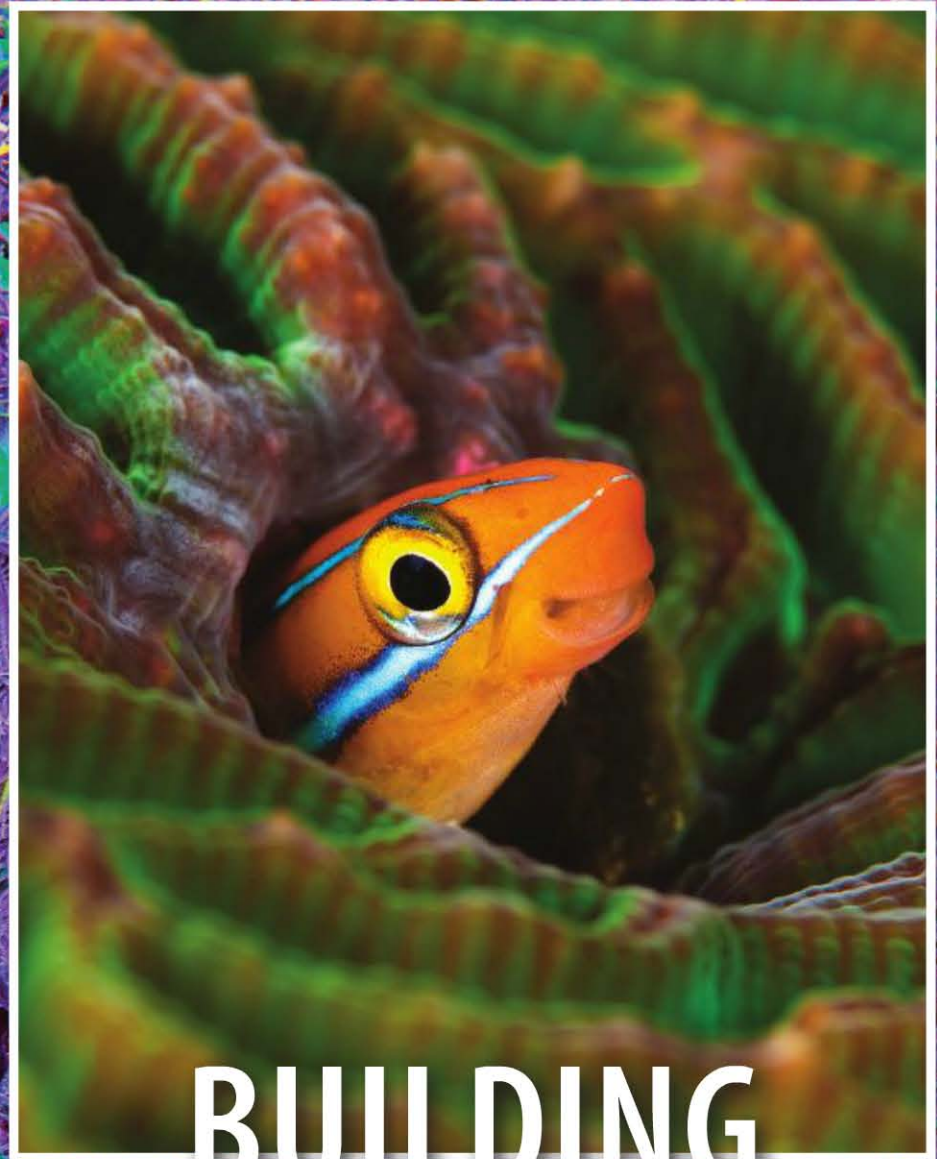




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NEWSSTAND | Howard White & Associates

PRINTING | Dartmouth Printing | Hanover, NH

CORAL®, The Reef & Marine Aquarium Magazine,
 is published bimonthly in January, March, May, July,
 September, and November by Reef to Rainforest Media,
 LLC, 140 Webster Road, PO Box 490, Shelburne, VT
 05482. Periodicals postage paid at Shelburne, VT, and
 at additional entry offices. Subscription rates: U.S., \$37
 for one year. Canada, \$49 for one year. Outside U.S. and
 Canada, \$57 for one year.

POSTMASTER: Send address changes to **CORAL**,
 PO Box 361, Williamsport, PA 17703-0361.

ISSN 1556-5769 (print)

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 Natur und Tier Verlag GmbH | Muenster, Germany

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COVER CREDITS: Blue-Lined Sabretooth Blenny,
Plagiotremus rhinorynchos, Gary Bell/Oceanwide Images
 Background: *Clavularia* sp. encrusting coral under
 blue light. Daniel Knop



CORAL

6 LETTER FROM EUROPE by Daniel Knop

9 EDITOR'S PAGE by James M. Lawrence

10 REEF NEWS

22 RARITIES CORAL staff report

FEATURE ARTICLES

30 INTERVIEW

Marine biologist Christiane Schmidt on
 the Disney-Pixar movie *Finding Dory*
 by Daniel Knop

36 BOMMIES by Gary Bell

46 SMALL BOMMIE BASICS by John Ciotti

50 BUILD YOUR OWN BOMMIE by Daniel Knop

54 KALEIDOSCOPIIC CORAL VISIONS

A portfolio of extraordinary reef animals
 by Matt Pedersen

62 DORY DOUBLES

Blue Demoiselles (genus *Chrysiptera*)
 by Scott W. Michael

74 STARTER SMALL-POLYP STONY CORALS

by Daniel Knop

AQUARIUM PORTRAIT

87 DIVING IN THE LIVING ROOM

Low-maintenance, but wired for video blogging
 by Daniel Knop

DEPARTMENTS

93 SPECIES SPOTLIGHT: *Wunderpus photogenicus*
 by Daniel Knop

100 CORAL SOURCES: Outstanding aquarium shops

102 CORALEXICON: Technical terms that appear in this issue

104 ADVANCED AQUATICS:
CULLING CROWN-OF-THORN STARFISH
 Can we salvage impacted reefs?
 by Andrew Bruckner and Georgia Coward

112 ADVERTISER INDEX

114 REEF LIFE: by Denise Nielsen Tackett and Larry P. Tackett





Culling Crown-of-Thorns Starfish (COTS): Can we salvage impacted reefs?

The news of accelerated worldwide degradation and loss of coral reefs due to coral bleaching, ocean acidification, and other manifestations of man-induced climate change has attracted considerable press attention. While these global threats are of significant concern, certain other, more localized threats can cause substantial damage on their own or aggravate the losses due to climate change. One such threat that often spreads under the radar is the Crown-of-Thorns Starfish (COTS), *Acanthaster planci*. These starfish are the most voracious coral predators found on shallow water tropical coral reefs. They have destroyed entire reef systems during severe outbreaks. In fact, a single starfish will eat one coral every day and can consume all of the corals within a 65–108-square-foot (6–10 m²) area within just one year.

During population explosions, scientists have documented densities of six to ten COTS per square meter or more, with tens of thousands of animals invading a single reef system. They tend to aggregate—dozens of starfish may occur simultaneously on large table and branching corals. Their path of destruction often resem-

bles the spread of a forest fire: they slowly devour their way through a reef system in a systematic manner, leaving only a few less preferred corals in their wake.

Under “normal” circumstances, COTS occur at low densities on a reef, and when uncommon they can actually serve an important role, increasing coral diversity by preventing common fast-growing corals from taking over. Unfortunately, outbreaks appear to be increasing in frequency and distribution. COTS also appear to be less selective and are consuming both their preferred species of coral—the fast-growing branching and plating corals—as well as the longer-lived, slow-growing, massive corals that form the framework of the Indo-Pacific reefs. Further, COTS are now appearing in reef systems for the first time. One relatively recent invasion of COTS has taken place in the Maldives, where they appear to be spreading rapidly from one atoll to the next.

The Maldives’ first starfish invasion went largely unnoticed, possibly because it occurred in the 1970s, before the large expansion of tourist resorts, and perhaps because it was small in scale, being confined to just two areas on North Malé Atoll (Vahibinfaru and Ari Fesdu).

GEORGIA COWARD



Low-tech removal of Crown-of-Thorns Starfish by a diver from Coral Reef CPR, a new non-profit group.

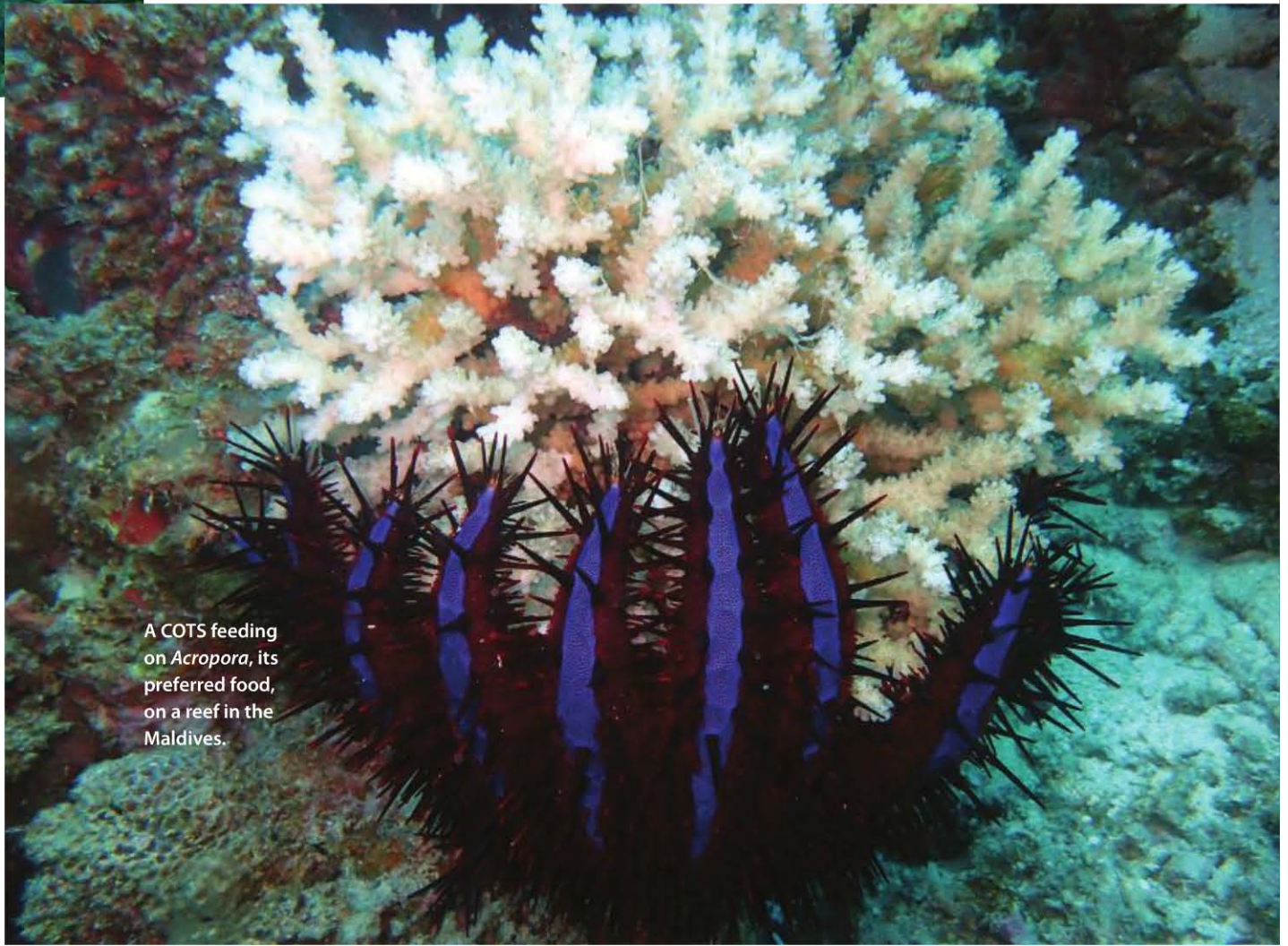
The second outbreak of COTS, nearly 15 years later, received much more attention. The starfish emerged on the western side of North Malé Atoll near Reethi Rah and spread to Ari Atoll and South Malé Atoll, with additional outbreaks reported from the south, near Gaafu Dhaalu and Gaaafu Alif. The populations of COTS peaked around 1988 on North Malé Atoll, and localized population explosions continued until at least 1992. Dive centers and resorts became quite concerned, foreseeing a loss of reef-based tourism revenue, and began conducting the nation's first large-scale eradication effort. By January 1991, over 30,000 starfish had been removed, mostly from Nakatchafushi (18,700) and Makunudu (11,400).

The third COTS population explosion started 25 years later. This outbreak, which began once again near Reethi Rah in 2013, has become much more severe. The starfish have caused widespread and total devastation to a number of affected house reefs. By May 2015, COTS had expanded throughout North Malé Atoll, occurring in 11 different locations, and North and South Ari Atoll in 24 locations. By October 2015 there were also reports from two locations on Baa Atoll, one on Lhaviyani Atoll,

and four on South Malé Atoll; localized outbreaks were noted for the first time in 2016 on Shaviyani Atoll. As the range of the starfish has expanded, efforts to eradicate them have also grown. To date, at least 100,000 animals have been eliminated from the Maldives through direct removal or injection.

Globally, similar infestations and even larger eradication efforts have been undertaken for at least the past three decades, beginning in Japan in the 1950s, when over 10 million COTS were killed. Over the last few years, 10 countries have implemented programs to eliminate these starfish. One of these is Australia, which spends millions of dollars each year to control population explosions on the Great Barrier Reef. This massive Indo-Pacific effort has raised ethical questions regarding the removal of starfish, questions regarding the suitability of the control methods and their effectiveness, and questions pertaining to the reasons for the outbreak.

Acanthaster planci are echinoderms in the Family Acanthasteridae and Class Asterozoa (starfishes). They are a normal inhabitant of coral reefs throughout the Indian Ocean, Pacific Ocean, and Red Sea. They are multi-armed (14–22 arms) and have a central disc with the



A COTS feeding on *Acropora*, its preferred food, on a reef in the Maldives.

Beef ?



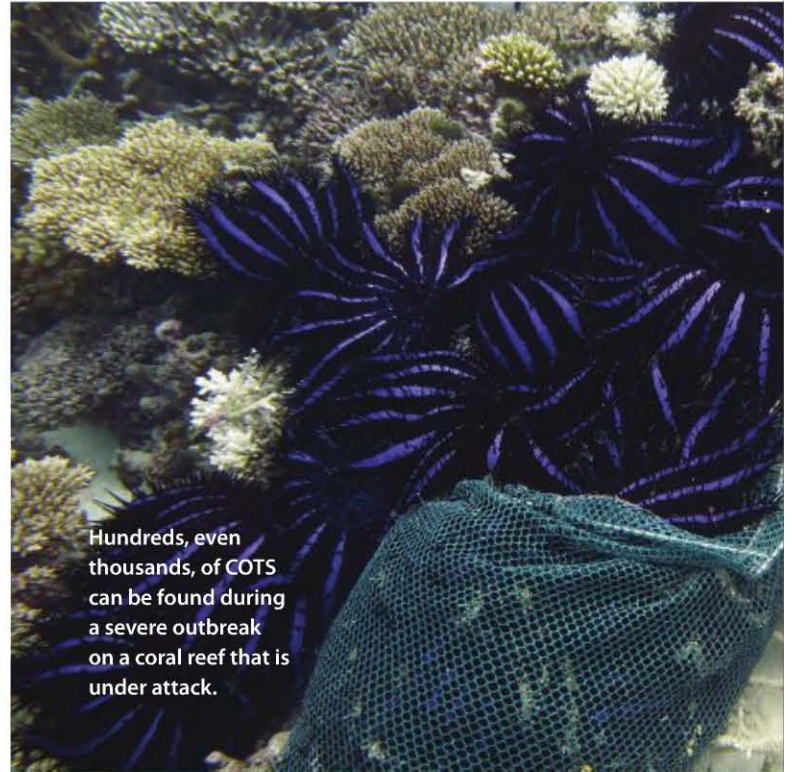
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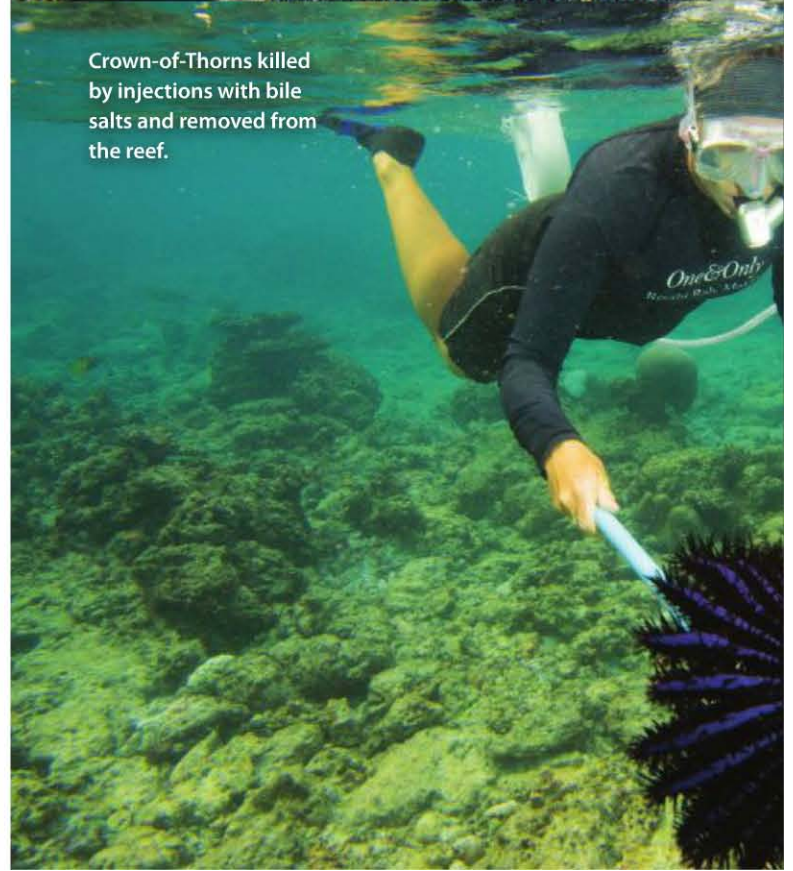


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mouth located on the underside. The top surface is covered with 1–2-inch (3–5-cm) long venomous spines, and the oral surface has rows of tube feet with suckers extending down each arm. In addition to their razor-sharp spines, their soft tissue and the outer surfaces of the spines contain poisons that are toxic to humans, as well as surfactant- and detergent-like compounds. As with other echinoderms, a large part of the body is made up of a water vascular system that is filled with fluid and



Hundreds, even thousands, of COTS can be found during a severe outbreak on a coral reef that is under attack.



Crown-of-Thorns killed by injections with bile salts and removed from the reef.

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COTS are the most influential corallivores in the Indo-Pacific. They are responsible for shifts in species assemblages and near-complete elimination of all reef-building corals during outbreaks. Normally, their impacts are minimal, as they tend to be rare or at very low densities for extended periods. Every 10 to 30 years, COTS have been reported to undergo brief episodes of unsustainably high densities. There is a good deal of evidence that

the periodicity and spatial extent of these unusual population explosions have increased and some speculation that it is related to climate change.

Nevertheless, there is considerable debate about whether these outbreaks are a natural cycle of events or an unnatural process resulting from human activities. One theory is that humans have eliminated the starfish's predators through shell collecting (Triton's trumpet snails) and overfishing (certain wrasses, triggerfishes, and a few other fishes), but this seems rather unlikely because these species would never achieve the abundance necessary to control an outbreak. More likely, their increase is related to a higher than normal survival of larvae. The starfish tend to reproduce once



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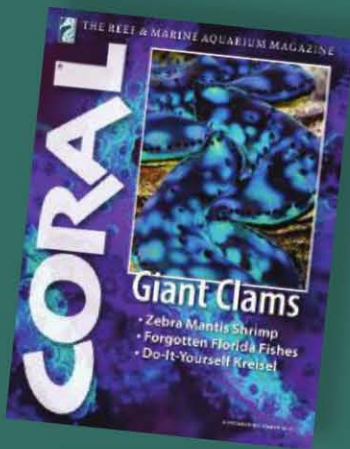
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Coral Reef CPR director Andrew Bruckner, center, showing resort staff a juvenile starfish. Raising awareness of their presence, their ecology, and efforts to remove them is key to being successful at eliminating outbreaks.

each year through broadcast spawning, in which the animals release eggs and sperm into the water column synchronously. Most of the resulting larvae typically die due to food limitations or become prey for planktivorous fishes. However, if there are unnaturally high levels of nutrients that trigger plankton blooms, the increased food availability may allow many more larvae to survive and settle onto the reef.

To some extent, 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 bodies, remarkable ability to regenerate detached limbs, ability to go for prolonged periods without feeding, and tendency to aggregate. One animal can produce more than 60 million eggs each year. If you multiply that by thousands of animals on a single reef, the number of possible larvae is enormous!

We initially began working in the Maldives to assist the resorts and dive centers in controlling the COTS outbreaks. The problem was first highlighted in the spring of 2015 through social media. Local marine biologists began posting reports on Facebook of the occurrence of COTS and actions they had taken to control the starfish. Early attempts primarily involved the removal of the starfish, but this was a tedious and dangerous process, and often only a few dozen animals were removed on each dive. Some divers attempted to kill them by cutting them into pieces, but because of their ability to regenerate missing limbs, this may have worsened the situation. Others began relying on more sophisticated technology, using injection guns and toxic chemicals. Divers experimented with a host of chemicals ranging from bleach to various petroleum products, sodium bisulphate, and even dish soap. Most were ineffective, and many caused more damage to the reef. A few dive centers purchased bile salts, which have been shown to rapidly kill starfish after one or two injections with minimal impacts on other organisms or the reef. The only difficulty was acquiring this expensive chemical and battling with border control and customs departments. Many divers have now switched to common household vinegar. Although it is a low cost alternative, it may require multiple injections and the correct location of injection is crucial. Some resorts and dive operators have not taken action, partially because of limited capacity, lack of equipment and manpower, and fear of injury but also due to a general lack of understanding of the gravity of the situation. Our intent was to raise awareness about COTS, their potential impacts, and options to control outbreaks, as well as to assist in removing the starfish.

Coral Reef CPR is also interested in understanding the origins of the starfish, as this could help us identify factors that are responsible for the outbreak.

GEORGIA COWARD

Collected starfish are measured and tube feet are removed for genetic analysis.



moved from different locations. We can extract DNA from the tube feet that will provide us with abundant information on their population structure and how closely related distant populations are. Our samples will include tube feet from many of the reefs in the Central Maldives,

Unlike the large-scale outbreaks of COTS in Australia, where the starfish have spread throughout large areas of the Great Barrier Reef, most Maldivian outbreaks have been confined to individual reefs on specific atolls, and the COTS need to migrate great distances, across deep water, to move from one atoll to the next. After mapping the distribution of the COTS and the pattern of spread, it seemed possible that they originated on the west side of North Malé Atoll and radiated outward throughout the atoll and to neighboring atolls. To verify this, we are collecting tube feet from the starfish that we have re-

where the most severe outbreaks have been documented, as well as those we find on the northern atolls.


It is imperative that we concurrently determine whether removal (or injection) is even a feasible and effective solution that could benefit the reef by preventing further coral losses and future outbreaks and speed up recovery. To answer our second question, we established permanent sites within a number of different reef systems on two atolls, South Malé Atoll and Baa Atoll. In these sites we are quantifying the types of corals, the amount of living coral cover, the condition of the corals,





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and the impacts of COTS. We included reefs that were visibly damaged by COTS and some that have never been affected. We also established sites on different types of reefs: fore reef communities on the outside of the atoll, farus and thilas within the lagoon, and kandu (channel) reefs that connect the deep lagoon with the open ocean. To understand the current condition of these sites and future trends, we are also looking at the impacts of other stressors and whether certain sites tend to recover more quickly than others. In particular, we are studying the effects of the mass bleaching event that occurred in April and May 2016 as a result of a very severe El Niño event, and the relationships between bleaching and COTS and the resilience of these reef systems. The reality is that Crown-of-Thorns Starfish population explosions, like most other threats to coral reefs, are increasing in both intensity and frequency. However, outbreaks of these voracious and damaging coral predators can be tackled at a local level, and research to understand their source and the outbreak drivers can be undertaken, to assist in reducing the impacts from global-scale threats.

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