* spp. eating a crown of thorns starfish

Table 1. Documented reef fish predators of the crown of thorns starfish	
Reef fish	**Reference**
Arothron hispidus	Vine 1973
Balistoides viridescens	Vine 1973
Pseudobalistes flavimarginatus	Vine 1973
Cheilinus undulatus	Randall et al. 1978
Lehtrinus miniatus	Unknown
Epinephelus lanceolatus	Endean 1976
Batrachoididae spp.	Unknown

COTS were first described in 1705 by Georg Rumphius. For nearly 300 years they were thought to consist of a single species, but recent genetic data suggest that *A. planci* may be made up of four sibling species (Vogler et al. 2008). Their wide distribution can be attributed to their dispersal during the planktonic phase. This should also promote gene exchange between widely separated populations, reducing genetic variation, while localized pressures on adult populations may enhance genetic differentiation (Nishida and Lucas 1988). There is considerable variation in the morphology of starfish, including shorter spines and arms in eastern Pacific starfish. Notably, there are dramatic color differences between populations from the Pacific and parts of the Indian Ocean. Starfish from Maldives, Sri Lanka and surrounding areas are distinctively purple-blue in color, compared with the brown, green and reddish starfish found in the Red Sea, Chagos Archipelago, the Western Indian Ocean and the Pacific Ocean. Further understanding of these differences may help in identifying triggers of population explosions, characterizing differences in prey preferences, and development of more effective mechanisms to control destructive populations of COTS.

Fig. 9. Example of color variation among COTS from the Indo-Pacific.

Feeding patterns

Shortly after a starfish egg is fertilized it develops from an embryo into a gastrula larvae, and begins feeding on phytoplankton. While floating in the water column, it goes through several developmental phases (gastrula to bipinnaria and brachiolaria) before settling on the reef. Upon settling it metamorphoses into a pre-juvenile with five rudimentary arms. The starfish finds refuge within the interstices of the reef, and begins feeding on algae. These animals generally emerge from the reef matrix when they are 200-300 mm in size (Birkeland 1982) and 6-18 months old, and they switch from feeding on algae to coral. At this point, they undergo a rapid rate of growth.

Fig. 10. COTS begin feeding on coral as juveniles when they are only a few centimeters in length. The starfish seen feeding on *Pavona* in this photo is 6 cm diameter.

Juvenile and adult starfish feed predominantly on stony corals. Juveniles and adults will also feed on soft corals, corallimorphs, hydrozoans and other cnidarians, as well as molluscs and other invertebrates when their preferred food is in short supply (Moran 1986). They tend to feed on the fastest growing corals with the highest levels of replacement (e.g. *Acropora, Seriatopora, Stylophora,* and *Montipora*) and avoid slower growing massive corals such as *Porites* (Moran 1986; Birkeland and Lucas 1990; De'ath and Moran 1997; Pratchett 2001). Furthermore, they have the strongest feeding preferences among closely related species with similar morphologically. While predation pressure during COTS outbreaks can cause major changes to the community structure by selectively targeting certain taxa, their overall impact to reefs is usually minimal when starfish numbers are low, and recovery may be relatively quick if only the fast growing corals are consumed.

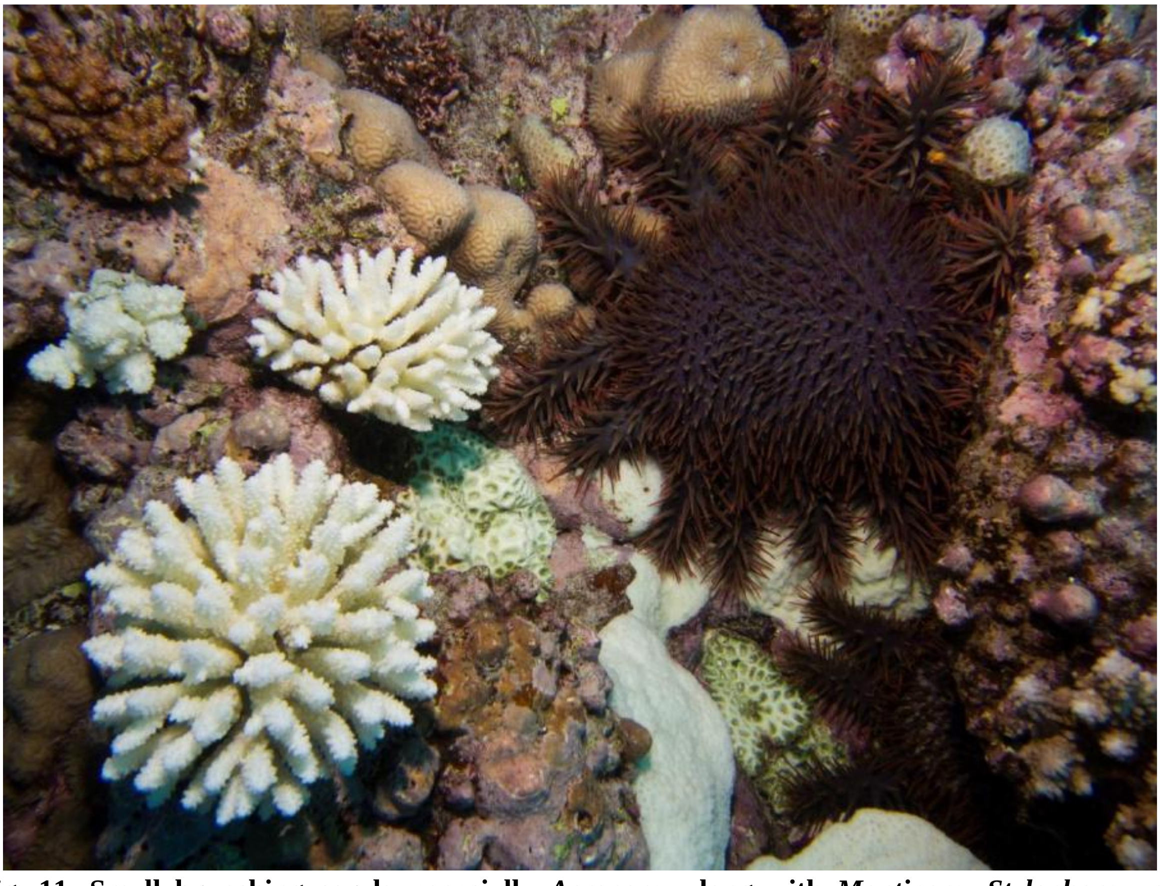


Fig. 11. Small branching corals, especially *Acropora*, along with *Montipora, Stylophora* and *Pocillopora* are the preferred food of the COTS.

Fig. 12. COTS tend to feed on massive corals such as *Porites* only after all preferred species have been consumed.

Fig. 13. COTS often avoid *Pocillopora* due to the presence of protective *Trapezia* crabs. When they do feed on this taxa, larger colonies often survive with partial mortality because the starfish is only able to eat the branch tips and tissue remains at the bases of the branches because they are not accessible to the COTS.

To feed, a starfish will wrap its body around or over a coral to feed. It then everts the gastric folds of its stomach through its mouth and turns them inside out onto the coral, releasing enzymes (wax esterase) to digest its prey (Benson et al. 1975). An individual starfish can readily consume one coral per day, or part of the coral if it is larger than their body size.

Fig. 14. The oral surface of a COTS immediately after it was pried off a coral. The stomach is everted through its mouth to dissolve the coral.

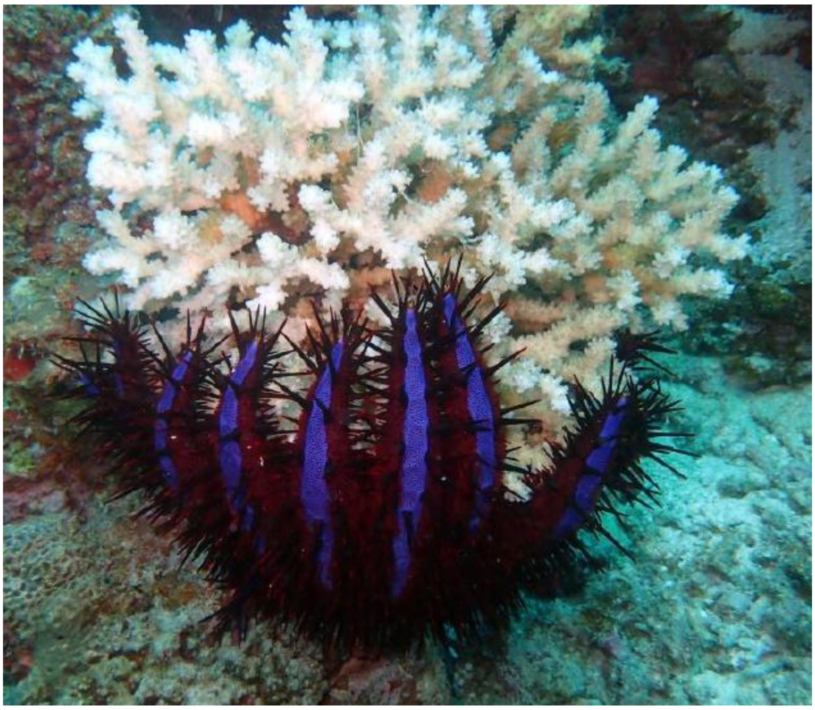


Fig. 15. This COTS consumed a coral approximately twice its size in two days. Strands of mucus and decaying tissue can be seen streaming off the upper branches.

In Australia, large starfish (40 cm and greater diameter) were found to consume approximately 161 cm²/day in winter and 357-478 cm²/day in summer. Smaller starfish (20-39 cm) ate 155 and 234 cm² of coral per day in the equivalent seasons. On average, a single starfish will consume all the coral found within a 5-6 m^2 patch of reef over a year (Moran 1990). At elevated densities, starfish can eat everything in their path, devastating entire reef tracts (Pearson and Endean 1969; Moran 1986; Colgan 1987; Birkeland and Lucas 1990).

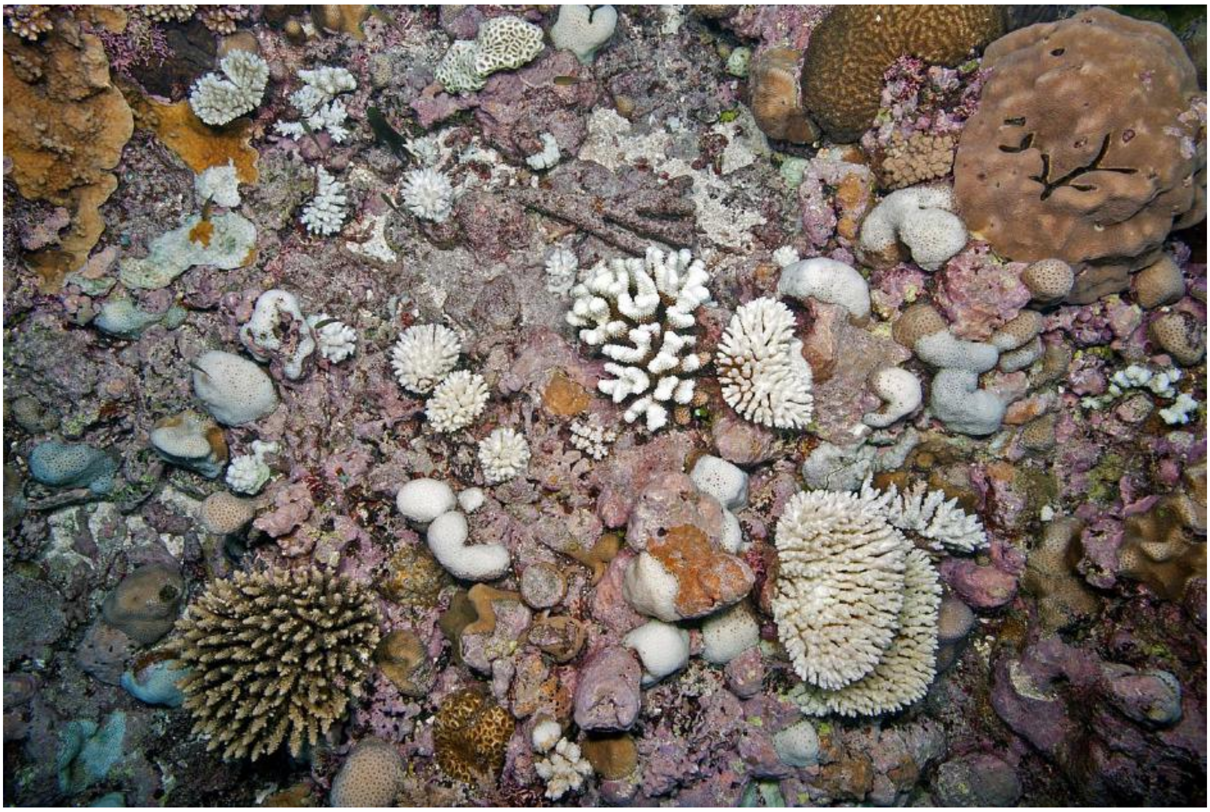


Fig. 16. Typical damage to a reef from an aggregation of COTS. A few massive corals and one acroporid were spared.

Causes of population explosions

COTS populations typically display cyclic oscillations. For extended (10-30 year) periods low-densities of animals are distributed throughout large expanses of reef habitats, but this may be followed by brief episodes of unsustainably high densities. There is still considerable debate whether outbreaks are a natural cycle of events or an unnatural process resulting from human activities. Two key hypotheses have been proposed as the primary cause of abnormal starfish abundances: the "Predator Removal Hypothesis" and "Terrestrial Run-off Hypothesis". The *Predator Removal Hypothesis* states that more juveniles survive to adults due to the removal of the organisms that normally feed on juveniles and adults. This includes the trumpet triton (*Charonia*) which may have been overharvested for the shell trade; and certain fishes (especially the Napoleon wrasse, *Cheilinus undulatus*) that have been overharvested by man (Birkeland and Lucas 1990). The *Terrestrial Run-off Hypothesis* suggests that outbreaks are due to a higher survival of larvae. While marine environments in the tropics tend to be oligotrophic, larvae tend to be food limited when plankton concentrations are low. Terrestrial runoff of sediments and nutrients fuel the growth of phytoplankton and zooplankton. The plankton provide the food needed to sustain larger populations of COTS larvae, and hence more larvae are able to settle onto the reef and metamorphose into juvenile starfish (Faure 1989; Brodie et al. 2005). This latter condition is believed to be the most critical parameter, and it may occur:

1) During periods of unusually high runoff associated with flood rains;
2) When coastal vegetation is cleared, mangroves are cut and seagrasses are removed;
3) In areas with excessive coastal development and discharge of sewage; and
4) In coastal environments with run-off of fertilizers from agriculture.

Nutrient pulses may also be associated with natural factors such as oceanographic upwelling and inputs of guano in nearshore waters from seabirds and other vertebrates (Allaway and Ashford 1984). In general, high volcanic islands with large human populations tend to have more issues with degraded water quality than low, sparsely inhabited atoll islands. However, it is also possible that high numbers of larvae from an upstream source could recruit onto reefs off a low atoll.

A third hypothesis is that outbreaks are correlated with El Niño/Southern Oscillation events, which can be associated with unusually high rainfall (and more run-off), higher ocean productivity, and temperature and current reversals.

Once population size reaches 30-40 animals/km^2 it approaches outbreak status (Faure 1989). Particularly severe outbreaks consisting of thousands of animals, at densities of 4-6 animals/m^2 have also been observed (Carpenter 1997). Outbreaks have been reported to last from about 2-3 years (e.g. the Great Barrier Reef in the 1980s) and up to 20 years in the Ryuku Islands of Japan (Moran 1988).

Fig. 17. Densities of COTS can exceed 5 animals per square meter during severe outbreaks.

Reproduction

Fluctuations in COTS abundance may also be related to biological aspects of these animals, such as their high fecundity, short generation times, highly defended spine-covered body, remarkable ability to regenerate detached limbs, ability to go for prolonged periods without feeding, and tendency to aggregate.

Fig. 18. COTS will frequently shed arms and other body parts when threatened and are capable of regenerating lost body parts relatively quickly. This COTS is missing about half of its legs.

The starfish have separate sexes. The female release her eggs into the water column, which are fertilized from sperm released by a neighboring starfish. An adult female is capable of generating up to 60 million eggs during a single spawning cycle (Birkeland and Lucas 1990; Babcock and Mundy 1992). Individuals may spawn annually for 4-8 years, producing increasingly larger numbers of eggs as they grow. For instance:

- A 200 mm diameter female produces 0.5-2.5 million eggs (2-8% of its wet weight) in a single breeding season
- A 300 mm diameter female produces 6.5-14 million eggs (9-14% of its wet weight) in a single breeding season
- A 400 mm diameter female produces 47-53 million eggs (20-25% of its wet weight) in a single breeding season

Spawning tends to be synchronized and it typically occurs between November and February in the southern hemisphere and April through August in the northern hemisphere. In the Maldives, they are reported to spawn during the monsoon inversion in late March through early April (Ciarapica and Passeri 1993). During peak reproductive periods, larval concentrations that are 4 orders of magnitude higher than the number of adults have been recorded (Uthicke et al. 2015). The planktotrophic larvae drift in the water column for a period ranging from 14 days under ideal conditions to 7 weeks in oceanic areas with marginal food supplies (Lucas 1982, Olson 1987), and larvae may be carried 500 km or more before settling onto the reef. Somewhere between 16 months and 3 years of age, the juveniles (only about 2-5 cm in diameter) emerge and begin eating coral (Faure 1989; Birkeland and Lucas 1990). The starfish have a lifespan of up to 8-10 years (Chesher 1969; Lucas 1984; Zann 1990).

Movement

The movement of starfish varies depending on the substrate. Typically they remain hidden under corals and ledges and in crevices during the day, emerging at night to feed. During outbreaks, they will also feed during daylight and can be seen aggregating on the upper surfaces of corals, especially table acroporids. The starfish tend to aggregate in areas with high coral cover, and advance relatively slowly in a wave across the reef as they consume all the coral in their path. COTS tend to avoid very shallow areas that have high wave exposure and prevailing winds, as well as protected areas with little coral (Ormond and Campbell 1974).

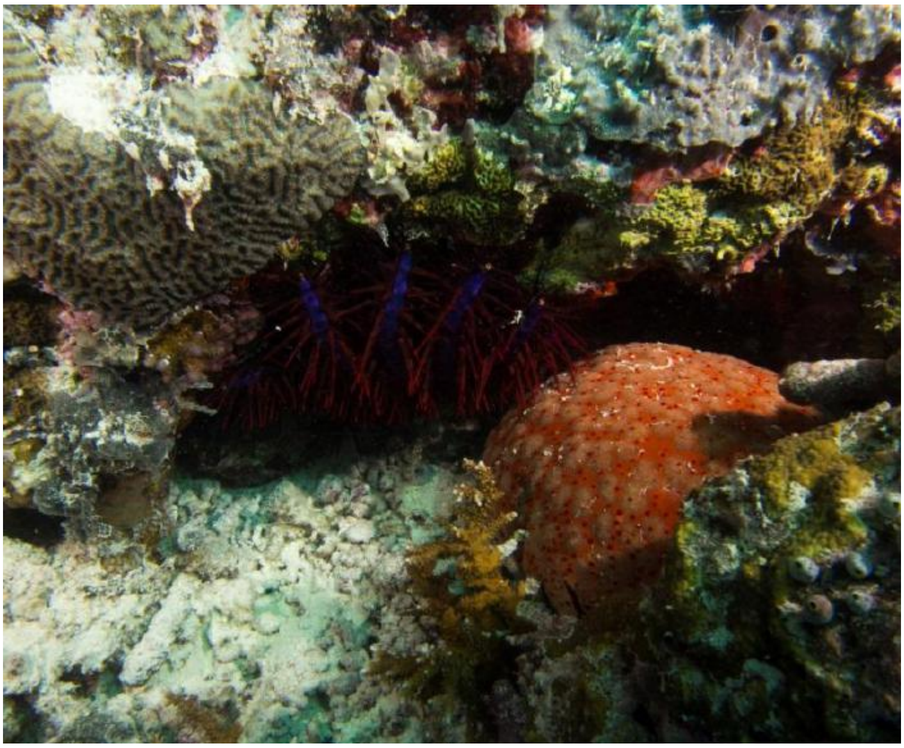


Fig. 19. A COTS hidden in a crevice next to a *Culcita* starfish; which is also a coral predator.

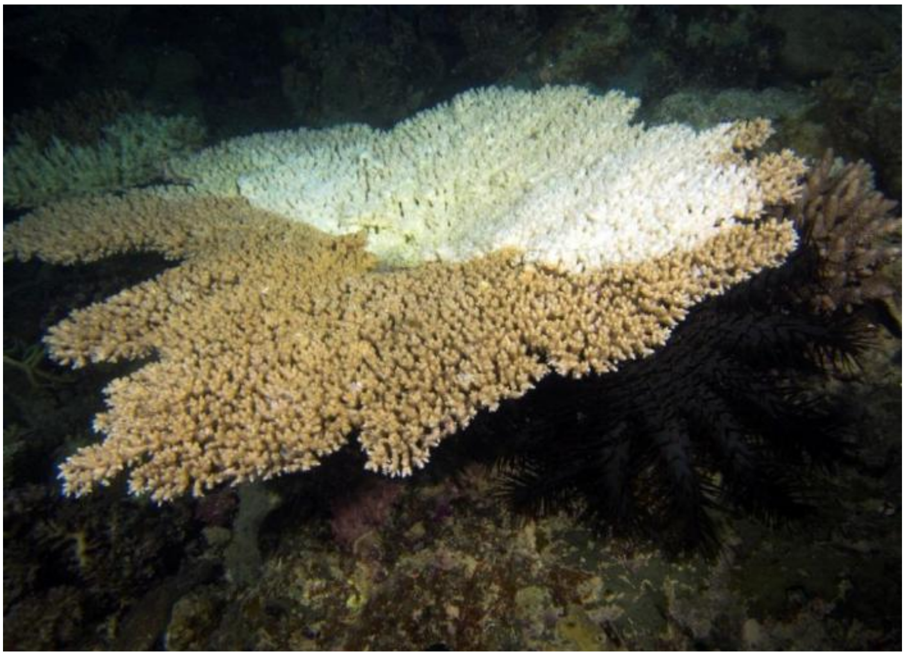


Fig. 20. A COTS hiding under a table acroporid during the daytime. Large feeding scars are visible on the upper right side of the coral from three previous feeding events.

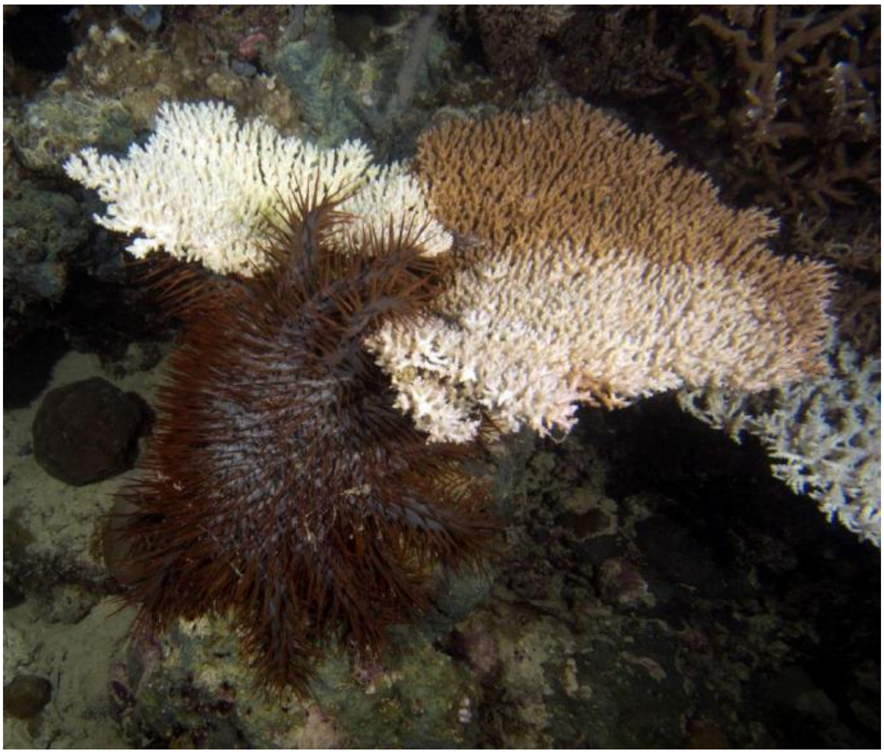


Fig. 21. A COTS emerging at night to continue feeding on a table acroporid. There are two white lesions from two previous feeding bouts.

The starfish have been observed to move from deep water up the fore reef slope. Also, once food becomes scarce they will migrate across extensive sandy areas in search of a new food source. They have been recorded to move up to 20 meters per hour over sand and cover distances of up to 580 meters in a week (Moran 1986). In North Malé Atoll, we have observed the migration of starfish from the fore reef into back reef and neighboring sand flats in search of food, and have even seen them crawling up onto the stairs of water villa and on the beaches. Starfish have also been observed in deep water between reefs.

Fig. 22. A COTS moving across the sand at the base of the reef in search of coral.

Impacts and patterns of reef recovery

Severe outbreaks of COTS have been associated with near total loss of corals and dramatic shifts in coral species assemblages. For instance in Australia, over half the living coral cover disappeared from 214 surveyed reefs over 27 years (from 28.0 % live coral cover in 1985 to 13.8 % in 2012) with 42% of this loss attributed to COTS predation (De'ath et al. 2012).

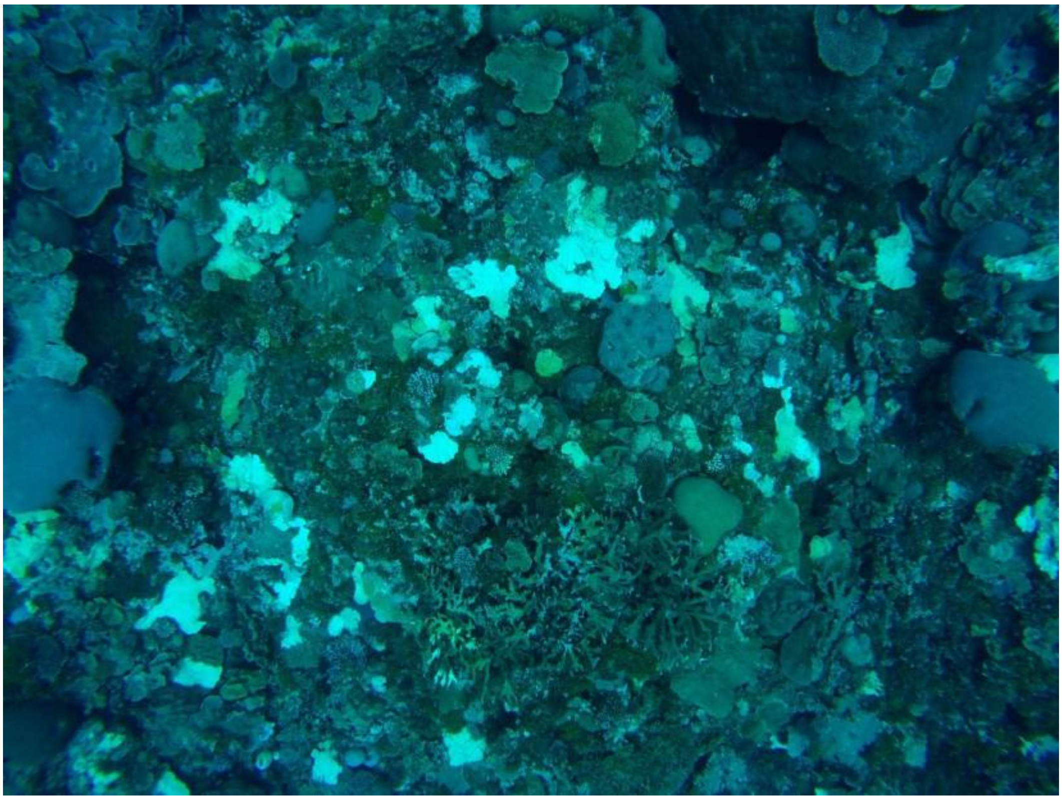


Fig. 23. A portion of a patch reef (approx. 8 m x 10 m) showing moderate damage caused by 12 COTS over several days. All of the white spots are recently killed corals. The boulder corals have been avoided.

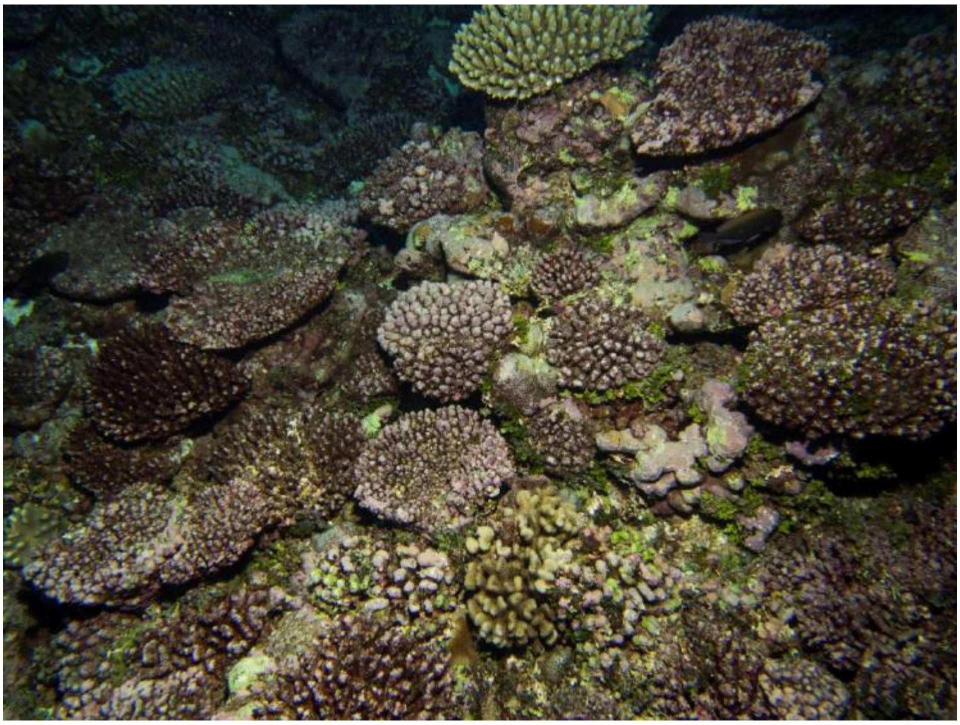


Fig. 24. A shallow reef that was devastated by COTS predation. Two colonies in the field of view survived. The remainder of the skeletons are now colonized by algae.

Once all the coral is consumed on a reef, COTS will usually disappear and the reef can begin to undergo recovery. Corals may recruit into a reef system relatively quickly, if conditions are ideal, but full recovery may take a long time. During the 1980s, reefs in Okinawa, Japan were completely destroyed and little recovery was observed after 10 years. In Guam and the Great Barrier Reef full recovery of coral cover following an outbreak was reported to take 10-25 years, with 25% of the reefs showing no recovery (Lourey et al. 2000). Outbreaks in the Ryukus (Japan) continued for more than 20 years (1967-19876), completely destroying these reefs (Yamaguchi 1987).

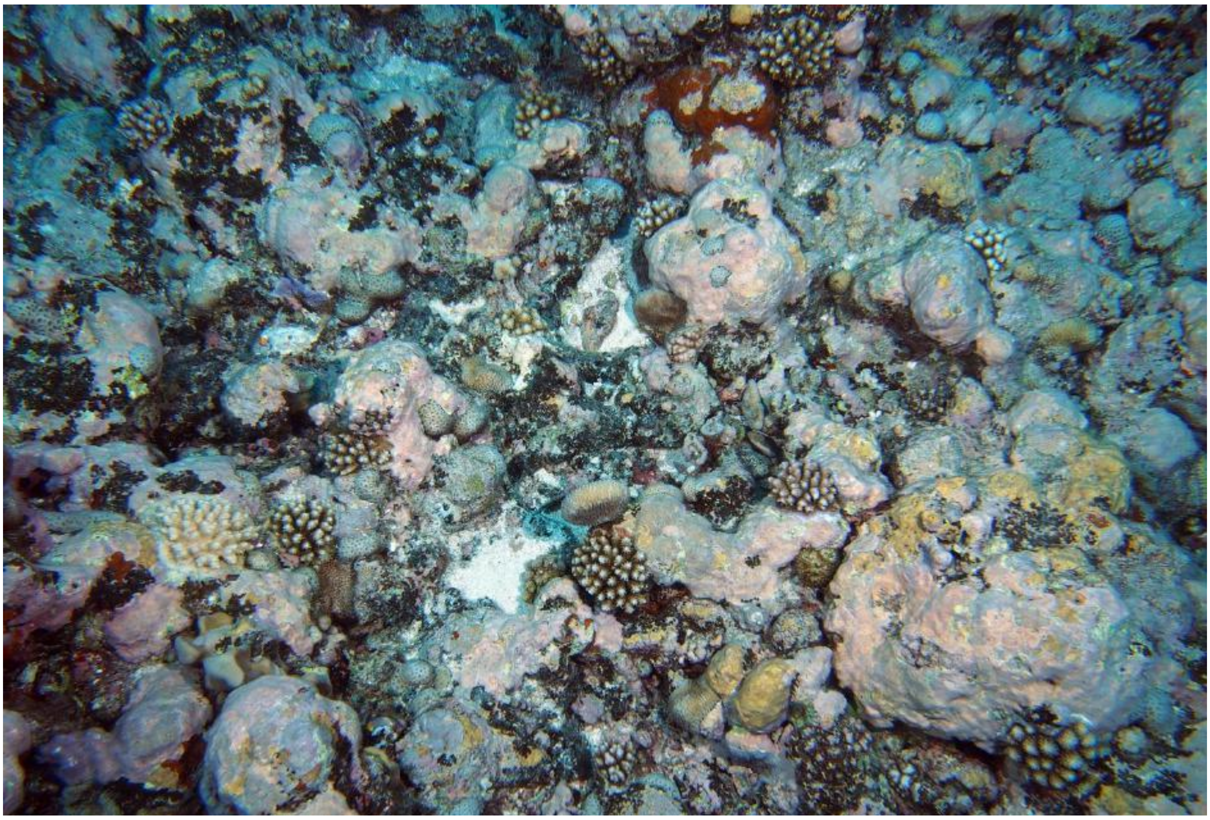


Fig. 25. A reef devastated by COTS in 2013 is now undergoing recovery. Numerous small acroporids and faviids have colonized the reef within two years after the COTS disappeared.

During many of the recent outbreaks reported from the Indo-Pacific, intensive predation pressure by these starfish resulted in near elimination of branching corals, as well as many of the slower growing massive coral species including the important frame builders (*Porites*). Recovery to pre-COTS conditions in these situations could be delayed by decades to centuries as these corals grow much slower (approx. 1 cm/year) and they have lower recruitment rates (Done 1988; Endean et al. 1989). The presence of tissue remnants on these species, however, can help speed up recovery rates.

History of COTS infestations in the Maldives

Historic outbreaks

There have been two previous outbreaks of COTS, one during the 1970s on Alifu Atoll and a second in the late 1980s (Adam 1989). Little information is available on the outbreak in the 1970s. The second outbreak is believed to have peaked in 1987 on the western side of Kaafu (North Malé) Atoll near Reethi Rah (Fig. 26) and continued at least until 1991. The MRC sent out questionnaires to obtain more information on the occurrence of COTS during this outbreak. In 1988, COTS were documented at 29 sites, out of 190 that were dived, with most on North Malé atoll. Over the next four years dive operators reported outbreaks Alifu (Ari) Atoll in May 1991 and a southern atoll (Gaafu Dhaalu and Gaafu Alifgu), with lower numbers of COTS at South Malé Atoll, Vaavu and Faafu (COT Newsletter, MRC). The MRC also surveyed 80 sites on 8 atolls in 1987/1988, observing COTS only at five sites. In 1990, they conducted assessments at 111 sites across the entire archipelago, observing COTS at 21 of these sites; only one site contained more than 99 COTS. Ciaparica and Passeri (1993) also reported low numbers of COTS between 1991 and 1992 with tens of individuals observed off Bodumora Island in Felidu Atoll.

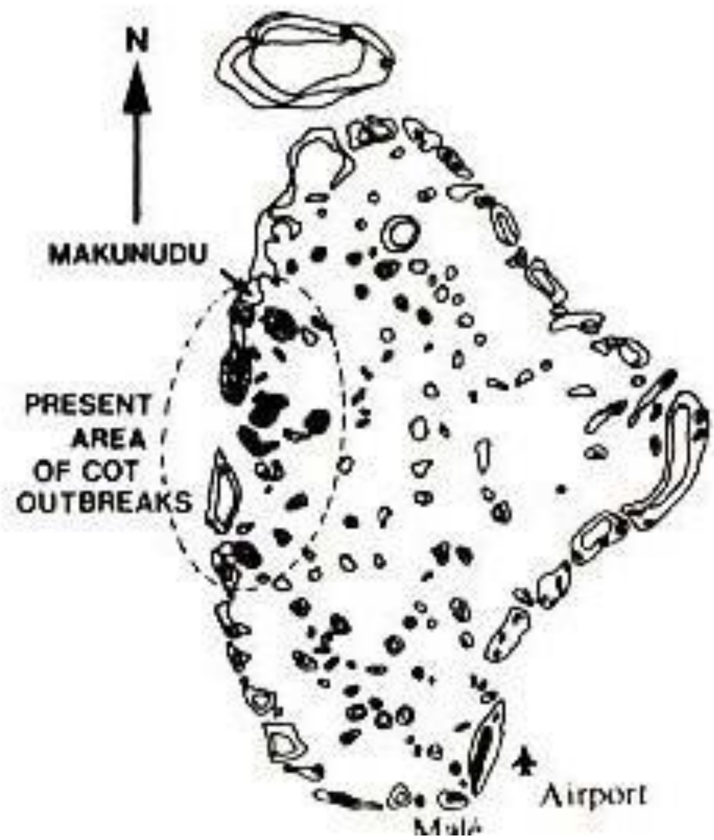


Fig. 26. Area of emergence of COTS in the Maldives in 1988.
Source: COT Newsletter, Marine Research Section, Ministry of Fisheries and Agriculture

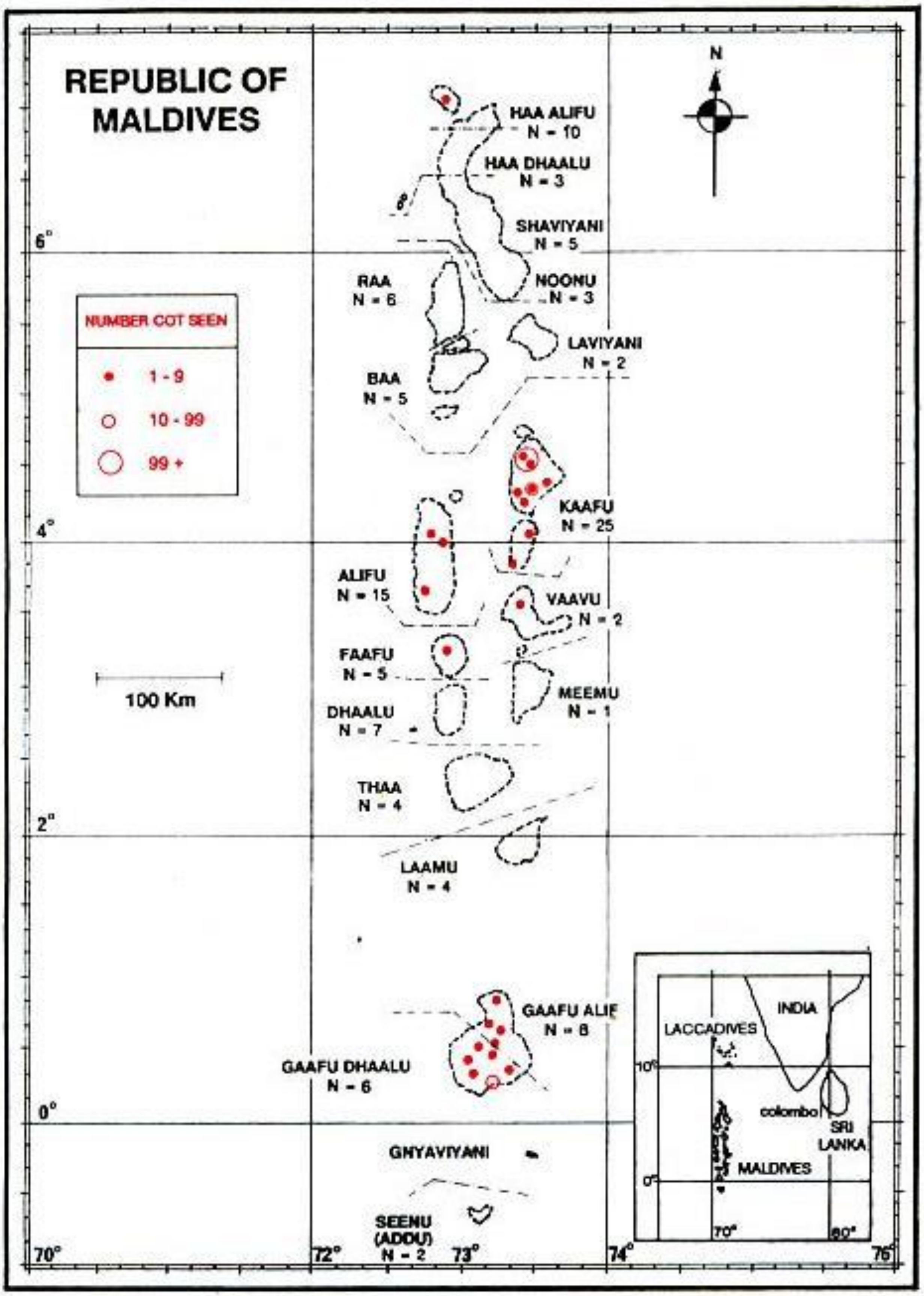


Fig. 27. Locations of stations examined in 1990 for COTS and the numbers recorded (red dots). Source: COT Newsletter, Marine Research Section, Ministry of Fisheries and Agriculture

Reports of COTS occurrence in the Maldives

Sporadic reports on COTS have occurred since 1993. Surveys conducted between 1996-1997 revealed low numbers of COTS (1-4 per site, with one site having 13 COTS) in five out of 34 locations examined on Laamu Atoll (Sluka and Miller 1999). COTS were only observed in shallow water, including a reef flat, the lagoon and channel areas, with no starfish recorded on deeper sites. In 1999, 17 out of 32 resorts responded to a questionnaire on COTS. These resorts identified COTS on 37 out of 189 sites that were surveyed, with most containing only 1-2 COTS and three sites having over 60 (Ministry of Tourism, 2000). Outbreaks were also reported from Haa Alif and Haa Dhaalu Atolls in mid 1999 and Noonu Atoll in late 1999.

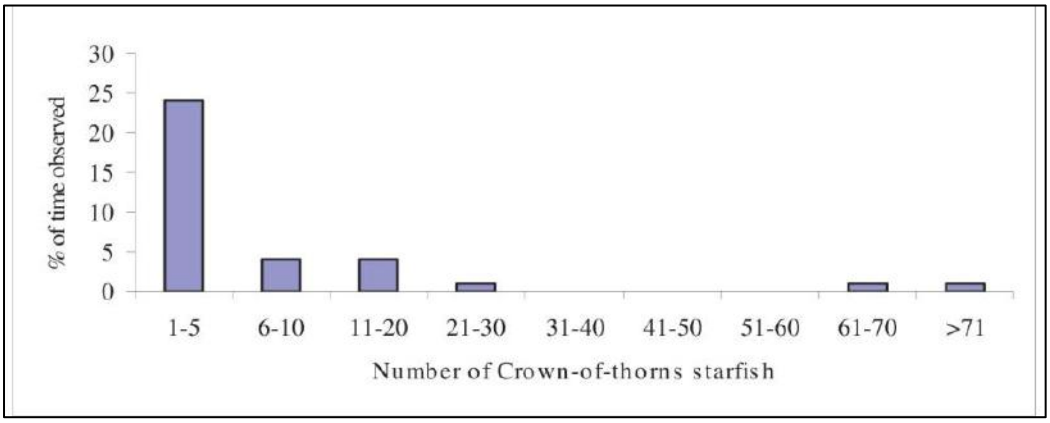


Fig. 28. Frequency of COTS observations within the Tourism Zone in 1999. COTS were seen in about 20% of the sites examined. Source: Ministry of Tourism, 2000.

The Maldives Protected Area System Project identified two adult COTS at Addu Atoll in 2003. In 2006 and 2007 a total of 84 COTS were collected at Vabbinfaru and 66 COTS at Ihuru reef, North Malé Atoll. During the NCRMS surveys of five atolls in 2009 a single juvenile COTS was documented at Bodumohoraa Island, Vaavu Atoll.

Since the re-emergence of COTS in North Malé Atoll in 2013, outbreaks of COTS have been reported from 24 reefs on Ari Atoll, two locations on Baa Atoll, one on Lhaviyani Atoll, 11 on North Malé Atoll and four reefs on South Malé Atoll. The coordinates of outbreaks are listed in table. It is likely that this list is incomplete, as this represents reports from social media and observations by the authors.

Since 2016, additional observations of COTS have been made on Shaviyani Atoll, Baa Atoll, and Lhaviyani Atoll (Agnes Van Linden pers. Comm).

Table 2. Reported outbreaks of crown of thorns starfish in the Maldives in 2015-2016				
Atoll	**Date**	**Latitude**	**Longitude**	**Reef Name**
Ari	2015	3.8502959	72.9500771	Hangnaamedhoo House Reef
Ari	2015	3.6324938	72.9208946	Ali Thila
Ari	2015	3.9883314	72.796011	Villigili Faru
Ari	2015	3.9926125	72.8232193	Fesdu Mahaa
Ari	2015	3.9435601	72.8802001	Meerufenfushi
Ari	2015	3.9398674	72.9048872	Fish Head
Ari	2015	4.0186199	72.8816217	Kandolhu Thila
Ari	2015	3.9624729	72.796483	Hohola Thila and Reef
Ari	2015	4.0911365	72.8621945	Maayaa Thila
Ari	2015	4.1540588	72.8366518	Hafza Thila
Ari	2015	3.9786345	72.8946948	Bodu Giri Cave
Ari	2015	4.0715953	72.8838587	Maayafushi House Reef
Ari	May-15	3.8873759	72.8160095	Unkn.
Ari	Jul-15	3.7859587	72.7310157	Unkn.
Ari	Aug-15	3.5730449	72.865963	Unkn.
Ari	Aug-15	3.6330077	72.919178	Miyaru Thila
Ari	Sep-15	3.8025948	72.9572868	Kudadhoo/Omadhoo Thila
Ari	Sep-15	4.220507	72.7756691	Das Kurani
Ari	Oct-15	4.0531453	72.8318024	Unkn.
Ari	Oct-15	3.5939682	72.883054	Unkn.
Ari	Oct-15	3.9976642	72.7907753	Fesdu Wreck
Ari	Nov-15	4.19594	72.7642107	Maagiri
Ari	Nov-15	4.0713572	72.9459196	Bathala House Reef
Ari	Jan-16	3.7424722	72.7476883	Rahdigga Thila
Baa	2015	5.1470245	72.9851818	Aanugandu Reef
Baa	2015	5.0598243	72.9430389	Anemone Garden
Lhaviyani	Oct-15	5.5517474	73.4683228	Unkn.
North Malé	Jan-14	4.4802524	73.3934784	Hembadhoo Wreck- Taj Vivanta Resort
North Malé	Jun-14	4.5326184	73.3745956	Summer Island Resort Reef
North Malé	Apr-14 -	4.4727223	73.3727074	Washimas Thila
North Malé	2015	4.5695803	73.3776855	Finger Point
North Malé	Mar-15	4.454068	73.3721924	Maska Reef
North Malé	Mar-15	4.2693819	73.4911537	Unkn.
South Malé	May-15	4.00382	73.53084	Faanu Faru
South Malé	Aug-15	3.917925	73.4703398	Unkn.
North Malé	Oct-15	4.2936898	73.5575867	Unkn.
North Malé	Oct-15	4.1746894	73.4827745	Villimale West and North
North Malé	Oct-15	4.54477	73.39008	West Point
North Malé	Oct-15	4.53052	73.39713	Reethi Reef
North Malé	Oct-15	4.3147000	73.568540	Himmafushi
North Malé	Oct-15	4.3046300	73.559260	Gili Lankanfushi
North Malé	Oct-15	4.5268001	73.3908176	Snorkel Reef
South Malé	Oct-15	4.00006	73.49592	Stage
South Malé	Oct-15	3.9642	73.50117	Veli
South Malé	Oct-15	4.00999	73.48357	Raaebundi Reef
Dhaalu	Mar-16	2/7039	72.8829	Vallalohi

When is an outbreak of COTS a concern?

Determining whether control mechanisms are necessary

Once a discovery of COTS is reported, quick investigation of the location is needed. Preliminary surveys must be done to obtain data on the size of the outbreak location, the number of COTS present, and the condition of corals. This information can help determine if COTS are at normal background levels, in which only follow-up monitoring is needed, or whether they are undergoing an outbreak which is having significant negative impacts. It is helpful to collect as much information as possible through interviews with fishermen, divers, dive centers, marine biologists and other community members about the extent of COTS populations. Useful knowledge includes:

1) The numbers of COTS they have been seeing;
2) How long they have been a problem;
3) Whether their numbers have recently increased;
4) If certain areas or depths are affected more severely than others; and
5) Have the conditions on the reef changed as a result of the starfish.

In outbreak situations, consideration of implementation of a COTS control project can be done rationally and in an informed manner. This should first include a meeting with full participation of local councils, government officials, and other stakeholders to discuss the scientific information available on the outbreak, and to determine if and how COTS control will be carried out. This should be followed up with a second meeting discussing possible schedules, numbers of people involved, the control method that will be performed, safety, and follow-up monitoring. It is beneficial to draft an agreement signed by officials. Once the initial eradication is undertaken, follow-up monitoring is necessary to determine the effectiveness of the effort. Subsequent monitoring can determine if additional control efforts necessary. Often, eradication can require multiple visits to one site.

If a clean-up is determined to be feasible and beneficial, it helps to obtain as much information on the affected reefs and starfish. Knowledge of their size can give some indications of the age of the starfish (although it varies depending on their food source), and whether the outbreak represents a single invasion (all the starfish are roughly the same size) or multiple recruitment events that occurred at different times (the population consists of different sized cohorts). The prey they are feeding on also is an indication of how long they have been on a reef and how much damage they have done. If they are only feeding on fast growing branching corals (*Acropora*) it is likely that there is a high abundance of resources, starfish numbers are low, or the outbreak is relatively recent. Conversely, if they are only feeding on massive Porites, they may have exhausted other more preferable prey items (Acropora) and they have switched to slower growing species. This also provides an indication of the time that may be required for full reef recovery, as faster growing branching corals tend to be replaced much quicker.

The likelihood of success of any COTS culling effort depends on:

- The size of the outbreak and the amount of resources available. It is much easier to remove/kill COTS on a small reef system than on a very large reef, and smaller confined outbreaks are easier to control. Future monitoring is also easier on smaller reefs.
- Timing of removal. If their spawning period has just passed, there is the potential for a future outbreak, while removal shortly before the spawning event will prevent further damage to the reef and also reduce the potential for a secondary outbreak.
- Degree of migration of the animals. Control efforts are most successful if the outbreak is concentrated in one area; and less successful when it has spread to surrounding areas,
- Reef topography and weather. Animals may become difficult to detect and remove when environmental conditions deteriorate and time underwater is reduced in deeper habitats.

Fig. 29. COTS tend to prefer to eat branching and table acroporids. While it is easy to find the COTS based on the occurrence of numerous white, tissue-denuded skeletons, they often hide under large table corals during daylight and can be very difficult to remove.

Approaches to cull COTS

Major control programs for COTS have been implemented in the Indo-Pacific since the 1950s, including Japan (Yamaguchi 1986), American Samoa, Cook Islands and Micronesia (Birkeland 1982), and the Great Barrier Reef (Zan and Weaver 1988) with smaller efforts undertaken in Fiji, Western Samoa, Vanuatu, Maldives, Hawaii and many other locations. In some countries (e.g., Australia), removal programs and culling of starfish through injections of poisonous chemicals have been ongoing for decades. The largest effort overall to date was undertaken in Japan with removal of over 13 million starfish! (Yamaguchi 1986), with hundreds of thousands removed from Micronesia (658,000), American Samoa (487,000), the great Barrier Reef (93,000), Cook Islands (81,000) and other countries in the 1970s and 1980s (Birkeland 1982; Moran 1986). Culling of starfish has been successful in situations where the outbreak is identified early and/or it is fairly small and contained within a restricted area. In contrast, macro-scale efforts involving massive outbreaks of hundreds of thousands of COTS across large scale reef systems have proven unsuccessful, due to the scale and difficulty in eliminating all of the animals, and in some cases (e.g. Japan) the removal efforts were initiated too late and there is some thought that it actually worsened the situation (Yamaguchi 1987).

The main challenge with any chosen method is the successful identification of the center of the outbreak and elimination of most of the starfish from affected areas. It is most critical that the areas with the densest populations are targeted, as these animals will have the highest successful rates of fertilization during spawning events (sperm and eggs are released in the water and fertilization is external, with higher success when animals aggregate) and they are causing the greatest and most rapid loss of corals. In the center of the outbreak animals can be easily seen feeding on the corals, and also in crevices next to white, recently eaten corals. It is impossible to eradicate every single COTS from reefs where they are in outbreak densities. Starfish are known to hide in holes and crevices and under corals, especially in areas of high wave exposure, emerging at night to feed. These can be difficult to see, especially for the animals that are similar in color to the substrate. However, with sufficient effort, small areas can be protected and their population size can be reduced to a less destructive level. The most effective means of removal requires elimination of as many animals as possible during daylight, followed by a revisit to the treated site on several occasions and if possible at night.

Historical efforts to eradicate COTS in the Maldives

The first attempt to control COTS in the Maldives is reported to have occurred during the 1988-1991 outbreak with most effort directed at the house reefs affiliated with certain resorts. The *January 1991 COT Newsletter* identifies four resorts that removed 30,500 COTS in total, with most collected by Nakatchafushi (18,700) and Makunudu (11,400), along with Ihuo (300) and Vabbinfaru (100).

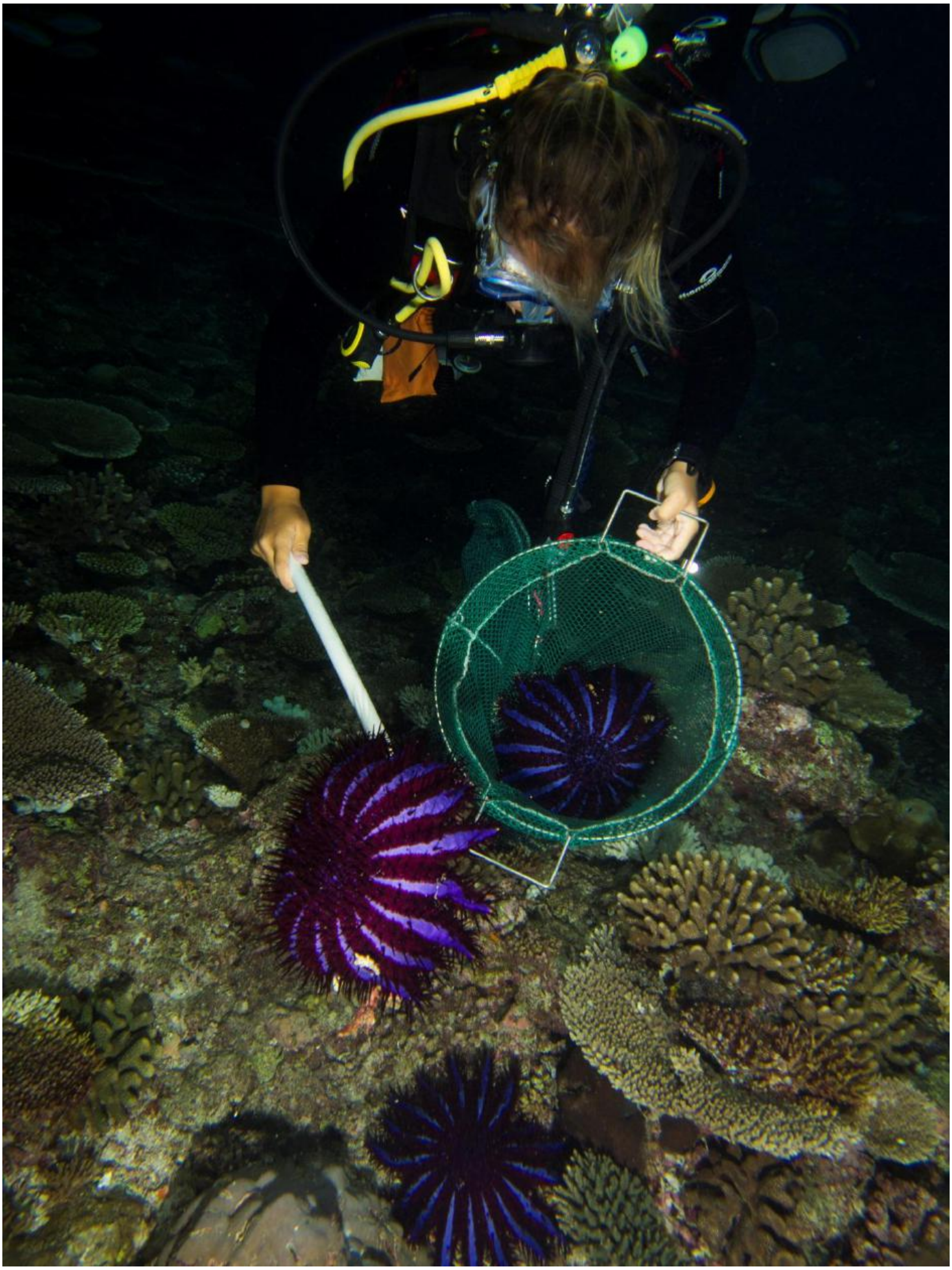


Fig. 30. Removing COTS from an affected reef in South Malé Atoll.

Efforts to control COTS in the Maldives between 2013-2016

Recognizing the rapid and extensive losses of corals, and in particular complete devastation of house reefs surrounding a number of resorts, a number of dive centers have implemented large-scale efforts to either remove or inject starfish. Marine biologists have established several social media outlets, including Facebook, which provides details on COTS occurrence and control efforts. Some of the tables presented here were compiled from direct contacts with marine biologists, MRC, and the Facebook posts.

The most extensive attempt to eradicate COTS, involving tens of thousands of animals removed between 2013-2015, has been undertaken in the vicinity of Reethi Rah. The outbreak around these reefs continues, and the loss of coral has been alarming. Outbreaks have been nearly as severe on Ari Atoll, with over 25,000 animals removed from the reefs around one resort over the last 8 months.

There are numerous resorts and dive operators that have not taken action, partially because of limited capacity, lack of equipment and manpower, and also a general lack of understanding of the gravity of the situation. Others have attempted to kill starfish by cutting them into pieces or injecting them with a host of readily available chemicals (e.g., bleach, petroleum products, dish soap), potentially worsening the situation. Without a coordinated effort to remove starfish or properly inject them to control these outbreaks as soon as possible, they will continue to spread to other atolls and will devastate these reefs.

Fig. 31. On Feb. 27, 2016 the Divers Association of the Maldives organized a COTS clean-up, where over 400 COTS were removed.

Fig. 32. Healthy shallow fore reef community without COTS.

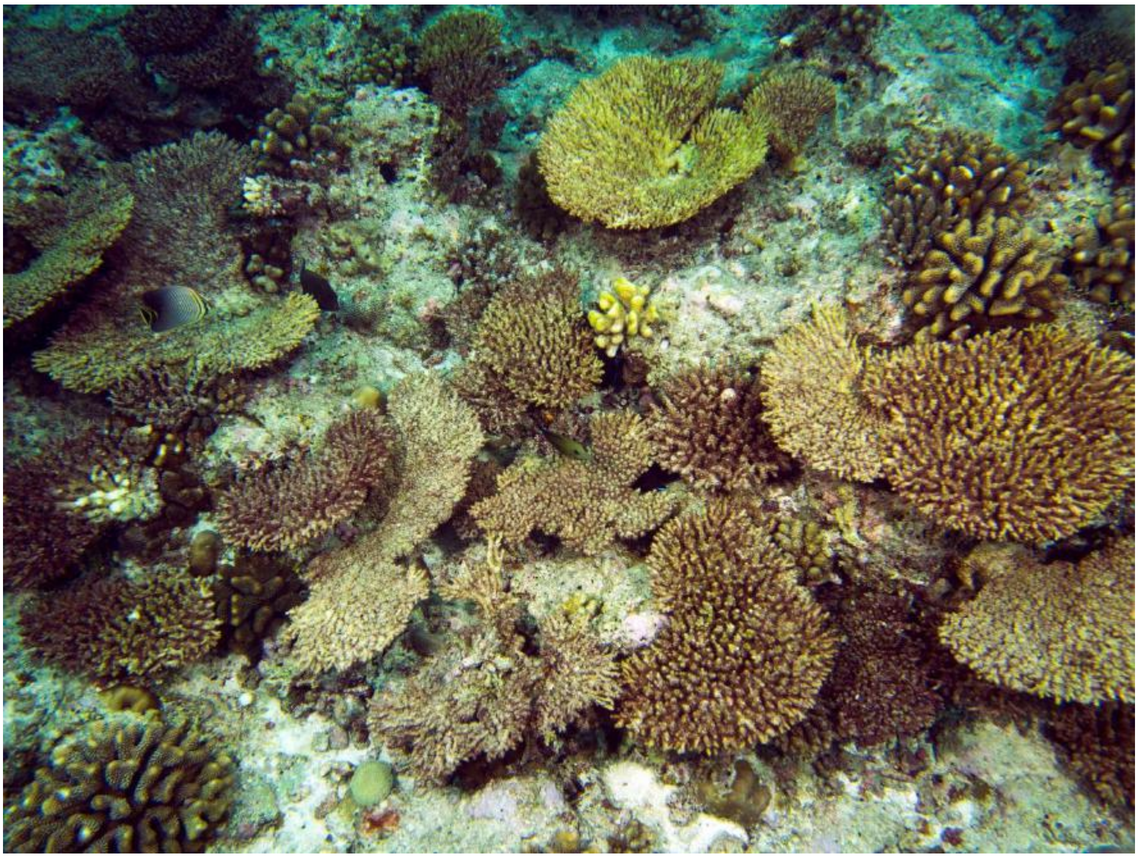


Fig. 33. A neighboring reef at the same depth that was destroyed by COTS. All the table acroporids are dead and only their skeletons remain. Over time these will become bioeroded and disappear.

Table 3. Reported removals of crown of thorns starfish at Ari, Huvadhoo and Dhaalu Atolls, Maldives in 2015-2016					
Atoll	**Date**	**Latitude**	**Longitude**	**Reef Name**	**Number COTS Removed**
Ari	13-Nov-14			Hiyama & Bohwa Thila	92
Ari	23-Feb-16			Dhigurah	3,115
Ari	27-Feb-16			Unkn.	118
Ari	25-Apr-15	4.0234788	72.8105164	Gaathafushi	19
Ari	30-Jul-15	3.8873759	72.8160095	Athuruga Reef	1,696 (injected bile salt)
Ari	31-Jul-15	3.7609719	72.7993798	Myaru Gali Thila	1,172 (injected bile salt)
Ari	04-Dec-15	4.2279967	72.7642107	Kandinmaa Ghiri	14
Ari	15-Nov-15 20-Dec-15	4.0564201	72.8446341	Kuda Faru	500+
Ari	Mar-15, Aug-15, Sep-15	3.6078292	72.9001772	Unkn.	1,400+ (removed, injected sodium bisulphate)
Ari	Unkn.	3.6559333	72.9376333	Lucky Rock	30
Ari	Unkn.	4.0027159	72.881788	Kandolhu Island Resort	200+
Ari	Unkn.	4.002459	72.8796959	Kandolhu Island Resort	(injected with vinegar)
Ari	Unkn.	3.6700113	72.9021835	DRIFT Thelu Veliga	200+
Ari	Unkn.	3.524044	72.8582382	LUX Eurodivers	10
Ari	Unkn.	3.6376333	72.9329109	Baipolhi Thila	10
Ari	Unkn.	3.591848	72.8833008	Unkn.	1,329
Ari	Jun-Sep 15	4.006347	72.809259	W House Reef; Fesdu Island	34
Ari	Jun-Jul 15	4.006352	72.809457	Gaatafushi; Fesdu Island	72
Ari	20-Oct 15- 8 Apr 16	4.006347	72.809259	W House Reef; Fesdu Island	20,015
Ari	Oct 15- Apr 16	4.006352	72.809457	Gaatafushi; Fesdu Island	1,013
Huvadhoo	Jan-15	0.4619358	73.1550407	Outrigger Konotta House Reef	30
Huvadhoo	Oct-15	0.5067378	73.4545898	Unkn.	30
Dhaalu	Mar-16	2/7039	72.8829	Vallalohi	136

Table 4. Reported removals of crown of thorns starfish at North and South Malé Atolls, Maldives in 2015-2016					
Atoll	**Date**	**Latitude**	**Longitude**	**Reef Name**	**Number COTS Removed**
North Malé	2015	4.309683	73.424023	Banyan Tree Resort House Reef	449
North Malé	Jan-15	4.4973659	73.3625793	Madivaru Beyru	80
North Malé	Apr-15	4.4299365	73.3848953	Unkn.	400
North Malé	May-15 to Nov-15	4.4165867	73.3811188	Kuda Hithi House Reef	200
North Malé	Jun-15 onward	4.3301716	73.5936785	Kuda Huraa House Reef and Channel	30
North Malé	Jul-15, Aug-15 & Oct-15	4.2943103	73.5578012	Unkn.	1,000+
North Malé	Aug-15	4.5192706	73.3676434	Unkn.	2,398
North Malé	Sep-15	4.4613415	73.4066534	Sandbank	30 (injected bile salt)
North Malé	Oct-15	3.971806	73.5008526	Reethi Rah (area)	4,000
North Malé	Oct-15	4.3275826	73.5931957	Kuda Huraa House Reef	30
North Malé	Oct-15	4.5179015	73.3691025	O&O Reethi Rah	25,000+
North Malé	Oct-15	4.5467895	73.3896053	West Point	614
North Malé	Oct-15	4.3147000	73.568540	Gili Lankanfushi	382
North Malé	Oct-15	4.3046300	73.559260	Himmafushi	592
North Malé	Oct-15	4.54477	73.39008	West Point	993
North Malé	Oct-15	4.53052	73.39713	Reethi Reef	885
North Malé	Oct-15	4.50919	73.37359	Reethi Rah	371
North Malé	02-Oct-15	4.4661014	73.6614418	Unkn.	360
North Malé	Oct-15 & Nov-15	4.3791036	73.3867836	Coral Garden	615
South Malé	Oct/Nov-15	4.00006	73.49592	Stage	1,076
South Malé	Oct/Nov-15	3.9642	73.50117	Veli	1,620
South Malé	Oct/Nov-15	4.00999	73.48357	Raaebundi	1,340
North Malé	Nov-15	4.2693819	73.4919262	Bandos Reef	150
North Malé	03-Nov-15	4.5286825	73.3993042	Reethi Reef	885
North Malé	15-Feb-16			Banana Reef	15 (200+ observed)
North Malé	27-Feb-16	4.3275826	73.5931957	Kuda Huraa	200
North Malé	27-Feb-16			Hulumale Beryru/Back Faru	432
North Malé	27-Feb-16			Unkn.	27
North Malé	Unkn.	4.4217213	73.4133911	Madivaru Beyru	40
South Malé	Oct-15	4.1211322	73.4366834	Unkn.	60
South Malé	27-Feb-16			Unkn.	37
South Malé	27-Feb-16	4.3275826	73.5931957	Kuda Huraa (area)	570
South Malé	Unkn.	4.122502	73.436354	Velassaru	Unkn.
South Malé	2-3 May 2016	4.00999	73.48357	Raaebundi	430

Reethi Rah removal efforts

Despite the physical removal of several thousand starfish around Reethi Rah since 2013, their numbers remain hard to control. The surrounding Resorts and dive centers reverted to use of bile salt injection techniques in 2015 alongside daily removals from shallow waters adjacent to resort beaches. In addition ot the thousands that have been killed via injection, it is estimated up to 100 starfish are removed each morning by resort staff. In October 2015, another several thousand starfish were removed from reefs surrounding Reethi Rah over a one-week period. The loss of coral around these reefs was astounding with several reefs now fully demolished. Removal efforts continue around these reefs with increasing rates of coral mortality and the loss of entire reef systems.

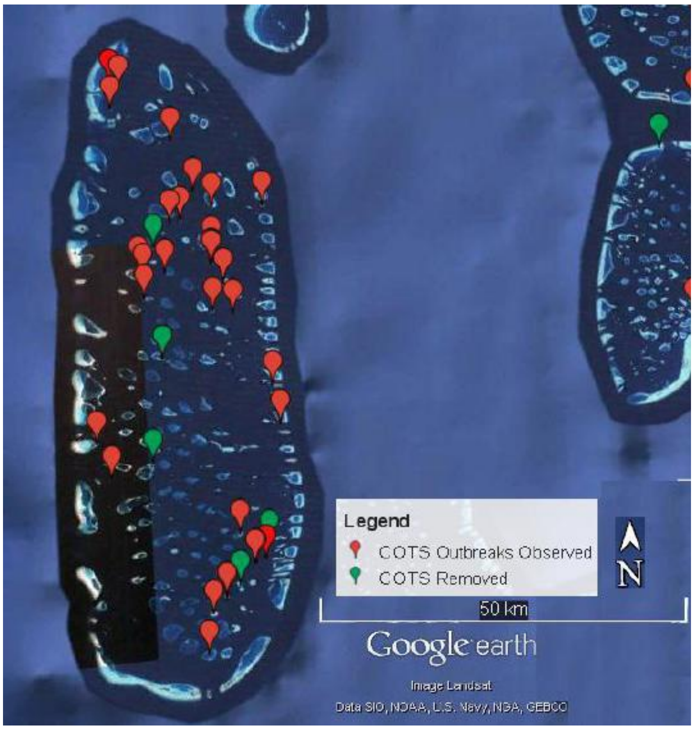
South Malé Atoll removal efforts

A large scale removal effort of COTS was undertaken on South Malé Atoll, on reefs near Dhigu, in October 2015. A total of 4,134 COTS were removed from these reefs over a one-week period. Extensive searches revealed three major infestations, while five other reefs had lower numbers, and COTS were absent from all other surrounding areas. Considerable damage was recorded on the reefs affected by COTS outbreaks, especially the fore reef north of Dhigu (Faanu Faru to Stage) and the lagoonal patch reef (Raaebundi). Coral losses were more localized off Veli and numerous healthy corals remained to the east and west of the outbreak. In areas with lower densities, the starfish had caused minimal damage. COTS were feeding on 31 species of corals, but were most common on the dominant and fastest growing taxa, especially table acroporids. The only exception was Maafushi Thilaa, where the starfish have been feeding for many months and were consuming the longer lived massive corals (e.g. *Porites*). Most COTS were medium-sized (28 cm), with very few large (max. 45 cm) and small (min. 18 cm) animals, indicating they had not been feeding on these reefs for an extended duration and they are similar in age.

Extensive surveys during January and April, 2016 illustrated the success of the removal. A total of 9 additional starfish have been seen on Stage and 2 on Veli Reef. At Raaebundi, the removal was never completed. Large numbers of animals were seen during repeat surveys and a secondary clean-up was undertaken on May 2/3 2016 involving removal of 430 animals. It is estimated that over 200 starfish remain on this reef.

Ari Atoll removal efforts

Staff at Down Under and Wave, W. Retreat & Spa on North Ari Atoll have been combatting an outbreak of COTS since September 2015. The starfish have spread primarily through the West House Reef, in the adjacent lagoon and also to Gaathafushi. On West House reef a total of 17,719 COTS have been removed over 7 months. An additional 729 starfish were removed from the lagoon and 1013 from Gaathafushi.



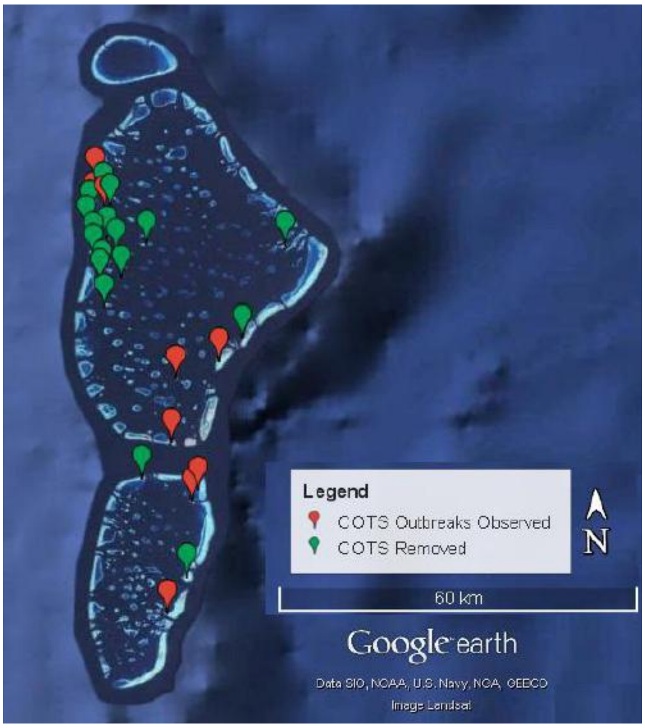


Fig. 34. Location of COTS outbreaks and COTS removals on Ari Atoll (left) and North and South Malé Atoll.

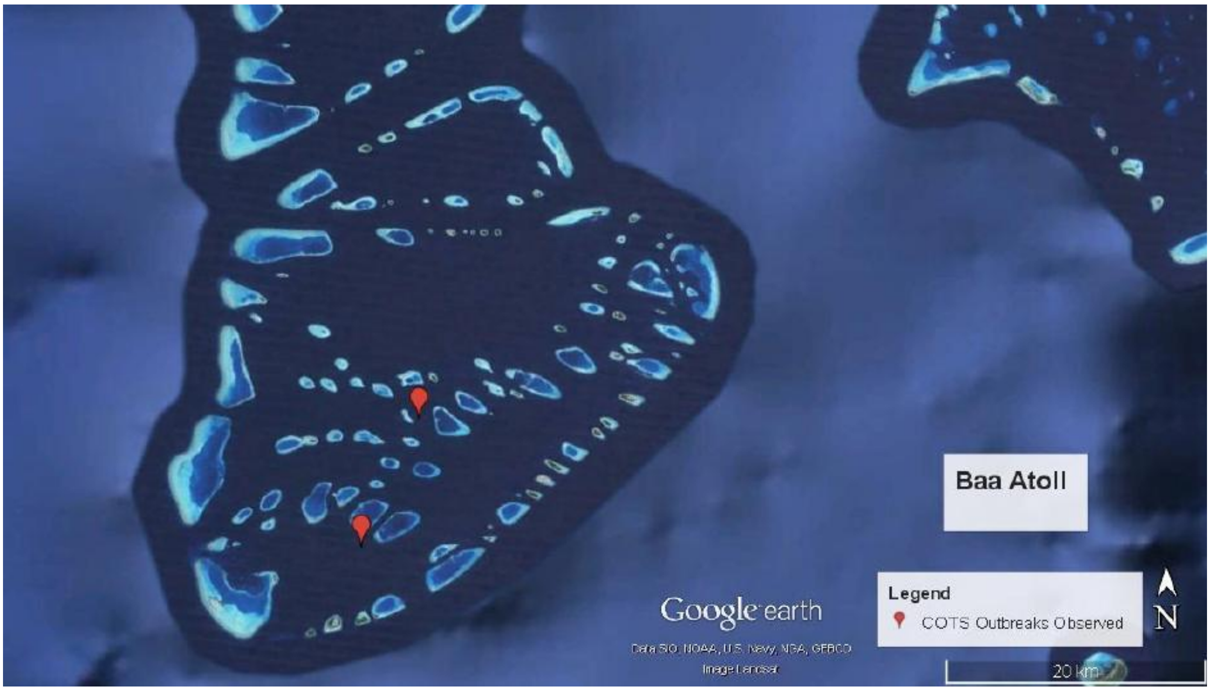


Fig. 35. COTS have been reported from two locations on Baa Atoll thus far.

Options for eradication of COTS

Major control programs have been implemented in the Indo-Pacific over the past three decades including Japan (Yamaguchi 1986), American Samoa, Cook Islands and Micronesia (Birkeland 1982), and the Great Barrier Reef (Zan and Weaver 1988), with smaller efforts undertaken in Fiji, Western Samoa, Vanuatu, Maldives, Hawaii and many other locations. During these attempts, as many as 15 million starfish have been killed. Culling of starfish has been successful if the outbreak is identified early and/or it is fairly small and contained within a restricted area. In contrast, macroscale efforts involving massive outbreaks of hundreds of thousands of COTS have proven unsuccessful, due to the scale and difficulty in eliminating all of the animals.

The main challenge with any chosen method is the successful location and elimination of all of the starfish. It is most critical that the areas with the densest populations are targeted, as these animals will have the highest successful rates of fertilization during spawning events (sperm and eggs are released in the water and fertilization is external) and they are causing the greatest and most rapid loss of corals. In the center of the outbreak animals can be easily seen feeding on the corals, and also in crevices next to white, recently eaten corals. It is impossible to eradicate every single crown-of-thorns starfish from reefs where they are in outbreak densities. Starfish are known to hide in holes and crevices and under corals, especially in areas of high wave exposure, emerging at night to feed. These can be difficult to see, especially for the animals that are similar in color to the substrate. However, with sufficient effort, small areas can be protected and their population size can be reduced to a less destructive level. The most effective means of removal requires elimination of as many animals as possible during daylight, followed by a revisit to the treated site on several occasions and if possible at night.

Approaches to control of populations

There are a large number of options available to control COTS populations, but the advantages and drawbacks must be seriously considered before implementing a particular method. The control mechanisms fall into five broad categories: collection and removal, collection and disposal in bags underwater, injection with poisons, maceration, and fencing off an area. Among the most important considerations is the available manpower and skill, cost, availability or access to equipment and supplies, potential harm to the environment, effectiveness, and human health risks. Regardless of the chosen method, a single clean-up effort on a heavily affected reef is unlikely to successfully eliminate these animals. It is critical to revisit the particular reef to remove/kill other animals that were missed on the first attempt. This also will allow the team to determine whether their injections, if used, were effective or a second treatment is required. Furthermore, animals from surrounding reef systems are known to migrate into regions that formerly had COTS, possibly due to pheromones released by the starfish or chemicals from the digested coral.

Table. 5. General methods used to eradicate crown of thorns starfish			
Method	**Approach**	**Advantage**	**Disadvantage**
Collection and Removal	Hooked rod, PVC pipe, BBQ tongs are used to extract COTS from on and under corals; animals placed in collection bags and removed from water. The starfish are dried on shore and then burnt or buried	Low cost; use as compost	Requires considerable manpower; requires disposal on land; potentially dangerous
Collection and Bagging	Animals collected and placed in bags that are secured to the reef	Low cost; no disposal; starfish sensitive to low oxygen levels and die quickly	Rotting starfish left on the reef; bags must be secured to avoid trash and release; starfish may spawn
Injection	Chemicals in a reservoir (sealed container) connected to an injection gun with a tube; The poison is injected with a plastic needle, a continuous injection system, or other injection system.	Efficient; less likely to cause injury; effective if the right chemical is used, correct needle size and animal is injected in the correct location	Some chemicals are toxic to other animals; potential for leakage if needle is too large or animal skin is torn; higher costs with supplies; may require removal from under coral to access animal
Maceration/cutting starfish into pieces	Starfish are damaged/macerated underwater with knives, hammer or other tools	Not recommended due to capabilities for regeneration	Time consuming; potential for spawning; May propagate and further spread of the starfish; can cause diver injury
Fencing	High value reefs have been enclosed with a fence to prevent migration of juvenile and adult COTS into an area	May preserve certain unique coral areas	Very expensive; not aesthetically pleasing; does not prevent settlement of larvae

Manual removal

Manual removal is the preferred method with the fewest negative consequences to the reef and the lowest cost, but it requires the most man power and has the highest potential for injury. Collection and removal of the animals is a time consuming process. It can result in minor injuries to collectors through contact with the venomous spines, unless proper precautions are taken. Care must also be taken to avoid damaging or breaking corals. We prefer a simple hollow PVC tube, approximately 50-75 cm long and 2.5-3 cm diameter, cut at a 45 degree angle, with animals placed into large mesh bags with an aluminum or stainless steel handle. Experienced divers could also easily implement this method using a wooden stick, PVC pipe, metal spear, boat hook or some other easily manipulated rod to remove the animals. Tongs and pointed spears will work, but care must be taken to avoid detaching arms and tearing the body. The collected animals can be placed in large canvas bags, rice/flour bags, mesh goodie bags or woven baskets. Mesh bags with a large opening and a stiff wire handle are preferable, as canvas bags and flour bags tend to compress underwater and are difficult to fill. The process can be facilitated by locating a small boat near the divers, with bags of starfish sent to the surface using ropes or lift bags. In shallow water, animals can be removed by snorkeling, but SCUBA is more effective and appears to have fewer injuries.

Fig. 36. Mesh bags filled with starfish are sent to the surface with an inflatable safety sausage. Tenders on the boat carefully lift the bag from the water onto the boat. The divers keep their distance from the bag to avoid accidental contact.

Provided that care is taken, it is possible to avoid significant injuries and animals can be extracted with minimal to no damage to the surrounding corals. Poor weather conditions (e.g. high surge), strong currents, high coral cover, high relief reef topography, and presence of animals in deep water can make collection more challenging.

Direct killing

While possible to kill animals by cutting them in four or more pieces with scissors or a knife, this is risky as 1) these animals are able to regenerate detached limbs and body parts; 2) this can also induce spawning; and 3) there is considerable risk of injury to divers. As an alternative, COTS can be collected and placed inside mesh bags which are left underwater. At high densities, the starfish will use up all of the oxygen because they are not able to move. They tend to die within 2-3 days (Chugoku-Shikoku Regional Environmental Office 2012).

Fig. 37. During severe outbreaks, starfish have been collected and placed into bags that are secured onto the bottom. The animals will die within a few days, but care must be taken to ensure the bags do not open and they are removed from the water. If this is attempted during the breeding season, they may spawn, setting the stage for a future outbreak.

Disposal of collected animals

The most common and best method to dispose of COTS is on land, where they can be composted, incinerated or buried. COTS should be buried onshore, above high tide to ensure they will not have further contact with the sea. They also must be placed deep enough such that the spines are not easily exposed. When exposed to stress (such as spearing or maceration), COTS may attempt to spawn. It is imperative to remove COTs from the water as quickly as possible, and prevent re-immersion of collected COTs, as they may release gametes in response to the stress. When the starfish are removed from the water, the body surface ruptures and the body fluid leaks out, causing the body to collapse and flatten. They are capable of recovering their shape and will survive if returned to the water too soon after collection. However, large aggregations of COTS, placed into plastic buckets without any water will die very quickly (one day) as they run out of oxygen and begin decomposing.

Burial on land has the additional benefit that:
1) Dead COTS are not left in the sea to decompose;
2) Accurate data on size and numbers eradicated can be obtained; and
3) Photographs and documentation of the effort can be used as an outreach mechanism.

Fig. 38. Burial of COTS above high water.

Fig. 39. One of the advantages of collecting the animals is that data on the abundance and size can be taken and samples for genetic analysis can be obtained.

Table 6. Chemicals used in injection guns to eradicate crown of thorns starfish		
Chemical	**Advantage**	**Disadvantage**
Bile Salts	The most effective mechanisms to kill COTS currently available. Requires a low dose and mortality is rapid	Can be difficult to access through international customs; more expensive than other chemicals; must obtain high quality bile salts
Vinegar	Effective, if volume is correct and animal is injected using a small needle between the oral disc and the arm ; readily available and cheap; does not require dilution or mixing	High concentrations may locally alter pH; may require multiple injections; not yet scientifically proven in the field
Acetic Acid	Generally not toxic when diluted	High concentrations may locally alter pH; can cause irritations and burns to the skin when diluting
Sodium bisulfate	Effective if correct dose is used; inexpensive; safe handling and safe for environment; cheap ($4/kg)	May require 10-15 injections
Copper sulfate	Effective, inexpensive and widely available. Disperses in highly flushed areas	Heavy metal pollutant that bioaccumulates in plants and animals. more toxic than biodegradable alternatives
Formalin	Will kill starfish at right concentration	Damage injection guns, human health risk; proper dosage difficult to determine; may require multiple injections
Ammonia	Unknown	Unknown
Hydrochloric acid	Will kill starfish at right concentration	Damage injection guns, human health risk; proper dosage difficult to determine
Agar-like protein matrix	Reported to increase Vibrio (bacteria) populations in starfish, which kill the animals	Potentially hazardous due to the propagation of harmful bacteria
Bleach, petroleum, dish soap	None	Toxic to surrounding organisms and reef; not effective

Injection with chemicals

The most efficient method to kill COTS, with the least likelihood of injury involves injection of poisons using a continuous syringe system, with a reusable syringe, needle, container, and hose. The syringe system should be made of plastic, stainless steel and other non-corrosive materials. Needles should be fairly long to avoid contact with the animals (10-20 cm) and with a small inner diameter (e.g. 2 mm). It is imperative that the animal is injected in the central disc, away from the mouth, near the proximal end of the arms.

Fig. 40. A starfish is injected near the proximal end of the arms in the vicinity of the digestive and reproductive glands, adjacent to the oral disc. Injection in the central disc results in variable mortality depending on which organ the needle penetrates. The chemicals are discharged if injected into the cardiac stomach or near the mouth.

Bile salts

A single injection of diluted bile salts (4 g/l Bile Salts #3) has been found to kill *A. planci* within 24 hours (Rivera-Posada et al. 2013, 2014). Laboratory and field studies have shown that the use of bile salts, including solutions that are dispersed into the water and ejected from the animals have no effect on the habitat and other organisms. The use of bile salts on *A. planci* is restricted by permits in Australia and the USA, and the salts can be subject to quarantine regulations when transported across borders. The salts are still a more expensive option than other injection chemicals below.

Bile is a substance composed of fatty acids, bile acids, inorganic salts, sulfates, bile pigments, cholesterol, mucin, lecithin, glycuronicacids, porphyrins, and urea that is produced by vertebrates to aid in the digestion of lipids (Murray et al., 1995). Two types of bile, used to kill starfish are Oxgall and Bile Salts No. 3 which are both collected from bovine after slaughter. Oxgall is natural dehydrated fresh bile directly extracted from the bovine gall bladder while Bile Salts No. 3 is a purified mixture containing sodium cholate and sodium deoxycholate that is used in agar as an inhibitory agent to prevent bacterial contamination. Bile salts #3 have been found to be 100% effective, while Oxgall is up to 80% effective and in some trials the starfish recovered after 7 days.

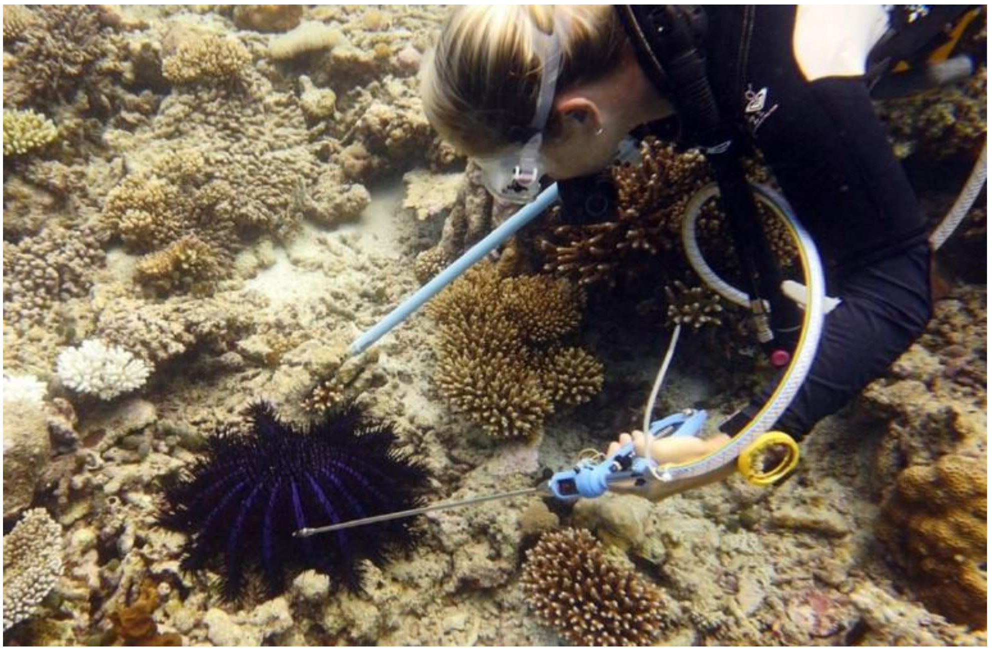


Fig. 41. Injecting a COTS with bile salts using continuous injection system.

Vinegar

Common household vinegar, used full strength (without dilution), is the cheapest and most readily available chemical that has been found to kill COTS. In Australia a single injection of 25 ml vinegar induced functional mortality in 24 h and 100 % mortality in 48 hours, while two injections of 15 ml also killed starfish (Boström-Einarsson and Rivera-Posada 2015). In experimental laboratory trials, injections were administered using a syringe with a 16-gauge stainless steel needle. Previous tests showed lower rates of mortality but these involved use of larger needle sizes (2 and 4 mm inner diameter) rather than the 29- and 16-gauge needles (0.2 and 1.2 mm, respectively). It is thought that the larger holes may allow small quantities of vinegar to leak through the multiple injection holes (Yamamoto and Otsuka 2013).

Starfish injected with vinegar displayed a matting of the spines in the first few hours post-injection, followed by immobility and tissue necrosis. Because echinoderms are poor acid-base regulators, it is thought that the decrease in pH from the vinegar induced acidosis, causing tissue walls to become necrotic.

Acetic acid

An approach to kill starfish, widely used in Japan, involves injection with acetic acid. Acetic acid is the main acid component of vinegar. A solution can be made from 90% acetic acid diluted by in fresh water or seawater to 15-18% concentration. Injection of 10 ml of 15 to 18% dilute acetic acid aqueous solution is effective at killing starfish, but it may require multiple injections. Lower concentrations (10%) do not kill all the animals. The starfish should be injected on the perimeter of the oral disc, away from the central area and not in the arms, with 10ml divided equally in four locations, evenly spaced apart. A 500 ml bottle of diluted acetic acid can kill 30-50 COTS (10-15 ml/individual) (Kuroshio Biological Research Foundation 2012).

This chemical appears quite harmless to the environment. In experimental studies, starfish were injected and killed with acetic acid, and left in aquaria with corals, molluscs, sea urchins and fish for 5 days, with no ill effects seen on other organisms.

Sodium bisulfate

A highly successful chemical, widely used in Australia to cull COTS, is sodium bisulfate ($Na(SO_4)_2$ a dry acid. Sodium bisulfate is a biodegradable chemical considered harmless to reef organisms. In Australia, during 2001, the Commonwealth and Queensland Governments spent AUD 2 million to support a two-year, industry-run COTS control program for Cairns, Townsville and Whitsunday areas. This was repeated last year: over 60,000 animals were eliminated through sodium bisulfate injections, at a cost of AUD 1.43 million. Australia has applied this approach in favor of copper sulfate to control recent outbreaks, due to the less toxic nature of the chemical. They also use injection instead of collection because of the large expanse of reef habitat and extremely high number of starfish.

Sodium bisulfate is about USD 4 per kilogram. Approximately 1/3 cup (140 grams) of the chemical is added to each liter of seawater, and one liter of the solution is sufficient to kill around 40 adult starfish. As the solution is colorless and difficult to see underwater, addition of food coloring is recommended to ensure it remains within the starfish and is not excreted. The mixture can be injected using a standard agricultural injection gun. A *DuPont Veldspar Spot Gun* fitted with a longer 50 cm needle and 5-litre plastic bladder has been widely used in Australia. To inject the starfish, set the dose meter on the gun to 2 ml. Push the needle under the skin of the central disk of the starfish and pull the trigger. Lassig (1995) recommends three injections.

Copper sulfate

During the 1980s and 1990s, the most widely used chemical was copper sulfate (CuSo). This approach was first tested on the GBR in 1986. Divers injected starfish with 5-10 ml of saturated copper sulfate solution using "*Dupont*" agricultural injection guns. In two weeks, 53 divers injected over 3000 starfish at a cost of AUD 35 per starfish (Johnson et al. 1990). Other larger scale efforts in Australia, in areas with higher numbers of starfish, have been accomplished at a cost of AUD 0.50-7.00 per starfish. Birkeland and Lucas (1990) concluded that a maximum of 130 starfish could be injected per hour by two divers at the site of an outbreak, with numbers declining as population size declines. The costs of this type of program was estimated to range from about AUD 500,000 for an outbreak consisting of 100,000 COTS, with an inverse relationship between density of starfish and cost per injection (Birkeland and Lucas 1990).

The main disadvantages of injection with copper sulfate or other chemicals is that spawning may be induced as the animals are dying, which could be setting the stage for a future outbreak, 3 to 4 years later. Chemicals such as copper sulfate are also extremely toxic to other animals and to the divers administering the chemical. High levels of copper sulfate can induce bleaching and mortality of corals within the vicinity of the starfish and it is bioaccumulated in giant clams, algae and other sedentary organisms. Approximately 1 kg of copper sulfate is required to kill 100 animals (Gladstone 1990). Today, divers typically inject about 10 ml of a saturated solution into each starfish.

Other chemicals

Other chemicals used include ammonia, Clorox® bleach and formalin. These have the same concerns as copper sulfate, although they are less toxic as these chemicals are biodegradable. Unfortunately, they are also less effective at killing starfish (Zann 1992).

Injection with agar

A new method to eliminate animals tested on the Great Barrier Reef in Australia in 2013 involved the injection of a common gelatin-like media high in animal proteins (agar) which is commonly used to culture bacteria in the laboratory. Starfish are known to contain small populations of pathogenic *Vibrio* bacteria. While these bacteria are normally kept in check by other host bacterial populations, the sudden introduction of a food source for the bacteria (agar) can cause an explosion in the population size of the *Vibrio* bacteria, which may lead to infection and death in the host starfish. The main disadvantage of this approach is the potential to flood the coral reef environment with unusually large populations of *Vibrio* bacteria, which may have the negative consequence of causing infections in corals and other organisms.

Crown of thorns starfish first aid

COTS are covered in sharp, venomous spines of about 5 cm in length that are prone to breaking off in wounds. It is very important to be careful when working with these starfish. While it is possible to carefully handle starfish without injury (the underside of the animal has no spines, only tube feet), this is not recommended as each arm of a COTS has 13 to 16 sharp spines and these can break off in the skin and penetrate through gloves and wet suits.

Minimize the likelihood of injuries when collecting COTS

1. **Wear protective gear**
   Wear a wetsuit, booties and gloves. Special gloves used by doctors to reduce likelihood of being stabbed by a needle will reduce injuries but COTS spines can still penetrate the glove.

2. **Avoid contact with COTS**
   Only pick up COTS using a bar, tongs or some other device, keeping your body away from the spines.

3. **Be aware of your surroundings**
   Control your buoyancy and monitor your surroundings to avoid contact with the reef and touching COTS on corals and/or on the reef, in your collecting bag, or in the collecting bag of your dive buddy. Special care must be taken when transporting full bags to the surface and when retrieving and emptying bags containing COTS.

As a precaution, remove all jewelry (rings and bracelets) from your fingers and arms before collecting COTS, in the event you do get pricked by a spine and swelling occurs.

Fig. 42. Small COTS can be handled if the aboral surface is avoided. The underside (oral surface) is not covered in spines.

Fig. 43. Injuries from the spines are very likely when emptying the bags into containers for disposal. The crew is using PVC pipes and thick wire to get the starfish out of the bags to protect their arms and hands, but they are still at risk of injury because they are not wearing any protection on their feet.

First aid kits

First aid supplies should include:

- tweezers and sewing needles (to remove spines)
- isopropyl alcohol and hydrogen peroxide (to clean wounds)
- gauze pads, bandages, adhesive tape (to cover injuries)
- iodine and antibiotic cream (reduce potential for infection)
- *EpiPen* (use only in the event of a severe reaction; such as shock. Seek instructions from a medical practitioner for dosage and administration methodology)
- antibiotics (use only if a serious infection develops; seek a medical practitioner for advice).

Consequences of an injury

Penetration by the spines is painful and can lead to bacterial infection. The pain is usually immediate, very severe and may persist for a few hours. It may be associated with significant bleeding and swelling. Within minutes, the puncture wound causes acute burning and the skin around the wound may turn blue. Four to six hours later, the area becomes red and swollen. Acute pain usually disappears several hours after the injury, but the puncture site may still remain tender. After 24 hours, the area around the wound is usually numb, but may still be red and extremely itchy. Tissue swelling may persist for a week. If the spines remain embedded, tenderness of the wound, and peeling of skin may last for a month or more.

More severe reactions or envenomations due to multiple injections can include numbness, tingling, weakness, nausea, vomiting, joint aches, headaches, cough, and in rare cases paralysis. Vomiting may commence about one hour after the injury and recur every few hours for the next few days. Localized allergic reactions may also occur in susceptible individuals.

Injury occurs from the spine and associated toxic compounds (called asterosaponins, a group of chemicals related to steroids) which are deposited in the tissues on penetration. *A. planci* has no mechanism for injecting the toxin; as the spines perforate tissue of a predator or unwary person, starfish tissue containing the saponins is also deposited in the wound.

Fig. 44. Stages in a COTS spine injury. Penetration of skin by spines causes swelling and redness within 24 hours and swelling may continue to increase for several days (left). Skin surrounding affected area may become discolored and blister (center left), wound may fill up with liquid and pus, eventually opening up (center right). Skin surrounding the injury will peel for several weeks (right).

Treatment of injuries

Treatment methods include cleaning the area, removing any spines if possible, antibiotic cream, and oral antibiotics if infection occurs.

- Use tweezers to remove any spines in the wound because symptoms may not resolve until all spines are removed. Scrub the wound with soap and water followed by extensive rinsing with fresh water.
- Immerse the affected area in fresh water as hot as the person can tolerate for 30 to 90 minutes. Repeat as necessary to control pain (water temperature should not exceed 140° F or 60° C). Some stings may require an injected local anesthetic for pain relief.
- See a doctor immediately if severe reactions begin to occur including, numbness, weakness, nausea, vomiting, joint aches, headaches, cough, and in rare cases paralysis.
- Minor wounds, abrasions and scratches may occur due to contact with coral skeletons while collecting COTS. These should be flushed gently with alcohol or hydrogen peroxide followed by water. The scrape should be covered with a sterile dressing and wrapped in a bandage. Iodine and/or hydrocortisone can be placed on the abrasion.
- Do not cover the wound with tape or any other type of occlusive dressing as it may increase the risk of an infection.
- You can apply hydrocortisone cream 2 to 3 times daily to reduce itching. Discontinue immediately if any signs of infection appear.
- Oral antibiotics are recommended if an infection develops.

Sources of equipment and supplies

Continuous injection systems

Association of Marine Park Tourism Operators (AMCO) (www.ampto.com.au) out of Australia sells needles, guns and high quality bile salts. Current prices[1] are AUD 94.25 for 12 needles; AUD 231 for a gun; and AUD 128.70 for 1 bag (0.5 kg) bile salts

Fig. 45. Various equipment available at http://www.ampto.com.au.

There are numerous lower cost options, but the needles and reservoir must be purchased separately. Avoid continuous injection systems that have a lot of metal parts, as these may corrode. One complication with these guns is that the needle may be excessively long, causing the user to overshoot the toxin, releasing it outside the starfish body.

Two examples of plastic syringes are below:

Simcro Ltd. of New Zealand manufactures the *Variable Syringe STV5*, a V-grip vaccinator with a 4.7mm tube spigot, clear polycarbonate barrel and metal tip with standard half-turn Luer-lock needle attachment. Available at http://www.pbsanimalhealth.com/details/Simcro-STV-Syringe/550-56.html for USD 28.67[1]. This does not include tubing, needles or reservoir.

[1] Prices accurate as of April 2016

Prima Tech® Economy Line Syringes are economy priced auto fill syringes available at QC supply (http://www.qcsupply.com/primatech-autofill-syringe-economy.html) for USD 22.00[1].

Spotguns

There are numerous brands of spot guns which are used for injection of herbicides and insecticides. These typically come with the hand gun, draw-off tube and backpack. They have a calibration dial allowing you to adjust the amount of toxin injected into the COTS. http://www.specialistsales.com.au/specialist-sales/products/4ml-spot-gun-soil-stem-injector-for-use-with-hexazinone-velpar.

One widely reported for use in killing COTS is the metal DuPont™ Velpar® Spotgun®. This gun may be problematic as it creates large holes in the starfish which allows the chemicals to leak out of the animal.

Protection

HexArmor® SharpsMaster II® 9014 needle puncture resistant gloves. http://www.safetycompany.com/work-gloves/hexarmor-gloves/hexarmor-9014-sharpsmaster-ii-needle-puncture-resistant-gloves/?gclid=CLK4wZSlyMsCFVUkgQodrx4Khw USD 36.00[1]

Crown of thorns references

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Appendix 1

Resorts, dive centers and organizations providing information on crown of thorns starfish.

Resort or Organization
Aadan Beach House - Dhigurah, Maldives
Anantara Resorts; South Malé and Baa Atoll
Aquafanatics
Best Dives Centara
Boutique Beach All Inclusive Diving Hotel
Dive Desk
Diveoceanus Holiday Island Resort & Spa
Diveoceanus Sun Island Resort & Spa
Diver's Lodge Maldives
Down Under and Wave/W Retreat and Spa
Eco Islanders Maldives
Extreme Maldives
Faculty of Marine Studies, Villa College
Four Seasons Kuda Huraa
Gili Lankanfushi
Immersion & Glide, Velassaru, South Malé
Island Divers
Kandolhu Island Resort
Kurumba Maldives
Liquid Salt Divers
Maldives Passions
Manta Trust
Marine Research Centre Maldives
One & Only Reethi Rah
Per Aquum Niyama Dhaalu Atoll
Pro Divers Lily Beach Resort and Spa
Project "Damage Control"
Save the Beach Maldives
Scuba Divine Maldives / Divine Sports
Sheraton Maldives Full Moon Resort & Spa
Summer Island Resort
Taj Vivanta Resort