Mitigating the impacts of an *Acanthaster planci* (crown-of-thorns starfish, COTS) outbreak on coral reefs in Aitutaki, Cook Islands

May, 2013

A report prepared for the Government of the Cook Islands,
Aitutaki Council and Mayor, and Concerned Dive Operators,
Hotel Owners and other Stakeholders

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Khaled bin Sultan Living Oceans Foundation Publication # 9

Front cover: Three crown of thorns starfish eating coral on a shallow reef in Aitutaki, Cook Islands. Photo by Ken Marks.

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Summary

The impact: Outer reef (fore reef) communities surrounding Aitutaki have been impacted by a severe outbreak of *Acanthaster planci* crown of thorns seastars (COTS). This outbreak was reported to have started at least a year ago, and is still ongoing. Coral cover has declined substantially throughout the fore reef as a result of COTS predation, with some additional damage possibly attributed to Cyclone Pat. Coral cover has declined by 80-99.9% throughout deep (15-30 m) fore reef sites surrounding the atoll, with <0.05% live cover remaining in most locations. Similar declines were noted at shallower depths (3-15 m) off the west, north, northeast and south sides. In these degraded areas, a very low number of intact, undamaged corals remain. Survivors are predominantly coral taxon that are not preferred food sources: deep populations of plating/foliaceous *Porites rus* were mostly intact; low numbers of plating/columnar *Coscinarea*, finger corals in the genus *Acropora* and large-branched cauliflower corals in the genus *Pocillopora* remained. The only healthy fore reef communities with high diversity coral populations identified during these surveys were located along an 8.2 km stretch of reef off the southeast coast, in shallow water (3-10 m) (Fig.1). Lagoonal reefs have been unaffected by these disturbances and are still mostly in good shape. What is most worrisome is that the shallow fore reef environments on the southeast coast, with the best remaining coral, currently have the largest populations of starfish and the highest number of recently eaten (white) coral skeletons.

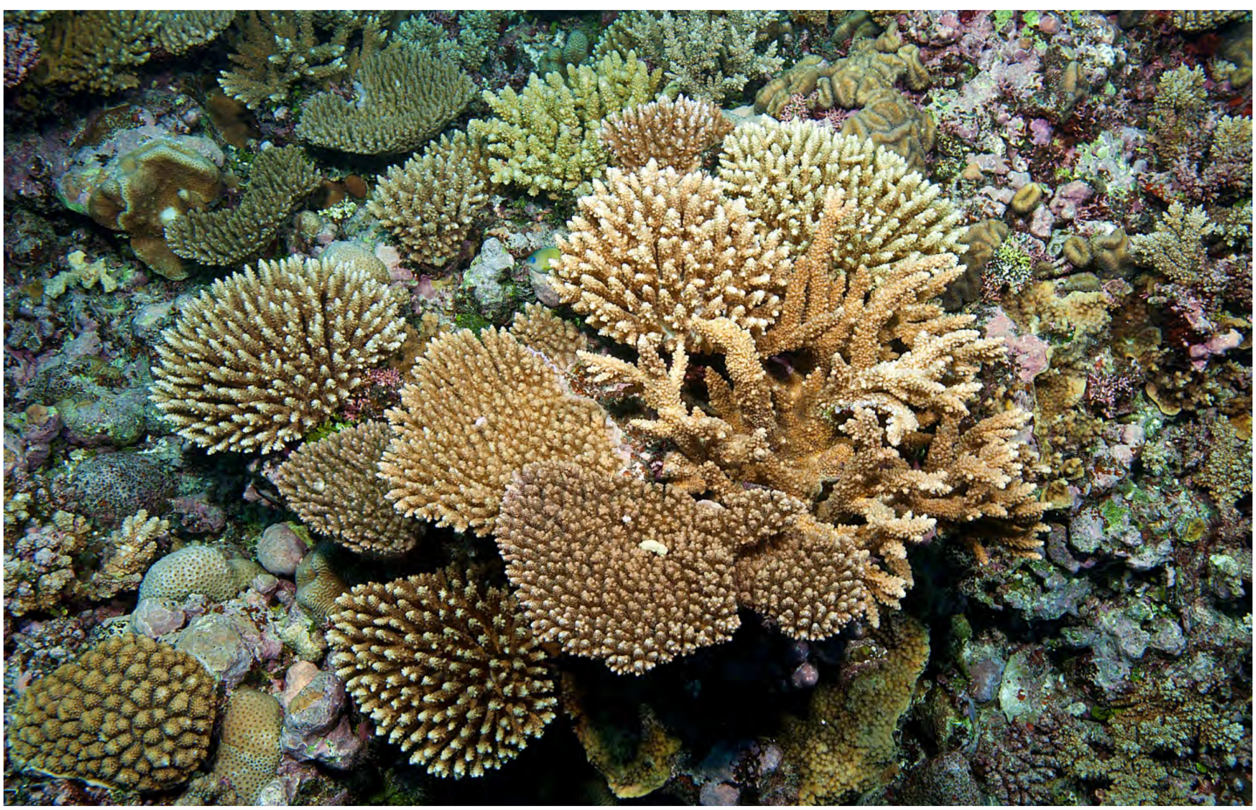

Fig. 1. An undamaged, healthy *Acropora* community in shallow water (8 m) at CIAT-22.

During the present surveys, COTS were observed on all fore reef sites, but were absent from lagoonal sites. The numbers of starfish, size of animals, and condition of animals varied depending on the availability of food, depth and location, with the highest numbers in the southeast and lowest in the west, near the channel. Sites with healthy coral populations corresponded to sites having the highest prevalence of COTS (aggregations contained 1-2 to 10 starfish/m^2) and the most rapid current and ongoing losses of coral. Smaller populations of starfish remain in degraded areas, occurring at all depths. These animals continue feeding on surviving corals, including less preferred stony coral species, small tissue remnants remaining on certain preferred species, and new recruits. Moderate to large populations of starfish are also are targeting soft corals and encrusting acroporids in the shallow, exposed reef crest and fore reef environments (2-3 m depth). The largest starfish and highest densities were found in areas with the best remaining coral populations; animals in other locations included large animals and smaller, weaker animals, many of which were missing arms.

The corals: Coral cover on fore reef communities (3-30 m depth) off the west and northeast has declined below 0.1% in most locations. These communities have very few remaining intact corals and low numbers of new recruits. The only survivors are the non-preferred species (several reefs had large populations of *Porites rus* below 15 m depth; Fig. 2) and small (< 5 cm diameter) tissue remnants on larger skeletons (Fig. 3). In some sites, shallow areas (1-3 m) had scattered live corals (2-10% live coral cover, predominantly encrusting acroporids), dispersed among older dead corals, recently killed (white) corals, and soft corals. Large expanses of pink, crustose coralline algae (CCA) encrusted coral skeletons and reef substrate from 1-20 m depth.

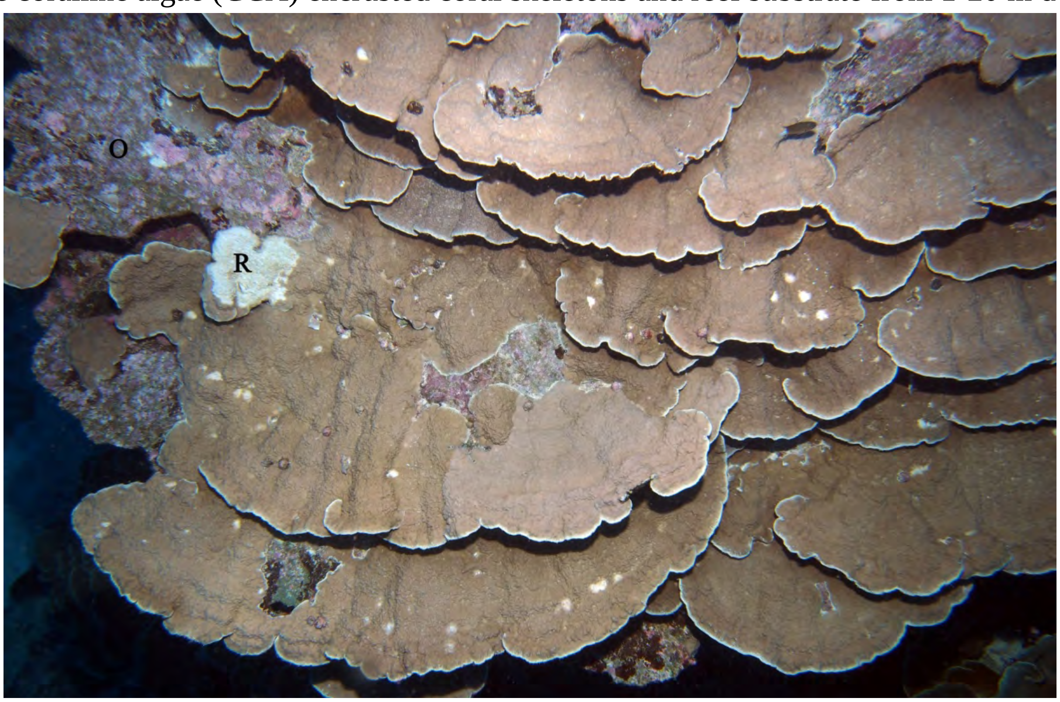

Fig. 2. *Porites rus* with old mortality (O) and a recent lesion (R) from COTS predation.

Coral colonies off the east and south coast were mostly dead (< 2% intact colonies remained) from 12-30 m depth. The survivors coral consisted of 1) small living tissue remnants (most < 5 cm diameter) on larger skeletons of important frame-building massive corals (*Goniastrea, Favia Leptoria,* and *Porites*), (Fig. 3); 2) isolated colonies (<1 colony per 10 m^2 area) of less preferred species (predominantly *Coscinarea*, digitate corals in the *Acropora humilis* group, and large erect "elephant ear" or cauliflower corals of the species *Pocillopora eydouxi* and *P. verrucosa*), and 3) very low numbers of recruits (<1/m^2). Dead, algal-encrusted skeletons of branching, tabular, submassive, and massive corals, in growth position, formed a prominent band from 8-15 m depth (Fig. 4).

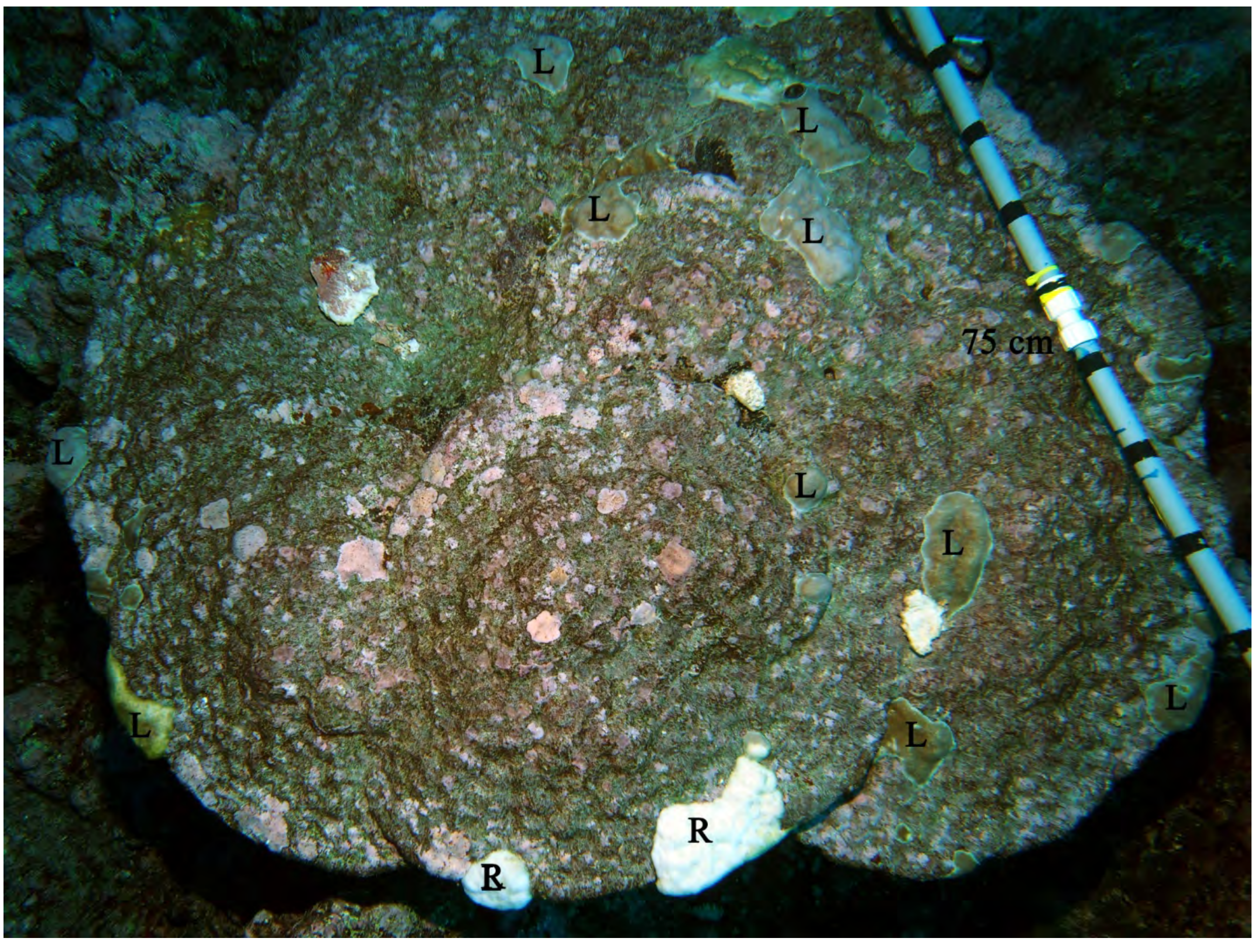

Fig. 3. *Porites lobata* in growth position. The coral was mostly eaten by crown of thorns starfish (COTS) weeks to months earlier. A single COTS had returned to consume small remaining live tissue remnants on this coral (R). Living, undamaged tissue is labeled "L". The coral is about 1 m X 75 cm in size.

Fig. 4. Survey site CIAT-22, at 12 m depth. Most corals are recently dead, in growth position, and skeletons are colonized by diatoms, cyanobacteria, filamentous algae and crustose coralline algae.

In some areas, living coral colonies, predominantly encrusting and digitate acroporids, were seen on the tops of the spurs in very shallow water (1-3 m). Colonies on the lower edge (2-3m) of this zone were dead and covered with filamentous algae, or partially dead with patches of white, recently denuded skeletal surfaces (Fig. 5).

Fig. 5. Feeding scar on an encrusting digitate colony of *Acropora* left by successive predation events. The white area (R) was eaten within the last 1-2 days. To the left of this is transitional mortality (T); this and was consumed by COTS within the last week to 10 days. The right side shows old mortality (O), consumed by COTS a few weeks earlier, and colonized by filamentous algae. The top of the colony is still live (L).

Shallow fore reef sites (3-8 m) along an 8.2 km stretch, beginning midway along the east coast and continuing to the southeastern tip of the atoll (located between CIATS-06 and CIAT-21), still contained thriving, high diversity coral communities. These communities were dominated by a high diversity and wide variety of growth forms of *Acropora*, as well as *Pocillopora*, *Goniastrea*, *Lobophyllia*, *Favia*, *Montastraea*, *Echinopora*, *Leptoria*, *Hydnophora* and many other species of branching, encrusting, massive, plating and submassive corals. Unfortunately, these communities also had the highest number of COTS, and live coral was intermixed with large patches of white, recently eaten corals (Fig. 6).

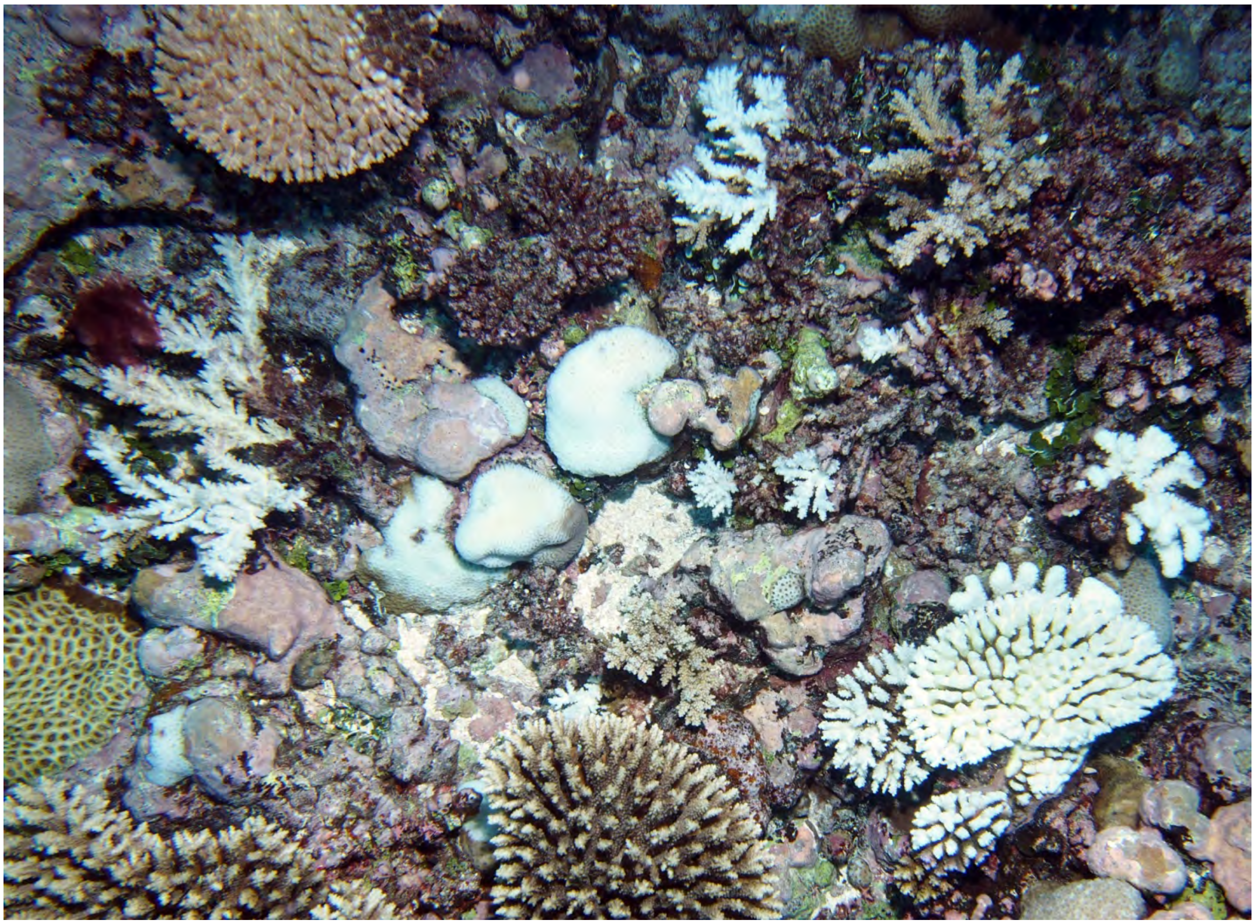

Fig. 6. Typical mortality within the high diversity shallow reef sites at 8 m depth on the east coast. All of the white skeletons are the remains of corals consumed by COTS within the last few days.

Lagoonal reefs located close to shore, at the northwestern end of the atoll, and offshore coral bommies, were in relatively good condition (an unrelated recent die-off of some corals was noted in shallow nearshore sites). No COTS were found, and no signs of recent (white) mortality from COTS were noted.

Recovery potential: In general, recovery from outbreaks of COTS has taken 12-15 years for reefs dominated by fast growing branching corals (Endean and Cameron 1985; Colgan 1987).

During more recent outbreaks, such as that observed in Society Islands and Austral Islands, French Polynesia (Bruckner, GRE), 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.

An effort to remove crown of thorns seastar populations from shallow fore reef communities in Aitutaki will help protect remaining healthy coral populations, and can facilitate regeneration of damaged reefs. The areas with surviving corals on the east coast contain a high diversity of corals, including most species that formerly occurred in other locations and depths on the fore reefs of Aitutaki. These corals could provide local sources of coral larvae that could reseed degraded areas.

Recently killed corals are rapidly colonized by filamentous algae and cyanobacteria, but over time, this is replaced by crustose coralline algae (CCA). The surrounding substrate, as well as degraded areas that no longer have high numbers of intact coral skeletons, also have a high cover of a thick, encrusting red coralline algae (Fig. 7). Reef substrates also have minimal amounts of filamentous turf algae and macroalgae, with exception of a few areas identified with high numbers of territorial damselfish. The lack of macroalgae and high cover of CCA are indicative of high levels of herbivory and minimal input of nutrients. Together, these factors suggest that the substrate is of high quality, and is conducive to the recruitment of new corals.

Fig. 7. A typical underwater scene on a shallow fore reef off the west coast. Intact skeletons with signs of partial and total old mortality and one coral with recent mortality from crown of thorns (COTS) predation are evident. The reef substrate and dead corals are colonized by crustose coralline algae (CCA) and turf algae.

In addition to a high potential for recolonization of barren reef substrates, many of the larger massive frame building corals, including long-lived *Porites* colonies, have tissue remnants that remain healthy. This is a critical component to facilitate more rapid recovery, as these corals tend to grow much slower than the branching acroporids and they exhibit lower levels of recruitment. These remnants, in absence of predation by COTS, are also likely to exhibit higher survival rates than smaller coral recruits. Alarmingly, at current densities of starfish, many of these continue to be preyed upon by crown of thorns seastars. Culling of starfish populations will ensure the remnants can survive and begin to resheet over older denuded skeletons. Ultimately, the surviving remnants can jump start the recovery process in absence of crown of thorns predation have higher potential for survival than recruits of the same species.

Finally, the absence of COTS within lagoonal areas is very critical to future persistence and recovery of the reefs, as many of the species found here also occur on the fore reef (Fig. 8), and thus they can be another source of seed stock for fore reef communities. Healthy lagoonal reefs are critical to the survival of other key reef species as well, including herbivorous parrotfish that use these areas as nursery habitats.

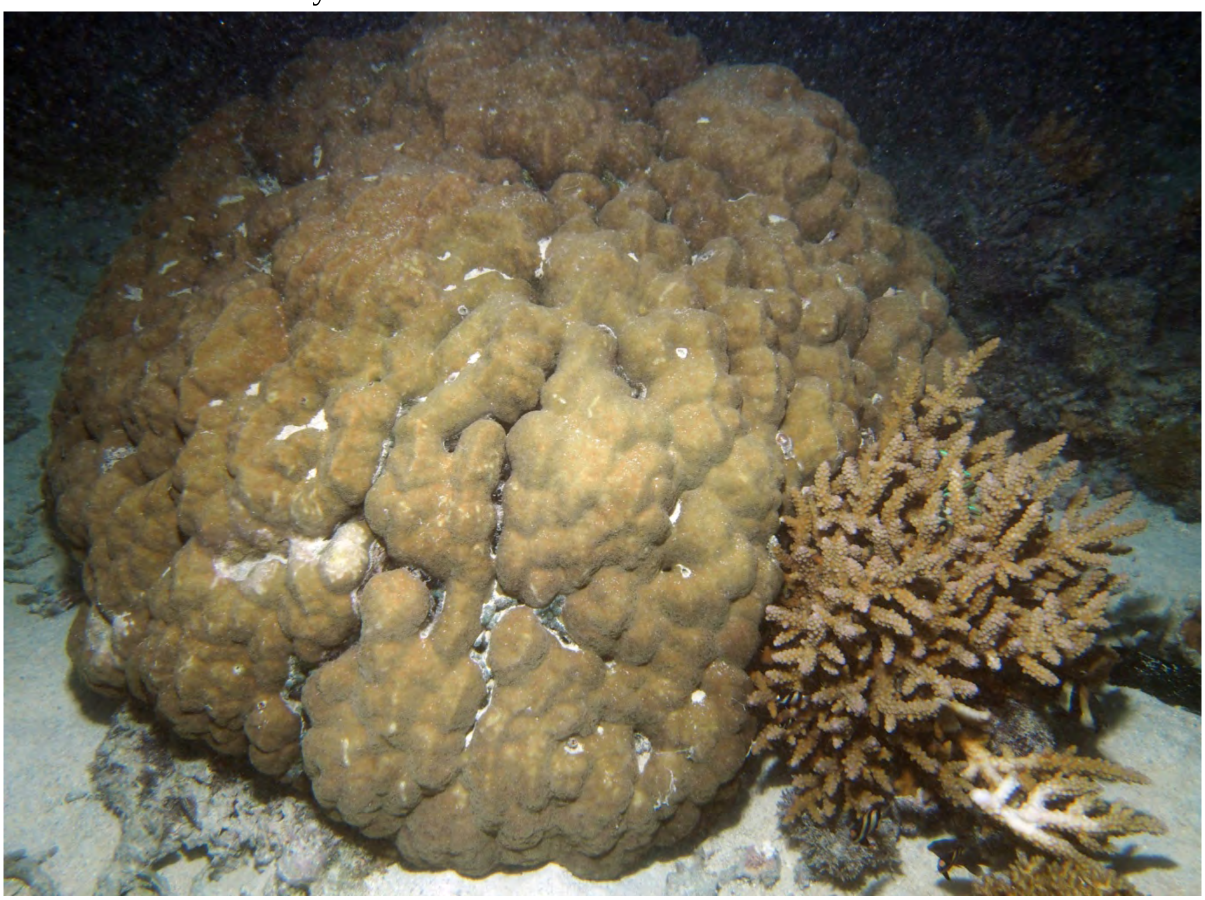

Fig. 8. Large (1.2 m diameter) *Porites lobata* colony in excellent condition in the lagoon. This long lived coral is estimated to be more than 100 years old and has the potential to contribute high numbers of gametes during spawning events.

Background

Acanthaster planci (COTS) are a normal inhabitant of coral reefs found throughout the Indo-Pacific and Red Sea. These starfish feed exclusively on corals ("facultative corallivores") and are the most influential corallivore in the Pacific (Birkeland 1989). They serve as a key food source for certain gastropods such as the helmet snail and trumpet triton (*Charonia;* Fig. 9). Certain invertivores (e.g. species of wrasse, triggerfish, pufferfish and filefish) also feed on juvenile and adult COTS (Ormond et al. 1973), certain polychaetes, shrimp and crabs will feed on juveniles and several species of planktivorous fish that feed on COTS larvae. Provided the ecosystem is intact, and water quality is high, COTS densities are usually kept low. These animals tend to feed on the fastest growing corals with the highest levels of replacement (e.g. *Acropora* and *Montipora*) and avoid slower growing massive corals such as *Porites* (Moran 1986; Birkeland and Lucas 1990; De'ath and Moran 1997; Pratchett 2001). Because of these two factors, their overall impact to reefs is usually minimal, if starfish numbers are low.

Fig. 9. Two trumpet tritons (*Charonia tritonis*) feeding on a crown of thorns sea star off the west coast of Aitutaki.

Crown of thorns starfish populations typically display cyclic oscillations. They exhibit extended (10-30 year) periods of low-densities of animals distributed throughout large expanses of reef habitats, followed by brief episodes of unsustainably high densities. Certain conditions can promote an unnatural population explosion of these species, many of which can be linked to man's activities (Potts 1981). The resulting consequences of a population explosion of these corallivores can be catastrophic.

Abnormal starfish abundances can be due to two key factors - 1) "predator removal hypothesis" which states that more juveniles survive to adults due to the removal of the organisms that normally feed on juveniles and adults (e.g. trumpet triton and certain fishes especially the Napoleon Wrasse) through overharvesting by man (Birkeland and Lucas 1990); or 2) "terrestrial run-off hypothesis" where heavy terrestrial runoff results in high sediment and nutrient loads and abnormal amounts of phytoplankton which provide the food needed to sustain larger populations of larvae (Faure 1989; Brodie et al. 2005). This latter condition is believed to be the most critical parameter, and it may be due to a period of unusually high runoff associated with flood rains combined with improper land clearing and high levels of nutrients from sewage and agricultural run-off. 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 possible that high numbers of larvae from an upstream source could recruit onto reefs off a low atoll.

The life history of COTS is particularly useful in explaining the patterns of coral damage resulting from their feeding. The starfish have a lifespan of up to 8-10 years (Chesher 1969; Lucas 1984; Zann 1990). Spawning typically occurs between November and February in the southern hemisphere and April through August in the northern hemisphere. An adult female can produce up to 60 million eggs during a single spawning cycle, depending on their size (Birkeland and Lucas 1990; Babcock and Mundy 1992):

- 200 mm diameter female produces 0.5-2.5 million eggs representing 2-8% of its wet weight
- 300 mm diameter female produces 6.5-14 million eggs representing 9-14% of its wet weight
- 400 mm diameter female produces 47-53 million eggs representing 20-25% of its wet weight

COTS have the highest rates of fertilization of any invertebrate measured, which is achieved due to their aggregating behavior and synchronized spawning. After a pelagic larval duration of 3-4 weeks, larvae settle on shallow reefs and metamorphose into pre-juveniles. These pre-juveniles migrate to 80-100 m depth and live in and among the rubble, feeding on coralline algae (Madl 2002). Somewhere between 16 months and 3 years of age, the juveniles (only about 5 cm in diameter) emerge from the depths, migrate up the reef and begin eating coral (Faure 1989; Birkeland and Lucas 1990). A crown of thorns starfish everts the gastric folds of its stomach through its mouth and turned inside out onto a coral, releasing enzymes (wax esterase) to digest its prey externally (Benson et al. 1975). Adults, measuring 25-35 cm, consume large volumes of coral. An individual starfish can readily consume one coral per day, or part of the coral if it is larger than their body size (Fig. 10). In Australia, large starfish (40 cm and greater diameter) were found to consume approximately 161 cm^2/day in winter and 357-478 cm^2/day in summer. Smaller starfish 20-39 cm killed 155 and 234 cm^2/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).

Once population size reaches 30-40 animals/km^2 it approaches outbreak status (Faure 1989). Outbreaks can consist of thousands of animals, at densities of 4-6 animals/m^2 (Carpenter 1997) or higher (Fig. 11). Often, selective feeding by starfish on a subset of all available corals exerts major influences on community structure and may result in a shift in coral dominance to non-preferred species (Colgan 1987). At elevated densities, however, starfish can eat everything in their path, devastating entire reef tracts (Pearson and Endean 1969; Moran 1986; Colgan 1987; Birkeland & Lucas 1990). Outbreaks have been reported to last from about 2-3 years on the GBR up to 20 years in the Ryuku Islands of Japan (Moran 1988). In Guam and the GBR, 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).

Fig. 10. Damage to massive and branching corals on the east coast of Aitutaki caused by three crown of thorns starfish over 1-2 days.

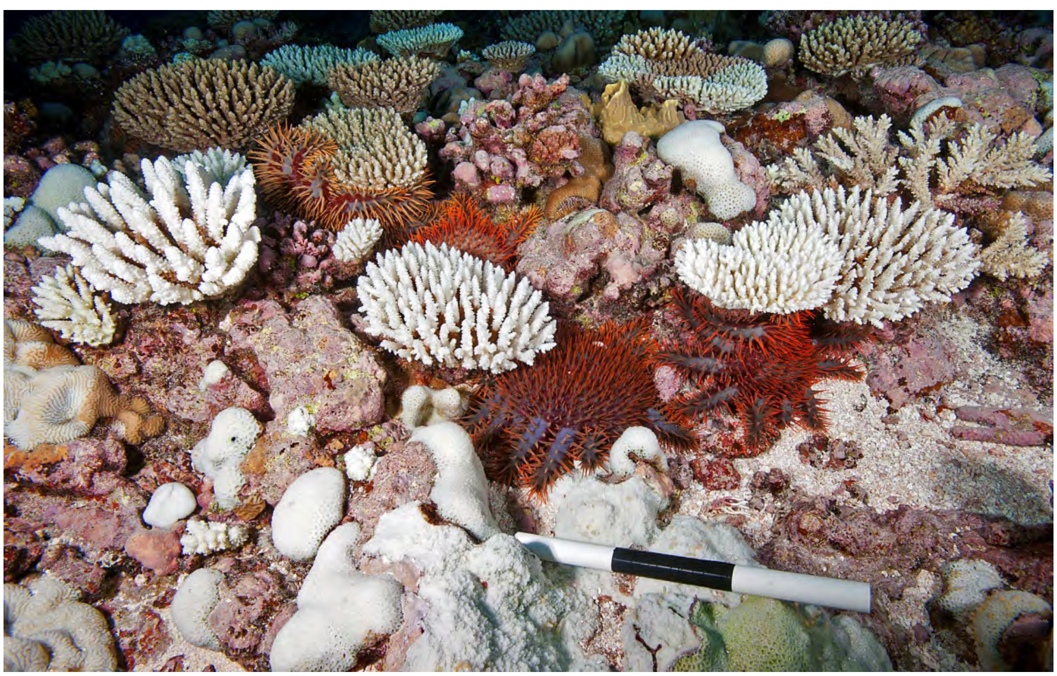

Fig. 11. A small area of shallow reef (8 m) on the east coast of Aitutaki with 4 COTS visible in the center of the photo. At the center of the outbreak, densities of starfish ranged from 3-10 animals/m^2. Scale bar is 30 cm.

Additional causes of coral mortality: During February, 2010 Aitutaki experienced a direct hit by Cyclone Pat (Fig. 12). The eye of the storm passed directly over Aitutaki. Damage reported is mainly wind damage with wind blowing consistently at 100 knots with gusts up to 130 knots; there was very little reported storm surge.

While the storm may have caused some damage to the coral reefs, it is likely that this was minimal. There were very few signs of broken or toppled corals and storm rubble was minimal in all sites. Many of the shallow areas (3-15 m depth), especially on the north, northeast and north west, had few remaining intact corals and the reef spurs were fairly smooth and covered in CCA. This could be partially due to the removal of branching corals by Cyclone Pat, although similar shallow areas devoid of coral skeletons were noted on the south coast and the east coast still contained many shallow areas with high densities of delicate branched acroporids, both live and dead skeletons. This would not be expected if there was considerable wave-related damage since the storm hit the east side of Aitutaki.

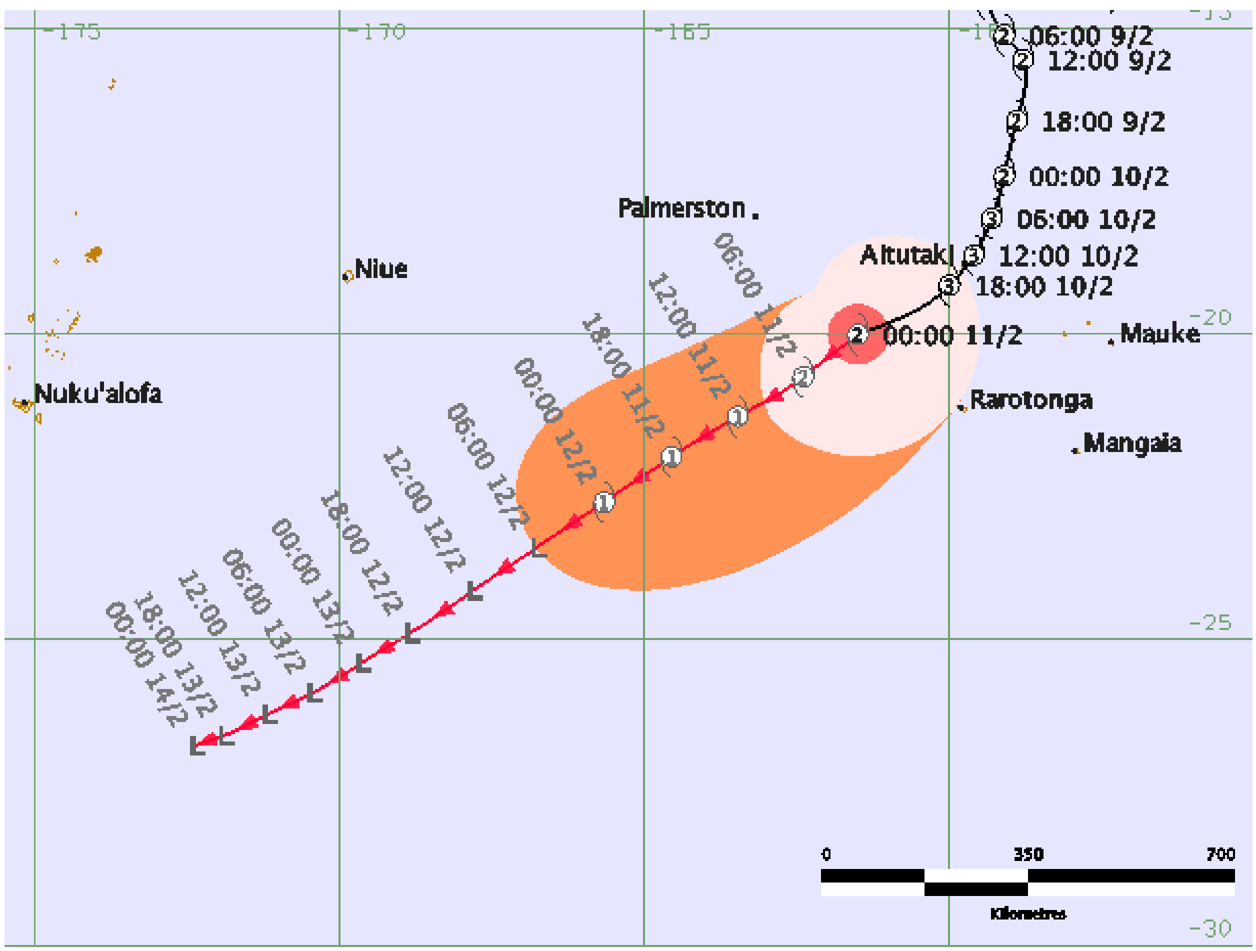

Fig. 12. Track of Cyclone Pat, which passed over Aitutaki on Feb 2, 2010.

Methods: SCUBA surveys and snorkel surveys were conducted in 13 fore reef locations around the island, and three sites within the lagoon (Fig. 13; Table 1). In each fore reef location, two divers began their assessment at 30 m and progressively worked into shallow water to 3-5 m depth, recording observations on the numbers of COTS, abundance and condition of the corals, and condition of the substrate. At each fore reef location, quantitative assessments of fish, corals and benthic community were also conducted along depth gradients, and 10 m X 1 m phototransects were collected. A roving survey covering an area of approximately 200 m wide (along a gradient from 30 m depth to 3 m depth) X 300 m long (300 m vertical distance, parallel to the reef crest) was used to assess population sizes within sites CIAT-13 - CIAT-22. Additional snorkel surveys were conducted in three lagoonal locations (CIATS-1-CIATS-3) and three fore reef sites at the northeastern end of the atoll (CIATS-4-CIATS-6).

In each location examined using SCUBA, two divers collected every COTS encountered during a roving swim over a 50 minute period, except for CIAT-13 where four divers collected starfish over the same period. Starfish were measured on board the M/Y Golden Shadow to get information on size structure and condition.

Table 1. Coordinates and oceanographic parameters of the survey locations. SCUBA surveys are labeled CIAT-13 - CIAT 22; snorkel surveys are CIATS-1- CIATS-6. A temperature and salinity profile was collected for each site from the surface to the depth indicated in column 6. The depth listed for each snorkel sites refers to the depths examined; no temperature or salinity data were collected.

SITE	DATE	Latitude	Longitude	Habitat	Depth (m)	Temp (°C)	Salinity (ppt)
CIAT-13	28-Apr-13	-18.9043	-159.7236	Windward fore reef, SE	27.35	28.6	35.5
CIAT-14	28-Apr-13	-18.8184	-159.7735	Windward fore reef, N	34.66	28.63	35.51
CIAT-15	29-Apr-13	-18.8897	-159.8272	Leeward fore reef, W	14.75	28.49	35.49
CIAT-16	29-Apr-13	-18.8672	-159.8188	Leeward fore reef, W	16.51	28.45	35.47
CIAT-17	30-Apr-13	-18.8331	-159.7941	Leeward fore reef, W	27.55	28.46	35.33
CIAT-18	30-Apr-13	-18.9173	-159.8452	Surgeward fore reef, S	19.85	28.4	35.37
CIAT-19	30-Apr-13	-18.8517	-159.8054	Leeward fore reef, W	20.4	28.43	35.53
CIAT-20	1-May-13	-18.9283	-159.7943	Surgeward fore reef, S	33.25	28.28	35.5
CIAT-21	1-May-13	-18.9519	-159.7445	Surgeward fore reef, S	19.74	28.2	35.5
CIAT-22	1-May-13	-18.9271	-159.7250	Windward fore reef, SE	24.95	28.31	35.47
CIATS-1	30-Apr-13	-18.9040	-159.8236	Lagoonal patch reef, W	0.2-4	-	-
CIATS-2	30-Apr-13	-18.8387	-159.7871	Lagoonal patch reef, W	0.2-4	-	-
CIATS-3	1-May-13	-18.8988	-159.8189	Lagoonal fringing reef, NW	0.2-1.5	-	-
CIATS-4	7-May-13	-18.8586	-159.7389	Windward fore reef, NE	2-15	-	-
CIATS-5	7-May-13	-18.8903	-159.7492	Windward fore reef, NE	2-15	-	-
CIATS-6	7-May-13	-18.8903	-159.7392	Windward fore reef, E	2-15	-	-

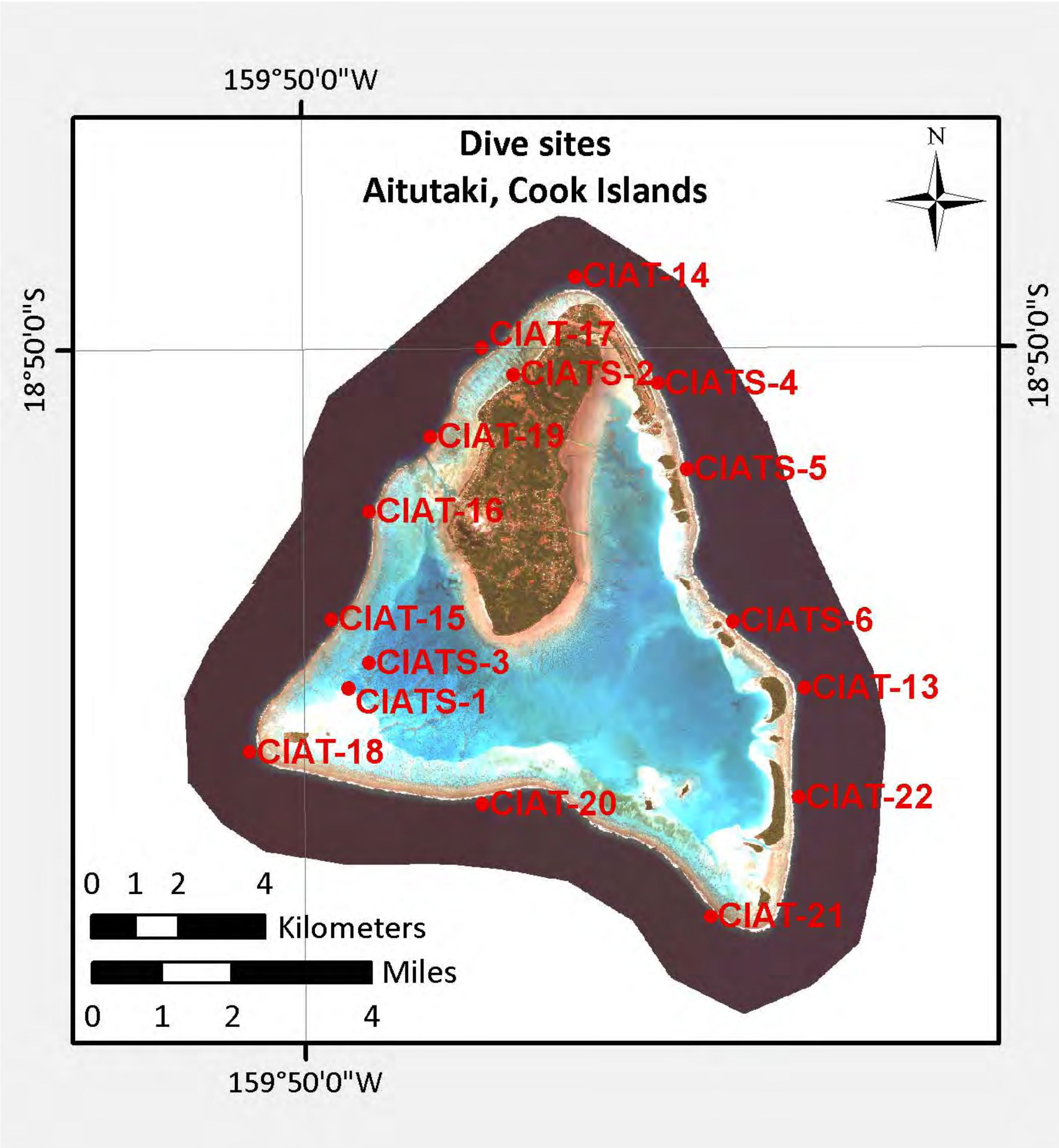

Fig. 13. Locations examined on the fore reef and lagoon during COTS surveys conducted in April and May, 2013. CIAT-13 - CIAT-22 were characterized using SCUBA. CIATS-1-CIATS-6 were examined by snorkeling.

Results: Damage to coral communities on the fore reef surrounding Aitutaki from crown of thorns starfish predation was extensive, occurring at every location examined (Appendix 1). The starfish appear to have emerged from deep water, consumed most corals on the outer reef slope, then progressively spread to the shallow fore reef. It is likely that the outbreak started on the west coast, with starfish migrating in at least two waves, to the south and north once food became scarce. This assumption is based on the following: 1) an absence of medium to large colonies of preferred coral species at all depths (2-30 m) on the west coast near site CIAT-16 and CIAT-19; 2) very few remaining coral skeletons of branching corals at shallow and intermediate depths in these locations; 3) a very thick layer of crustose coralline algae carpeting the rocks and on skeletons of dead corals; 4) an absence of turf algae on skeletons; and 5) very few remaining COTS (Fig. 14). Furthermore, one of the dive operators reported to have seen and collected hundreds of starfish from the reefs near the pass about 1 year ago.

From CIAT-16 on the west coast, continuing to the northern tip and down the east coast to CIATS-6 virtually all corals from 1-30 m depth (except *P. rus*) were dead and most of the skeletons of branching corals had been removed as well. In these locations, starfish were scattered throughout the reef, occurring at very low densities at all depths. They were feeding primarily on the remaining live coral. This included the less preferred surviving taxa (*Coscinarea*, *Porites rus*, *Acropora humilis*, and large-branched *Pocillopora*) and tissue remnants of massive corals (*Goniastrea, Favia stelligera, Lobophyllia, Porites lobata)* that had been mostly preyed upon during a previous feeding bout (Fig. 15).

Extensive mortality (>99% of all corals) was noted on the fore reef slope (15-30 m depth) off the southwest, south and southeast. The only remaining coral communities in fair to good shape were observed in the shallow fore reef habitats. These exhibited considerable variation in the cover and patchy survival of corals, with live cover ranging from <1%-60% (Fig. 16-17).

The highest densities of starfish were observed in areas with the most remaining coral. This included shallower areas (3-8 m depth) off a single site on the west coast in (CIAT-15), and on the east coast at mid depths (8-12 m; CIAT-22) and shallower (3-8 m depth; CIATS-6, CIAT-13). Starfish in these areas were found at densities of 1-10 animals/m^2. At CIAT-15, CIATS-6 and CIAT-13, coral communities at mid depths had been mostly consumed by sea stars and a prominent band of recently dead skeletons and skeletons with transitional mortality (skeletons covered in early colonizing filamentous algae) were apparent. Coral remained in very shallow water (1-3 m depth) at all of these sites, and also on the south coast in general, but live cover was fairly low (up to about 20%) and much of the substrate was occupied by large soft corals. On the south coast, most starfish were concentrated at 2-5 m depth, feeding on encrusting and tabular acroporids, small colonies of *Pocillopora*, and soft corals. Below 5 m depth, primarily dead skeletons, in growth position and heavily colonized by algae, were noted.

Further analysis of the quantitative data collected from different sites and depths will provide a more detailed understanding of the impacts of the starfish at the time of these surveys.

Fig. 14. Most of the shallow and mid-depth locations (2-20 m depth) off the west coast had few remaining corals or coral skeletons and the bottom was covered in a thick layer of crustose coralline algae (CCA; pink color) and peysonnelid algal species (brown color) as seen here. Starfish were still present, at low densities.

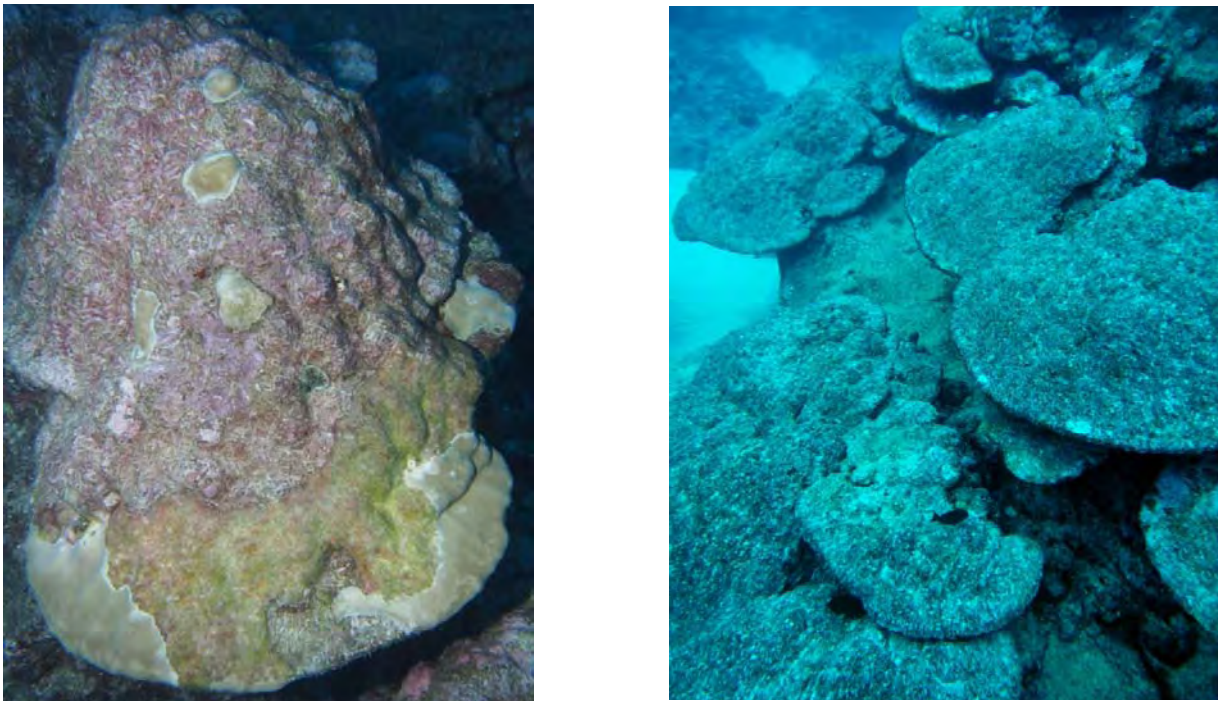

Fig. 15. Colonies of *Porites lobata.* The coral on the left has old mortality (top) and transitional mortality (lower center) from COTS predation, and some surviving tissue remnants. The corals on the left were completely eaten by COTS and their skeletons remain in growth position. Both are on the west coast at 25 m depth.

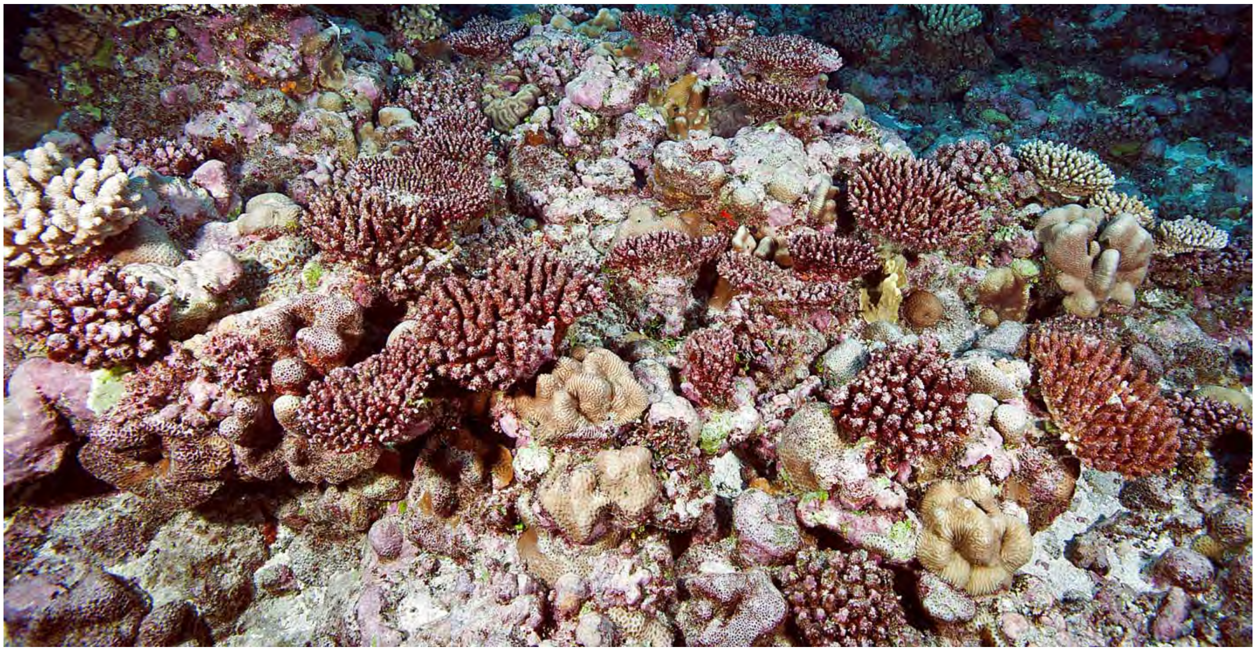

Fig. 16. Mid depth (15 m) off the east coast. Most of the branching corals have been eaten and are colonized by algae. Several smaller massive corals (*Goniastrea, Leptoria*) are still alive.

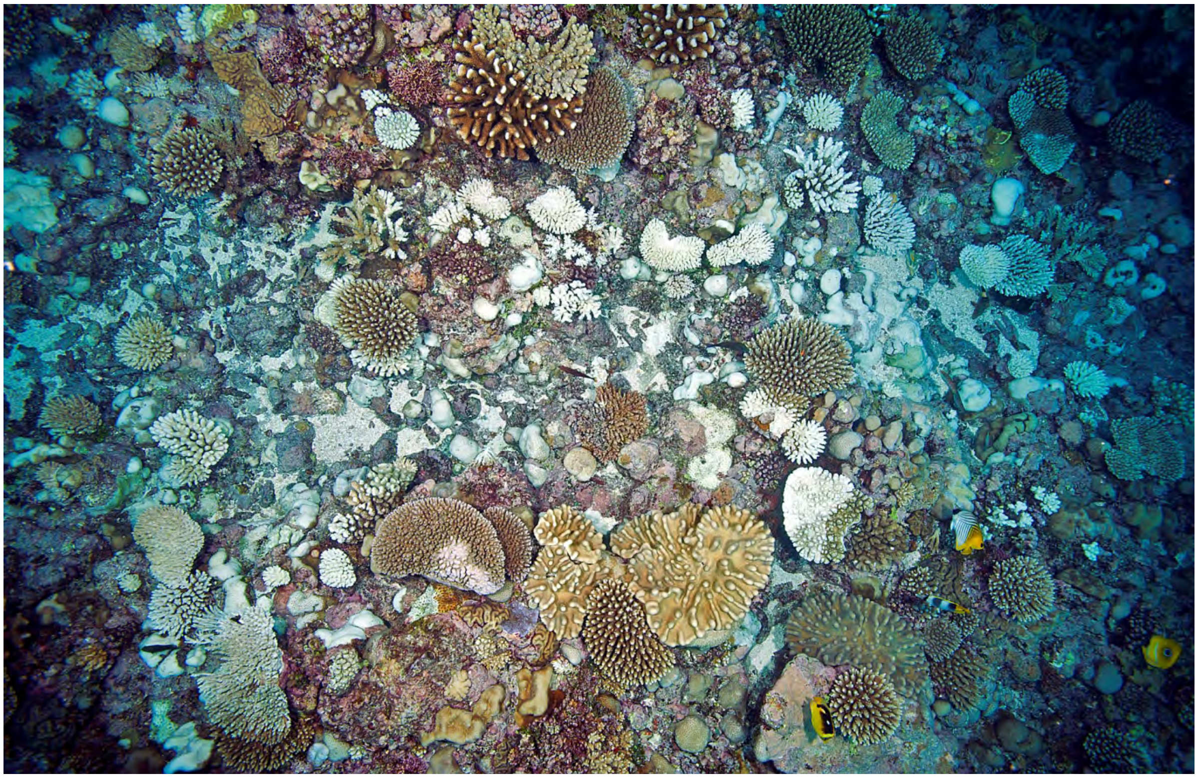

Fig. 17. A large section of reef habitat showing the path of destruction by crown of thorns starfish. Most corals (and soft corals) in the upper and lower sections of the photo are alive.

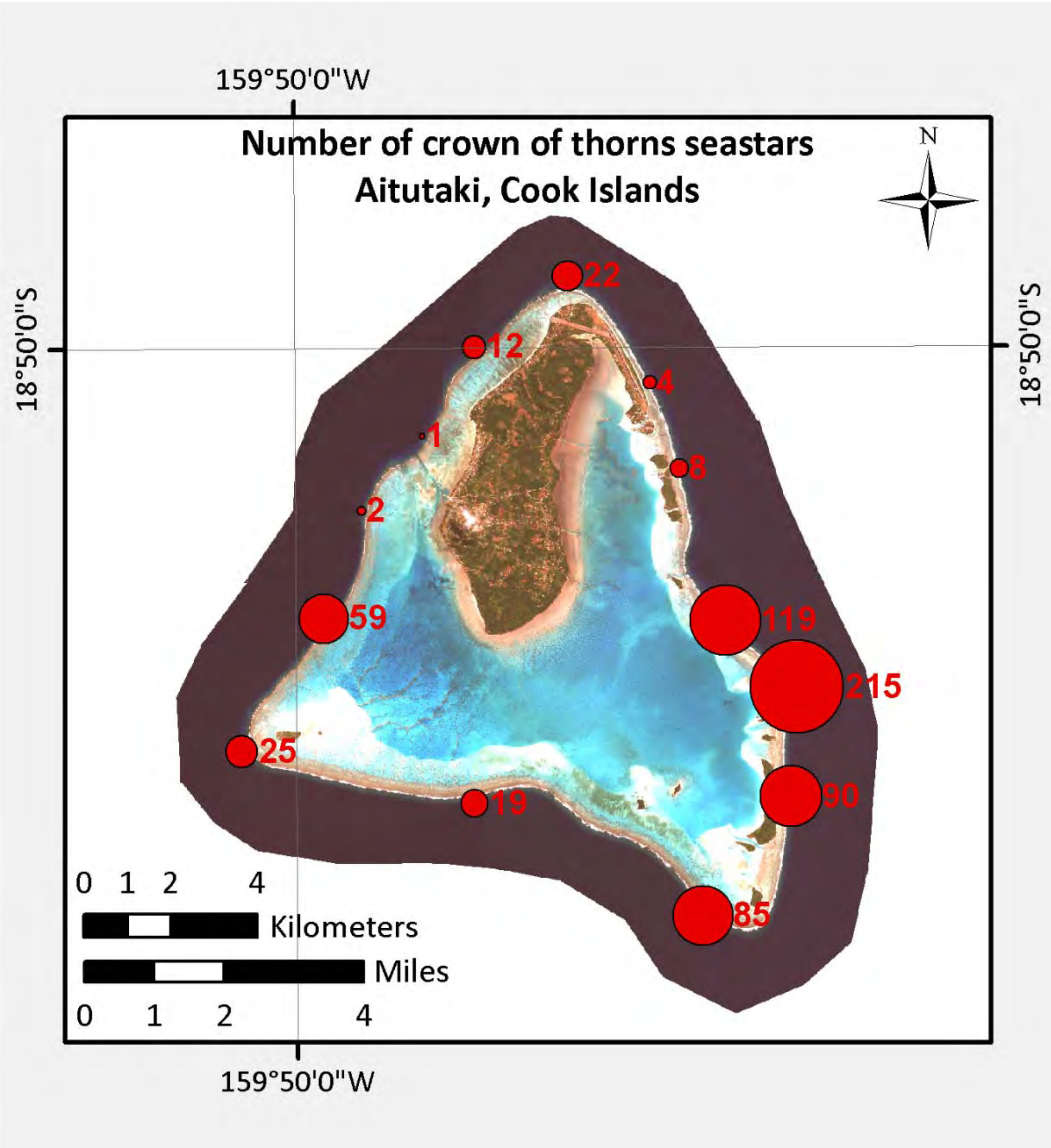

Fig. 18. Numbers of COTS observed in each location on the fore reef. SCUBA surveys were conducted from 30 m to 3 m depth, over an area of approximately 200 m wide X 300 m long in all locations. The three sites on the northeast (with 4, 8 and 119 COTS respectively) are each 100 m long X 30 m wide snorkel surveys conducted only in shallow water (1-10 m).

Collections: A total of 530 starfish were collected from 10 locations (Fig. 18-20). These animals were 9-38 cm in length (mean=26.8 cm) (Fig. 21). Starfish from the west coast were slightly smaller (mean= 26 cm) than starfish collected from the east side within the outbreak (mean=28 cm). The smallest animal overall (9 cm) was also found on the west coast and the largest (38 cm) on the east coast (Fig. 22). Many of the smaller animals collected from the west coast were missing part or entire arms.

Fig. 19. Removing starfish with a PVC tube. All starfish were placed in mesh bags and removed for measurement.

Fig. 20. Starfish were placed in a large bin after collection and measurement for disposal.

Fig. 21. Measuring a crown of thorns starfish.

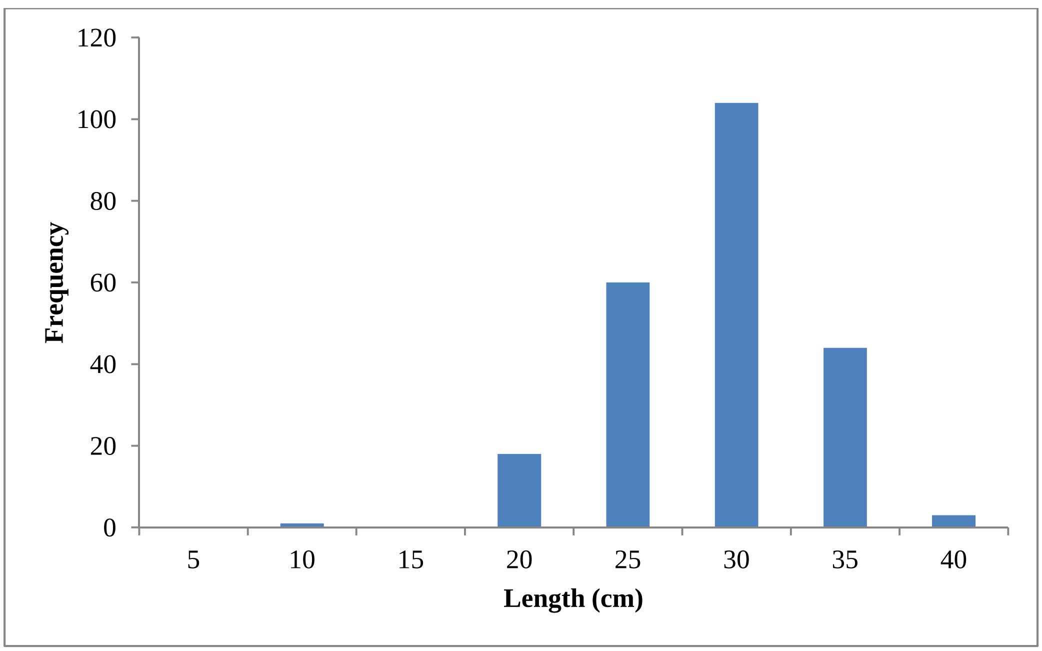

Fig. 22. Size structure of crown of thorns starfish collected in Aitutaki. Starfish sizes are pooled from all locations.

Discussion:

Natural factors reducing the impact: Because certain corals are preyed upon with much greater frequency, the destruction caused by a large outbreak is often patchy - some areas may be completely decimated while others remain relatively untouched. In Aitutaki, the only fore reef environments sustaining minimal damage were deeper coral communities dominated by monospecific stands of the plating/foliaceous coral *Porites rus*. These corals extended along the coast from the main passage on the west to the northeast tip at depths of 15-40 m. Crown of thorns starfish often avoided the larger branched pocilloporid colonies, possibly because these contained trapeziid crabs (*Trapezia* and *Tetralia* species) (Pratchett 2001). These crustaceans are known to be effective in the defense of these corals. Defensive mechanisms of scleractinian corals, including nematocysts, mesenterial filaments, and secondary metabolites also may deter starfish from feeding on certain corals (Potts 1981). Corals located in very shallow water on exposed coastlines (e.g. the reef crest off the south and east) were usually avoided because of the high wave action. These habitats may maintain breeding populations of corals that could help reseed degraded reef areas once the outbreak has ended, unless there is an extended period of calm water allowing the starfish to access the shallow environments.

Charonia tritonis (trumpet triton) mollusks are natural predators of starfish. These animals are reported to have been depleted from many locations around the Indo-Pacific by shell collectors, and this is believed to be one factor for increases in outbreaks of crown of thorns. Proposals were made to raise these animals in captivity and release them as a control mechanism. This is likely to be ineffective, however, as the gastropods typically consume about 1 starfish per week (Pearson and Endean 1969).

Movement of COTS: Crown of thorns seastars have been found to move relatively little in the presence of adequate food. However, shortages of food during outbreaks induce hunger-motivated directional movement of *Acanthaster*, with feeding fronts migrating in waves to surrounding localities (Kayal et al. 2012). This appears to be the case in Aitutaki, as four distinct feeding waves were identified, corresponding to the southwest tip (CIAT-15), and southeast sides (CIAT-06, 13, 22, 21) of the atoll. In each area a center of the outbreak was noted, where there were 50-300 sea stars and high numbers of white, recently eaten corals, with declining population sizes of COTS as one moves away from the aggregation. Currently, the COTS have consumed corals in deeper locations and they are moving parallel to the reef crest, over a band extending from about 3-5 m depth to 8-12 m depth. Once most of the corals in these locations are consumed, it is likely that COTS will spread into the lagoon, entering through one of the passes located on the east side, as this is closest to the largest outbreak and fewer starfish remain off the west coast.

Options for control of populations:

- ***Collection, removal and disposal of COTS on shore***
  - ***The preferred alternative.***
  - ***Strong sharpened sticks, barbeque tongs or a hooked steel rod are best for collection of starfish and removal of animals from under and on top of corals***
  - ***This method has the lowest cost, but it can be inefficient***
  - ***The animals can be buried on shore***
- ***Injection with poisons***
  - ***Chemical injection is a highly efficient alternative approach with some potential risks and higher costs.***
  - ***Copper sulphate is effective, inexpensive and widely available.***
  - ***In highly flushed environments, copper sulphate has proven effective at killing sea stars and relatively safe as it is quickly dispersed from the treated suite;***
  - ***Under low flow conditions and in enclosed lagoons it is a heavy metal pollutant that bioaccumulates in plants and animals.***
  - ***While this chemical is most effective in quickly killing the starfish, is more toxic than biodegradable alternatives such as sodium bisulphate and acetic acid.***
  - ***Other poisons used include formalin; concentrated ammonia solution and hydrochloric acid. These aren't as effective as copper sulphate, they tend to damage the injection guns and they are more hazardous to use. The proper dose is difficult to determine; insufficient exposure may not kill the animals.***
- ***Injection with sodium bisulphate***
  - ***This is the preferred chemical widely in use on the GBR, Australia today.***
  - ***It is widely available, inexpensive (about $4 per kilogram), considered to be safe to handle and it eventually breaks down in seawater.***
- ***Injection with acetic acid***
  - ***This is being implemented in Japan as a safe alternative to copper sulphate. It is effective at high concentrations, inexpensive, efficient and safe, but multiple injections may be needed to insure the starfish are killed.***
- ***Injection with an agar-like protein matrix***
  - ***This is in an experimental phase in Australia, and not recommended at this time until more information is available on potential implications.***
- ***Direct killing through maceration and or cutting starfish into pieces underwater***
  - ***It is possible to kill COTS in this manner, but is not recommended; it can result in propagation and further spread of the seastars and can cause diver injury.***
- ***Placing COTS in bags which are left underwater***
  - ***It is possible to kill starfish in this manner, as they are sensitive to oxygen deficiency; since they cannot move, they die in two or three days from lack of water flow. The animals may, however, may spawn before dying.***

Methods to eradicate 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. The largest effort overall, in Japan involved removal of over 13 million starfish! 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.

Manual removal: 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. This is, however, the method with the fewest negative consequences and the lowest cost. It has been undertaken in Cook Islands and other locations with considerable success. In Aitutaki (May 2013) two divers, while conducting other research, were able to remove over 100 starfish in fifty minutes in areas with a moderate density, relatively easily, with numbers removed increasing as the the density of the animals increased. Using a hollow PVC tube and a dive bag, animals were quickly collected and removed. During this process, the divers did not sustain any significant injuries and were capable of extracting the animals with minimal to no damage to the surrounding corals. Experienced divers could easily implement this method using a wooden stick, PVC pipe, metal spear, boat hook or some other easily manipulated rod to remove the animals. The collected animals can be placed in large canvas bags, rice/flour bags or mesh goodie bags and brought to the boat or shore. 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. Poor weather conditions (e.g. high surge) can make collection more challenging.

Injection with chemicals:

A) Copper sulphate: During the 1980s and 1990s, the most widely used chemical was copper sulphate. This approach was first tested on the GBR in 1986. Divers injected starfish with 5-10 ml of saturated copper sulphate solution using "Dupont" agricultural injection guns. In two weeks, 53 divers injected over 3000 starfish at a cost of A$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 A$0.50-$7.00 per starfish. Birkeland and Lucas (1990) conducted a detailed analysis of copper sulphate injection rates and modeled costs. They 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 A$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, 3-4 years later. Chemicals such as copper sulphate are also extremely toxic to other animals and to the divers administering the chemical. High levels of copper sulphate can induce bleaching and mortality of corals within the vicinity of the sea stars and it is bioaccumulated in giant clams, algae and other sedentary organisms. About 1 kg of copper sulphate is required to kill 100 animals (Gladstone 1990). Today, divers typically inject about 10 ml of a saturated solution into each starfish.

B) Sodium bisulphate: A highly successful chemical, widely used in Australia to cull COTS, is sodium bisulphate. Sodium bisulphate is a biodegradable chemical considered harmless to reef organisms. In Australia, during 2001, the Commonwealth and Queensland Governments spent $2 million to support a two-year, industry-run crown-of-thorns starfish control program for Cairns, Townsville and Whitsunday areas. This was repeated last year: over 60,000 animals were eliminated through sodium bisulphate injections, at a cost of $1.43 million. Australia has applied this approach in favor of copper sulphate 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 bisulphate is about $4 per kilogram. Add about 1/3 cup (140 grams) of the chemical to each liter of seawater. One liter of the solution is enough to kill about 40 adult starfish. Because the solution is colorless and difficult to see underwater, addition of food coloring is recommended. 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. Inject the starfish three times this way (Lassig 1995).

C) Acetic acid : A new approach to kill starfish, now 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 5-6 times in fresh water or seawater. Injection of 10 ml of 15 to 18% dilute acetic acid aqueous solution is effective at killing starfish. Lesser amounts (10%) dos not kill all the animals, so injection in multiple points can maximize effectiveness. A 500 ml bottle of diluted acetic acid can kill 30-50 COTS (10-15 ml/COTS) (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.

D) Other chemicals: Other chemicals used include Ammonia, Chlorox® bleach and formalin. These have the same concerns as copper sulphate, although they are less toxic as these chemicals are biodegradable. Unfortunately, they are also less effective at killing sea stars (Zann 1992).

Injection with agar: A new method to eliminate animals being tested on the Great Barrier Reef in Australia involves 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.

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.

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 so that the body collapses and flattens. 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 (Fig. 20).

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.

When is an outbreak of Crown of Thorns Starfish 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. 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.

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

- The size of the outbreak and the amount of resources available
- Timing of removal (e.g. whether they had already spawned will determine if there is a future outbreak).
- Degree of migration of the animals (most successful if the outbreak is concentrated in one area; less successful when it has spread to surrounding areas),
- Reef topography and weather (animals may become difficult to detect).

Crown of thorns seastar first aid

The spines of the crown-of-thorns starfish are very sharp, about 5 cm in length, and prone to breaking off in wounds. 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. 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 crown of thorns has 13 to 16 sharp spines and these can break off in the skin and penetrate through gloves and wet suits.

Skin penetration by the spines is painful and can lead to secondary infection and continued swelling. The pain is usually immediate, very severe and it 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 remain tender. After 24 hours, the area around the wound is usually numb and may still be red. 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.

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

- Some doctors suggest immersing the affected area in 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). Others indicate this does not reduce the pain. Some stings may require an injected local anesthetic for pain relief.
- Use tweezers to remove any spines in the wound because symptoms may not resolve until all spines have been removed. Scrub the wound with soap and water followed by extensive rinsing with fresh water.
- 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 only if an infection develops.

Appendix I. Description of survey sites

CIAT-13. Fore reef east, southeast. Shallow reef from 5-12 m is gently sloping with a very high diversity and abundance of branching, massive, plating and submassive corals. The reef is dominated by branching, digitate and small table acroporids, small pocilloporids, faviids, *Coscinarea* and many other taxa, with 60-80% live cover, very little algae and some large *Sinularia*. At the deeper end of this assemblage (8-12 m) there was an ongoing outbreak of COTS, with numbers of starfish increasing to the south. In some areas, single or small patches of corals were freshly eaten by COTS; at the center of the outbreak, several hundred animals were congregated over a 50 m^2 area, with hundreds of small, recently eaten, white coral skeletons in among the COTS. Surrounding this were numerous dead corals, in growth position, with transitional mortality (cyanobacteria and fine turf that colonized the skeletons in the last 7-30 days). Further away from the outbreak were many dead acroporids and other species that had become darker, as algae went through successional changes. Slightly deeper, there were few remaining branching coral skeletons, and more of a massive and thick-branched coral framework, covered in CCA and turf algae, with small tissue remnants. From 13-25 m, about 20-30% of the tissue remnants had small patches of bleached or recently exposed tissue, and patches with fine filamentous algae. Most mortality was originally caused by COTS, but corals were continuing to die due to snail predation, damselfish lawns, disease and continued feeding by COTS. On the steeper part of the reef slope (20-40 m) there was virtually no live coral. The only survivors at mid depths and on the slope were isolated *Coscinarea* colonies and digitate acroporids, at densities of 1/20 m^2 (cover < 1%). 215 COTS were removed from the reef in one hour by four divers. All COTS at the north end were collected, in an area adjacent to the outbreak; many were also collected from the outbreak zone, but hundreds of additional sea stars extended along the reef, to the south.

CIAT-14. Fore reef north tip. This reef had prominent very wide spurs that sloped gently from 3-12 m, then steeply to about 20 m, followed by a second series of mounds that extended from the seafloor to 10-15 m and gradually sloped seaward into deeper water. There were very deep and narrow channels separating these mounds, and wider rubble fields at the southern end of the reef. The substrate had very little coral from 0-20 m depth (<0.1%), no remaining coral skeletons, and was very smooth and covered in a thick layer of soft CCA. There are a lot of ledges and small caves with 30-80 cm microrelief on the tops of the mounds. On parts of the deeper reef were large dome-shaped *Porites lobata* colonies, mostly dead, but some had tiny tissue remnants. Between these were very large *P. rus* colonies. Some of the shallower colonies were a combination of plates and upright branches, but most of the deeper ones were large (2-3 m) foliaceous colonies and shingles. These species occurred from 20-35 m at about 20-30% live coral cover. Some *Porites rus* colonies had small patches of recent mortality, but most were intact. There were small surviving colonies of *Galaxea*, especially on vertical surfaces. Other species of coral included *Leptoria*, *Favia*, *Montastraea*, *Psammocora* and *Platygyra*, but these were all 80-98% dead with small (2-5 cm) tissue remnants. In deeper parts of the reef and under ledges were zoanthids, some *Palythoa* and soft corals. This site was devastated by COTS perhaps 6-8 months ago. A small number of COTS remained, feeding on small tissue remnants of *Porites*, *Coscinarea*, and *Goniastrea*. 22 COTS were removed from a 200 m^2 portion of the reef.

CIAT-15. Reef consisted of large mounds that extended from 3 m depth seaward, sloping steeply on their sides and seaward margin, with deep narrow channels between the mounds. The tops had a moderate cover of soft corals, and was relatively smooth with a thick layer of CCA. There were scattered surviving large *Pocillopora*, small remnants of massive corals, isolated digitate acroporids and a few other patches of coral. A moderate number of COTS (1-3/50 m^2) were seen on the tops of the reef, from 3-8 m depth; most were in cracks and depressions in this structure with some feeding on coral. The sides of the mounds were devoid of corals, smooth from CCA, with lots of holes and crevices. On the deeper portion of the reef, mounds and spurs extended seaward, sloping gradually, with 1-2 m relief and increasing near the edge of the drop. There were large skeletons of *P. lobata*, a few with tissue remnants, and 2-3 larger living *P. lobata* colonies (2-3 m diameter). There was a gradual increase in *P. rus* at the deeper end of the slope, near the drop off and continuing down the slope.

CIAT-16. Shallow reef had large spurs with little live coral, with patches of soft corals about 5 m. The tops and sides had a smooth surface due to CCA. These sloped steeply to a second reef terrace that gradually sloped seaward to 20 m, then sloped more steeply to the offshore reef slope. Numerous dead *Porites lobata* skeletons and some massive coral and branching coral skeletons, with only small tissue remnants. High numbers of damselfish lawns at the deeper edge of the slope. Scattered living colonies of *P. rus* in deeper water. Very few COTS (found 2).

CIAT-17. Southwest point. Shallow reef (3-12 m) consisted of a high cover of branching, table and digitate acroporids, *P. verrucosa*, both low growth forms and larger elephant ear varieties, intermixed with massive, submassive and plating corals, especially *Hydnophora, Lobophyllia, Goniastrea, Favia, Leptoria, Echinopora* and other species. Living cover was very low, with highest cover above 3 m (10-20%). There were 60-80% dead corals, in growth position, covered in filamentous algae from 4-12 m depth, with a prominent band of 100% dead corals at the deeper end of this. In general, there were live colonies of the digitate, some tabular acroporids and larger pocilloporids among the dead corals, with several of these having recently dead white patches. Moderate densities of COTS were seen (1-3/50 m^2). The reef below 15 m transforms to a low relief (30-80 cm) series of massive boulders, mounds, small spurs, with sand/rubble patches. It slopes gradually to 20 m, then steeply to 30+ meters. There was virtually no live coral below 15 m. Skeletons on the shallow part of the slope were covered in thick CCA, with less CCA and more Peysonnelid algae, turf algae and *Halimeda* on the steep part of the slope. Only tiny remnants of *Goniastrea* and *Favia*, and a few 20-30 cm digitate acroporids and massive *Coscinarea* survived, with many showing recent or transitional mortality.

CIAT-18. West side, midway along the coast. Shallows from 5-10 m were mostly dead. COTS had moved through the area and most skeletons were covered in turf algae. At 12-15 m a lot of dead branching coral skeletons and small table acroporids (esp. *A. hyacinthus*) with a high cover of turf algae; there were small numbers (5-10/10^2) of live corals intermixed with white, recently killed corals and COTS. At 18 m depth were scattered 50-70 cm tall boulders with 5-10% live coral, mostly consisting of medium to large *Pocillopor*a and *Acropora* and some small massive faviids. Lower relief ridges and mounds extend from 10-18 m depth with lots of sand patches and rubble and occasional live *Pocillopora* and *Acropora*. The slope is gradual to 28 m then increases deeper. There were small tissue remnants of *Astreopora, Goniastrea, Platygyra,* and *P. eydouxi* remaining on sides and in depressions within the skeletons, as well as scattered larger living *P. verrucosa*. Deeper reef had high numbers of *Herpolitha* colonies that had been eaten. High numbers of snails on surviving patches of *Porites lobata* and considerable recent mortality. Many of the tissue remnants of *Goniastrea, Coscinarea, Acropora, P. lobata* and *P. rus* had small white lesions from recent COTS predation. Dense turf algae was found within damselfish teritories on deeper parts of the reef, and also patches of *Halimeda*, and cyanobacterial mats on sediment.

CIAT-19. West, channel. Very large mounds extend from the reef crest seaward, sloping steeply on their sides and margins to 20 m with a second set that rises up to 10-12 m, forming a terrace 20-50 m wide, which plunges steeply on the seaward margin to 30-40 m. There are very narrow, deep channels filled with large boulders and some sand patches, and a near vertical sides with some undercut ledges on the sides of these. The tops and sides of the mounds have lots of holes, crevices and depressions, but the surface is very smooth and knobby due to a very thick layer of CCA encrusting dead coral skeletons. There is virtually no live coral - isolated small *Acropora* recruits and a few remnants of *Goniastrea*, *Montastraea* and *Favia*, but live coral is < 0.01%. Under the CCA is a dense community of massive coral skeletons, most small to medium. The depressions and crevices and sides of the mounds are a mix of CCA and Peysonnelid algae. In places there are very large aggregations of fleshy soft corals, some patches are over 5 m in diameter. At mid depths were high numbers of large *P. lobata* skeletons, a few with tiny tissue remnants. Surrounding the two set of mounds, and especially continuing on the seaward side of the outer mound is a very high abundance of *P. rus* colonies. Many of these are 5-10 m wide foliaceous clumps in deeper water, and the seaward side is carpeted in a nearly monospecific stand with 60-70% live cover. The deeper part of the reef, from 12-30 m is also mixed with a lot of *Porites lobata* skeletons. Some of these have tiny tissue remnants, but generally 99% is dead. A high proportion of the *P. rus* colonies were partially bleached. The tissue was streaked in bands of white to pale yellow alternating with darker tissue. There was also some partial mortality from *Coralliophila* snails and unknown causes.

CIATS-1 and 2. At western end near large vegetated island. Sand apron, 1 m deep surrounds the island. At the edge of this is a band of coral bommies, some 10-20 m wide/long. These are in 2-4 m depth. They resemble micro atolls. The micro-atolls continue into the lagoon, extending nearly to the dock. The tops of these hard structures have few scattered corals, some have small central sand patches, and lots of filamentous algae due to an unusually high number of damselfish. The damselfish are farming algae on corals at the margin. The rim is surrounded by a dense assemblage of branching acroporids, massive faviids, *Lobophyllia* and other species. the sides have 60-100% coral cover consisting of large *Porites, Montipora,* acroporids, large massive faviids include *Favia stelligera, Goniastrea, Montastrea, Leptoria* and other small faviids, *Astreopora, Pavona clavus* with sheets of *Montipora, P. varians,* *Coscinarea, Psammocora* on the sides and large mounding and plating *Galaxea* colonies. many of the *Galaxea* colonies are 2-3 m in diameter, but they have an unusual crenulated growth form with live tissue only on one face. Other miscellaneous species including fungids (*Fungia, Herpolitha* and *Sandolitha*), patches of *Leptastrea, Cyphastrea*, and *Acanthastrea*. Very little partial mortality on corals, although there are patches of *Halimeda* and long filamentous algae. Around the bases of the atolls are thick filamentous *Enteromorpha* or *Cladophora* like algae, intermixed with some large *Acropora* and *Pocillopora* colonies that have fallen off the sides, but are thriving at the base. There were a lot of large giant clams (*T squamosa*), including two that were 70 cm. The lagoonal floor is littered with sea cucumbers - mostly the black teetfish at densities of 5-10/m2. The coral bommies found within the lagoon are similar to those near the reef crest, but the visibility is much lower within the lagoon.

CIATS-3. Shallow lagoonal reef adjacent to shore, north of pier near hotels. Soft bottom community from 0.5-2 m deep with scattered large coral heads. Reef is dominated by unusually large *Pocillopora damicornis*, multiple species of branching acroporids, Branching, encrusting and branching/foliaceous *Montipor*a, hemispherical *P. lobata* and scattered colonies of *Montastrea, Goniastrea* and a few other species. Corals range from 30 cm to over 1 m diameter and height. Colonies offshore are larger and healthier. Substrate has large patches of zoanthids and some of coral heads are covered in *Turbinaria* algae. Dead areas also have numerous damselfish and algal lawns. About 30% of the *P. damicornis* colonies in shallow water, closet to shore have died and are covered in fine turf. Many colonies also have recent mortality only on their tips on the upper surfaces of the colonies. A single snail and a single COTS were found. This appears to be due to low water and possibly high irradiance as tides have been very low. Also, dead colonies were reported to be live until mid January/February. This may be bleaching related mortality due to low tides and high solar radiation as the summer months, during the normal rainy season were a drought period with no rainfall (and higher than normal sunshine). Eight juvenile Napoleon wrasse were seen. The sand has hundreds of sea cucumbers.

CIAT-20. Fore reef southern central area. Fewer COTS: 1-3/50m^2. Shallow to mid depth reef consists mostly of small to medium branching acroporids and pocilloporids, intermixed with smaller massive corals including *Leptoria, Goniastrea, Favia, Montastraea, Lobophyllia, Coscinarea, Astreopora, Echinopora* plates, and other species. The shallow part, from 3-8 m, has 10-15% live cover and a lot of dead skeletons covered in cyanobacteria and turf algae. From 8-12 m is a dense band of dead coral skeletons, mostly *A hyacinthus* and other finely branched table acroporids, *Pocillopora* and other species, all covered in turf algae. Deep reef is similar to other southern reefs, with low relief spurs and mounds extending down the slope, separated by sand/rubble patches. Slope is gradual from 3-20 m, then drops more steeply, with more rubble on the fore reef slope. A framework is small massive corals, especially *Goniastrea*, lacking *Porites lobata*, with some remaining branching coral skeletons. Corals are all dead, except for isolated *Pocillopora*, digitate *Acropora* and massive *Coscinarea*, with tiny *Favia, Goniastrea, Leptoria* remnants. 3 Cots were seen from 25-30 m, none from 15-20 m and then Moderate numbers of COTS (1-3/30 m^2) were seen in the shallow reef, with many consuming larger *Pocillopora*, some of the acroporids, soft corals and several of the massive species. Live cover in this area was still 5-10%. This site had a school of 20 Napoleon Wrasse.

CIAT-21 fore reef, southwestern tip. Shallow fore reef is very flat, low relief with some narrow grooves above 3 m depth. From 2-5 m are scattered living acroporids, mostly encrusting table acroporids, and a very high cover of soft corals (20-30%). The reef framework has cracks and some depressions, up to 20 cm deep, and some larger massive coral and table acroporid skeletons, up to 50-60 cm. These corals (and soft corals) had a moderate density of COTS among them, with 1-3/20 m^2. Mid depths (15-20 m) are similar to other south coast areas with a mix of massive coral structure and some branching coral skeletons mostly dead. Remnants of *Goniastrea, Favia, Leptoria* have a lot of recent mortality. There are a few living *Pocillopora* and digitate *Acropora*. There are no large *P. lobata* skeletons. Rubble and sand between the corals. Deep reef has low relief spurs with some taller mounds up to 1 m in height, separated by sand and rubble patches. No real defined spur and groove up shallow. The reef slopes steeply from 20-30 m, then there is a drop off and undercut ledge with an elongate cave running parallel to the coast at 29-32 m depth. Below this is mostly sand, rubble and small coral heads. The reef slope is largely dead, with <0.01% live coral consisting of scattered tiny (1-5 cm) remnants mostly of *Goniastrea*.

CIAT-22 Fore reef southeastern end, south of dive 1. Typical southern reef with a well developed branching coral community in shallow water, with high diversity and a mix of some plating and massive corals, a low relief massive coral with scattered branching corals at mid depths and a massive coral community dominated by *Goniastrea* running down the slope. In shallow water 2-4 m was a diverse community of corals, mostly live, with 10-15% cover by soft corals. Between 4-10 m was a very diverse community that was roughly 50% live with numerous patches of recently eaten corals and a lot of COTS (1-5 per patch, with 5-6 patches per 10 m^2). Most species were being eaten including all acroporids, pocilloporids, *Hydnophora, Goniastrea, Favia, Montastrea, Lobophyllia, Astreopora* and other corals. From 10-15 m he community transformed to branching and table acroporids, most 20-40 cm diameter, with 80-90% dead and overgrown by turf algae. Scattered larger pocilloporids, *Coscinarea*, digitate acroporids and a few table acroporids were still living. On the top of the slope, from 15-20 m depth, there were small mounds and spurs, mostly of massive corals and some thick branched corals that were mostly dead, with small tissue remnants, a lot of recent mortality on the remnants, and encrustations of CCA. Sandy areas between the mounds had rubble. The deep slope (20-35 m was very steep. 99.9% of the coral in deep water was dead, with very few remnants and no recruits. The hardground areas were 30-60 cm tall with fused skeletons of *Goniastrea* from 20-40 cm diameter and scattered dead acroporids and *Pocillopora*, and lots of rubble between coral mounds. Center of the outbreak of COTS extends from the southern tip of site 1, south of here, declining north of site 1 and on the east coast. 200 cots/30 m^2

CIATS-4. Northeast Fore reef, near the airport. The reef structure is similar to that seen to the north. The reef slopes very gradually from the reef crest to about 3 m, then drops more abruptly to a second terrace at 5 m. This terrace extends seaward, gradually sloping to 20 m before dropping more steeply. The shallow area, seaward of the reef crest has some encrusting digitate acroporids and 20-30% cover soft corals. Some of the acroporid crusts are up to 1 m in diameter. They are mostly live, about 10-15% cover very shallow, but many have partial mortality at 2-3 m deep and numerous COTS were seen among these corals. Below this there were few corals. Most of the substrate was covered in CCA.

CIATS-5. Northeast fore reef, south of the airport. The shallow reef, seaward of the reef crest is dominated by soft corals and encrusting and digitate acroporids. Below 2 m depth, most colonies have old partial mortality and are less than 50% alive; live coral cover is 2-5 %. As the reef slopes slightly deeper (3-5 m depth) there are more acroporid colonies with recent mortality and numerous COTS among these corals. Below 5 m depth, the reef substrate is devoid of live corals, with scattered skeletons of completely dead branching and submassive corals. Coral cover is < 0.1% from 5-20 m depth.

CIATS-6. East fore reef, just south of the channel. Shallow reef from 2-10 m is gently sloping with a very high diversity and abundance of branching, massive, plating and submassive corals, intermixed with large fleshy soft corals. The corals are live in some areas, with cover of up to 50%, and partially and completely dead in other areas. The best coral cover is very shallow (2-5 m depth) with declining live coral deeper. Between 4-10 m depth there is a very high density of COTS, but these are in small aggregations with some areas containing 1-2 COTS/m^2 and others having 5-6/m^2. This region has patches with extensive recent mortality, interspersed with live corals. Slightly deeper (10-15 m depth) is a prominent band of completely dead branching, massive and submassive corals in growth position, with the skeletons colonized by fine turf algae and some CCA. The deep reef was mostly devoid of corals and few branching coral skeletons remained. This appears to be the northern extent of the COTS outbreak. Areas further to the north have already been devastated by COTS.

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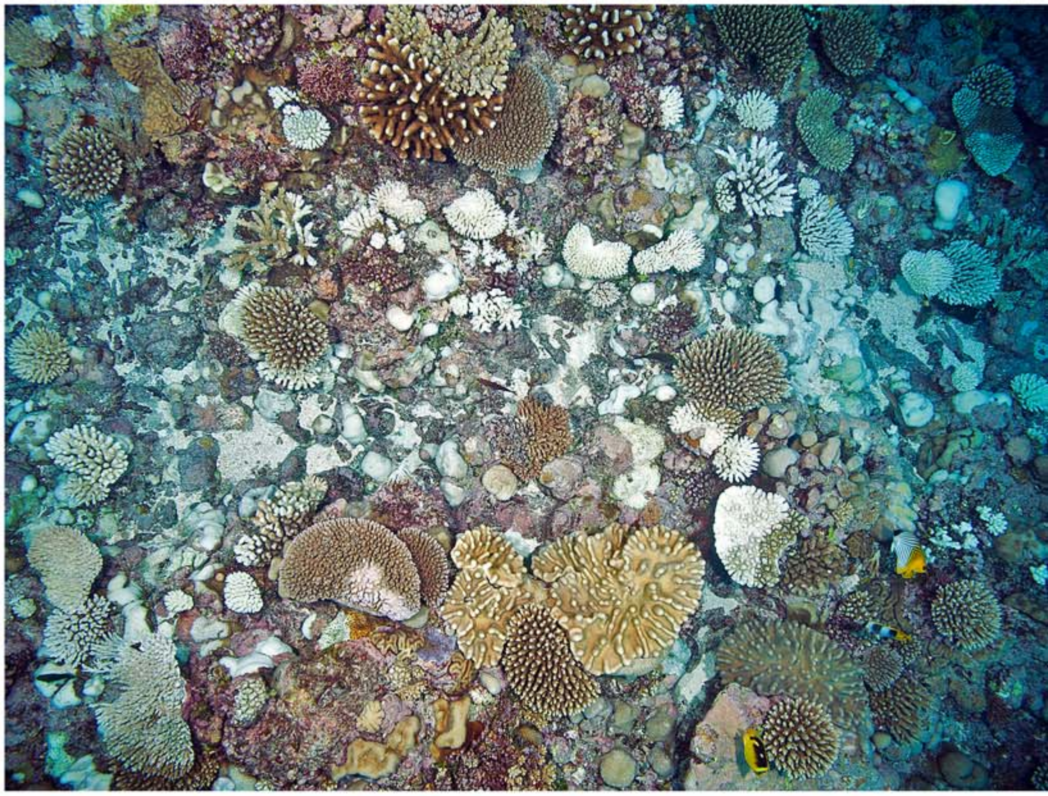

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