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Great Barrier Reef
Marine Park Authority

Crown-of-thorns starfish

Strategic Management Framework

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Executive Summary

Crown-of-thorns starfish (COTS) outbreaks are one of the major cumulative pressures that cause coral mortality across the Great Barrier Reef (the Reef). Although COTS are native to the Reef, they become a pest when they reach outbreak levels and these outbreaks are a leading cause of the Reef-wide decline in coral cover observed over the past 40 years. The impacts of COTS outbreaks compound the damage caused by tropical cyclones, coral bleaching events, coral disease outbreaks and flooding events. Of these major causes of coral mortality, mitigation of COTS outbreaks represents an immediate and viable Marine Park management strategy to counter the Reef-wide decline in coral cover. Indeed, the overarching goal of COTS management is not to eradicate COTS, but rather to support the health and resilience of coral communities across the Great Barrier Reef Marine Park (the Marine Park), as highlighted in the Reef Blueprint for Resilience.

An emerging theme from the Reef 2050 Long- Term Sustainability Plan is that, in the face of cumulative pressures, stronger, targeted actions are needed to ensure the Reef retains the values for which it was declared a World Heritage Area. To that end, research suggests that efforts to reduce the frequency and/ or severity of COTS outbreaks through adaptive management can minimise coral decline and support recovery. Targeted COTS management can be used to prevent predation on corals that survive bleaching events and tropical cyclones, and may be synergistic with other Reef Restoration and Adaptation initiatives, thus supporting the Reef's capacity to resist, repair and recover from the impacts of a changing climate. Effective COTS management represents a proven and targetable strategy to support the resilience of coral communities and contribute to improving the long-term Outlook for the Great Barrier Reef.

This **Crown-of-thorns starfish Strategic Management Framework** has been developed by the Great Barrier Reef Marine Park Authority (the Marine Park Authority) in partnership with the Queensland Government, scientists, and the tourism industry. It builds on several decades of COTS research and outbreak management, and supports an informed, collaborative and adaptive approach to enhance the resilience of the Great Barrier Reef. Although this Strategic Management Framework is focused on the Marine Park, the general management principles can be applied in other coral reef areas where COTS outbreaks occur, both nationally (e.g. the Torres Strait) and internationally.

The first section of the COTS Strategic Management Framework provides background information on the problem and its underlying causes. Unlike coral bleaching and tropical cyclones, COTS outbreaks on the Reef do not occur as a seasonal phenomenon but rather initiate approximately every 15 years and subsequently spread across the Reef over a period of at least 10-12 years. This means that COTS outbreaks are impacting the Reef most of the time, though the spatial location of that impact changes over time. These outbreaks cause significant coral mortality across the Marine Park and a multitude of factors contribute to their development and spread, including the biology of the starfish, the abundance of their coral food source, poor water quality, hydrodynamic circulation patterns, and reductions in natural predators.

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Given the sustained impact of outbreaks and their multiple drivers, effective COTS management requires a holistic approach that combines long-term management actions aimed at preventing outbreaks, with tactical response actions aimed at minimising coral mortality and promoting recovery when outbreaks are underway. The second section of the Strategic Management Framework outlines this holistic management approach and details how the objectives and strategic targeting of COTS management efforts vary across different phases of the outbreak cycle. Preventative actions, which are ongoing across the outbreak cycle, include improving water quality and the protection of COTS predators. Once an outbreak begins to develop, management then ramps up tactical response actions aimed at suppressing and containing the outbreak to the initiation region, or protecting coral at high value locations if the outbreak cannot be suppressed and contained. These tactical responses are currently delivered through the Marine Park Authority's COTS Control Program. This Control Program operates on modern principles of Integrated Pest Management (IPM) and will continue to evolve and apply new pest management tools and technologies as they become available.

The third section of this Strategic Management Framework details the monitoring information that underpins effective management of COTS outbreaks in the Marine Park. This monitoring includes environmental factors, such as coral cover, water quality and hydrodynamic circulation patterns, that can provide an early warning of developing outbreaks. Effective management also requires information on COTS presence or abundance across the Marine Park.

Given the large spatial extent of the Great Barrier Reef, the Marine Park Authority ultilises COTS information from a wide range of sources to inform its tactical response actions, including Eye on the Reef Sightings reports by members of the public, surveillance by marine park rangers from the Reef Joint Field Management Program, and highly detailed surveys by scientists from the Australian Institute of Marine Science (AIMS) and other research institutions. Where possible, this COTS survey information is interpreted against standard outbreak status thresholds in order to indicate the relative COTS impact amongst individual reefs in the Marine Park. Concurrently, the Marine Park Authority is building COTS monitoring information and decision support into the Reef 2050 Integrated Monitoring and Reporting Program (RIMReP). Once operational, RIMReP will integrate the environmental, biological, and management information required to deliver the Marine Park Authority's holistic approach to COTS management.

Ongoing research and innovation is central to our vision of delivering world-leading, science-based, adaptive management of COTS outbreaks on the Great Barrier Reef. The fourth section of this Strategic Management Framework outlines the priority knowledge gaps that should be addressed in order to improve COTS management. Several emerging tools are highlighted that hold particular promise for enhancing the efficiency and effectiveness of COTS management into the future. These priorities will be captured in the Marine Park Authority's Science Information Needs publications.

The final section of this Strategic Management Framework provides guidance on how stakeholders and community groups can contribute to COTS management on the Great Barrier Reef. Reef users can report their COTS sightings through the Eye on the Reef Program and this information may then be used in strategic planning and tactical response. Concerned stakeholders can also undertake culling. Details on permitting requirements and recommendations for conducting this activity safely and effectively are provided.

The Marine Park Authority's COTS Strategic Management Framework is intended to serve as a basis for the effective management of COTS outbreaks in the Marine Park. The effectiveness of this approach will continue to be evaluated and adapted based on learnings and research advances collaboratively with our management partners, scientists, reef stakeholders and the public. The application of this Framework is one of the key resilience-based management initiatives identified in the Reef Blueprint for Resilience. The Framework has been designed to integrate with other Blueprint initiatives, such as the Resilience Network, as they mature. This agile, holistic approach will ensure that COTS management can be targeted based on both COTS outbreaks dynamics and opportunities to enhance coral reef resilience to cumulative impacts in the Marine Park.

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Introduction to crown-of-thorns starfish management on the Great Barrier Reef

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The Great Barrier Reef is a World Heritage Area of Outstanding Universal Value, and a significant part of Australia's national identity.

It is protected by the Australian and Queensland governments, together with local governments, Traditional Owners, industry, research bodies and community organisations under the *Great Barrier Reef Marine Park Act 1975*.

Healthy, functioning coral reefs provide a host of ecosystem services and underpin the resilience of the Great Barrier Reef (the Reef). They support the integrity, biodiversity, cultural and heritage values of the Reef and its economic and community benefits. The Great Barrier Reef Outlook Report 2019 identifies crown-of-thorns starfish (COTS) outbreaks as a major threat to the health and resilience of the Reef.[1] COTS outbreaks can last over a decade, progressing through the Reef system in a manner likened to a "slow-motion wildfire". The damaged coral reefs left in the wake of a COTS outbreak can take years or even decades to recover, and this recovery is prolonged when the reefs are exposed to other pressures.[2]

Since the establishment of the Great Barrier Reef Marine Park (the Marine Park), the frequency and severity of COTS outbreaks have caused increasing concern about their impact on the Reef's resilience and its overall health. There have been four documented major COTS outbreaks on the Reef: in the 1960s, the late 1970s, the early 1990s, and the current outbreak, which was first detected in 2010.

Since the 1980s, the Great Barrier Reef Marine Park Authority (the Marine Park Authority) has worked with research partners, government agencies, and the tourism industry to understand the dynamics and causes of COTS outbreaks, and to explore and test potential management responses.[3,4,5,6,7] Over the last four decades, our understanding of COTS biology, population dynamics, ecological impacts and the factors contributing to outbreaks has improved substantially.[8] Meanwhile, COTS control methods have now become significantly more effective and environmentally friendly.[9,10]

It has also become evident that the recurrence of severe COTS outbreaks, combined with other disturbances (e.g. coral bleaching events, severe tropical cyclones and flood events), have created serious threats to coral communities and the overall resilience of the Reef.[1,2] Minimising the impact of COTS outbreaks is now considered one of the most scalable and feasible management actions available to protect corals on the Great Barrier Reef, and is a critical intervention for the Reef's long-term health and resilience.[11,12]

Our vision is to deliver world-leading, science-based, adaptive management of COTS on the Great Barrier Reef, in line with the policies and goals outlined in the Australian Government's Reef 2050 Long-Term Sustainability Plan, the Reef Blueprint for Resilience, and the Marine Park Authority's Corporate Plan.[11,13]

The Marine Park Authority's ***COTS Strategic Management Framework*** provides the guiding principles to actively manage COTS now, while also promoting and supporting research and innovation to improve COTS management into the future. It recognises that effectively addressing the COTS threat will require coordination across state and federal government agencies, research institutes, reef-based industries, and community action groups. This ***Strategic Management Framework*** seeks to inform, empower and guide these groups to deliver a coordinated approach to COTS management in the Great Barrier Reef Marine Park by:

(i) Providing background information on the COTS problem;

(ii) Outlining the strategic approach for management of COTS outbreaks in the Marine Park;

(iii) Outlining the monitoring that informs COTS management;

(iv) Identifying knowledge gaps and research that will support improved COTS management;

(v) Providing guidance to reef stakeholders and community groups on how they can contribute to COTS management.

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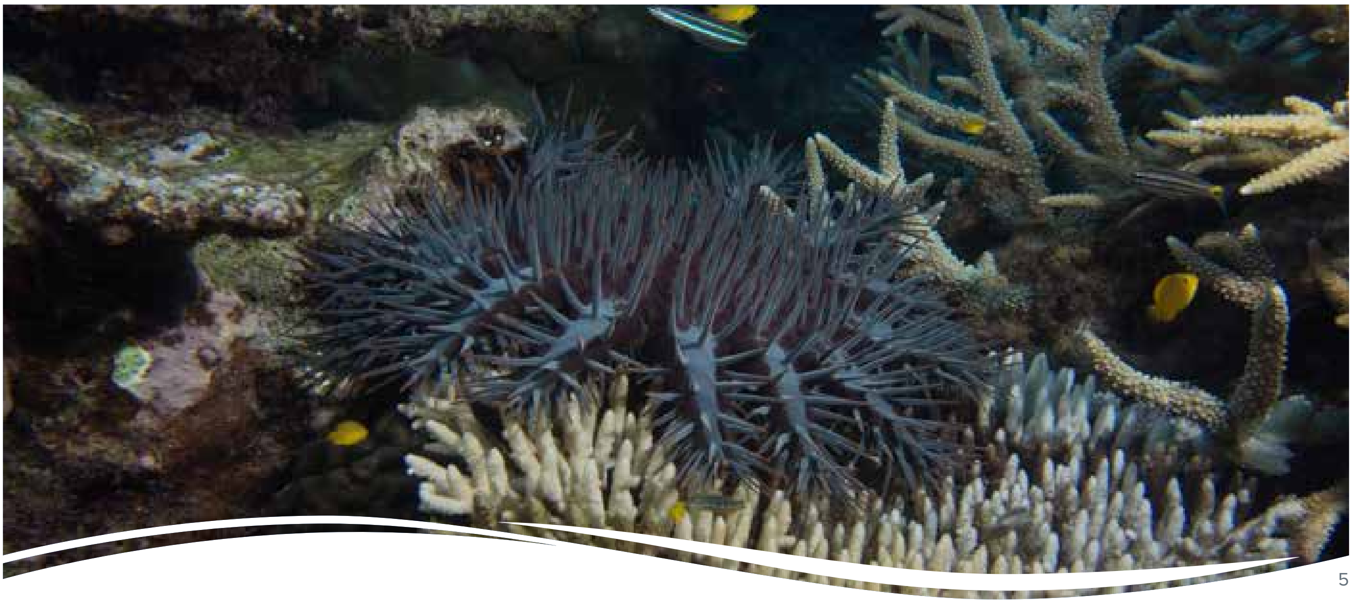
Reef 2050 Plan target:

MTR EHA 2 Implement an integrated crown-of-thorns starfish management framework within the Marine Parks to guide and coordinate efforts by all partners to reduce coral predation and maximise live coral cover on identified reefs.

2

Understanding the Crown-of-thorns starfish problem



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2.1 COTS biology

The Pacific Crown-of-thorns starfish (*Acanthaster cf. solaris*) is native to the Great Barrier Reef and is not an introduced species. These starfish feed exclusively on live coral as adults and have the ability to consume an area of coral equal to half their own body area (e.g. the size of a dinner plate) every day. At low densities, COTS contribute to the maintenance of coral diversity on reefs, by feeding preferentially on faster-growing corals thereby creating space for slower-growing coral species to colonise.

Although COTS are a natural part of the Reef ecosystem, their density can become so high that they reach pest levels.[6,14] A number of life-history characteristics enable COTS to reach these pest-level outbreak densities. These starfish have a long pelagic larval duration (e.g. 10-40 days) which promotes their widespread dispersal across the seascape, and once they settle onto a reef they grow rapidly and reach reproductive maturity quite quickly (within two years). Once they reach maturity COTS are highly fecund, with an average female producing at least 30 million eggs every spawning season (i.e. October to February on the Great Barrier Reef).[15]

2.2 Primary and secondary outbreaks

During outbreaks, COTS become much less selective in their feeding and can significantly impact Reef health because their consumption rate exceeds the growth rate

6A

6B

6C

Figure 1: Images show the impacts of crown-of-thorns starfish outbreaks on coral reefs.

(A) Healthy coral reefs often have high cover of living corals that provide structurally complex habitat to reef inhabitants

(B) During outbreaks, COTS feed on live coral, causing significant coral mortality.

(C) The ultimate consequence of outbreaks is a shift to reefs with reduced cover of living corals and reduced habitat structural complexity.

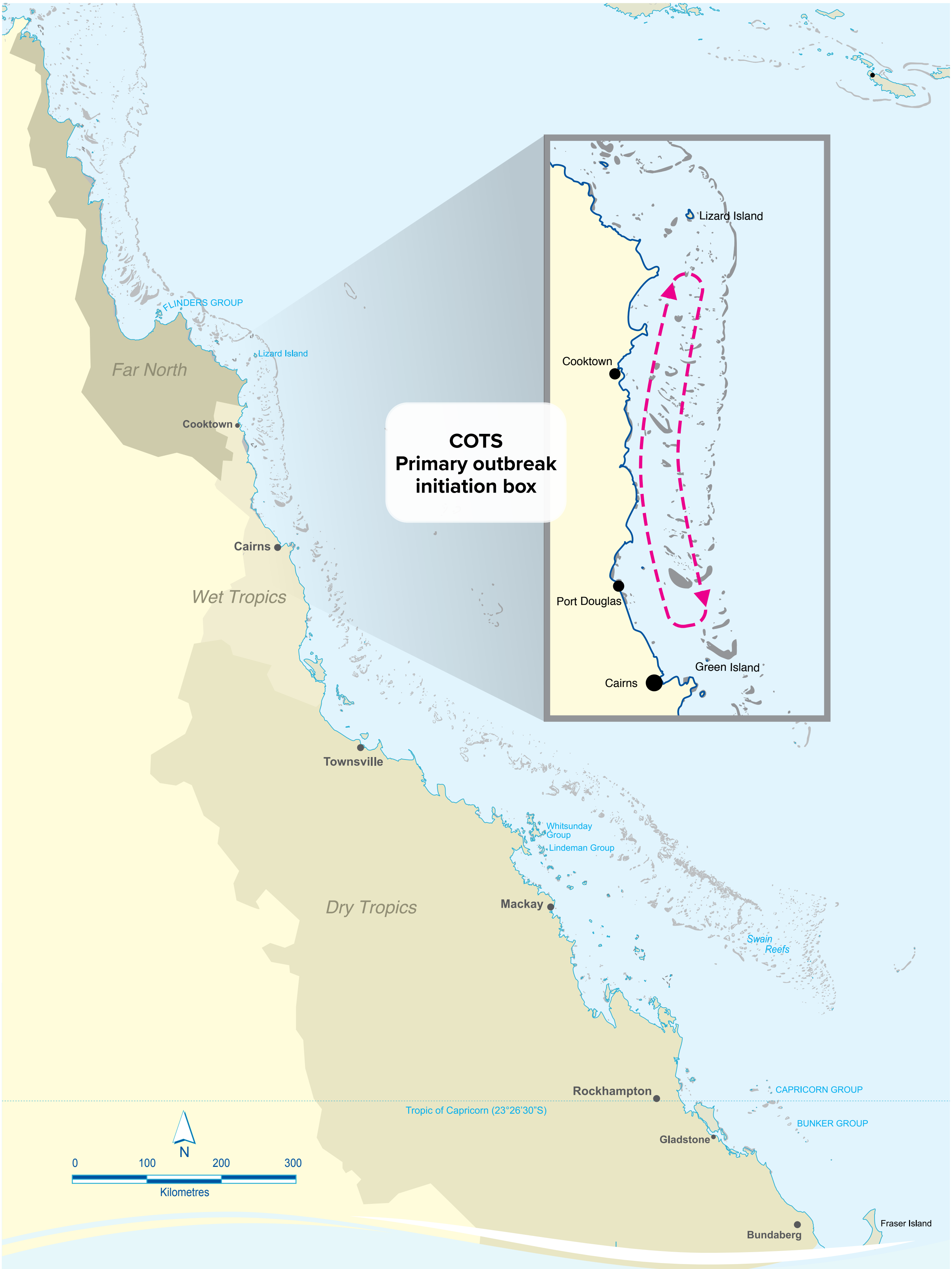

Figure 2: The Great Barrier Reef and its catchments showing the initiation region for primary COTS outbreaks. Outbreaks tend to originate on mid-shelf reefs in the north-central (Wet Tropics) region of the Great Barrier Reef between Lizard Island (14.6°S) and Cairns (16.6°S), where connectivity among reefs is high and facilitates the build-up of primary outbreaks. Populations are then spread southwards through mid-shelf reefs by southerly prevailing currents.

of corals. The consequence is often a shift from diverse three-dimensionally complex coral reefs with high cover of living corals, to reefs with very low coral cover and reduced habitat structure (**Figure 1**). This loss of live coral and reduced habitat structural complexity has significant negative consequences for the wide diversity of organisms that live on coral reefs.[16,17,18]

Crown-of-thorns starfish outbreaks on the Great Barrier Reef can have two distinct phases – a primary outbreak and a secondary outbreak phase.[14] Primary outbreaks involve the build-up of reproductively mature adults over successive generations in a relatively small area. This concentrated breeding population then spawns en-masse, triggering waves of secondary outbreaks that spread via the dispersal of larvae on ocean currents. On the Great Barrier Reef, primary outbreaks appear to originate on northern reefs in the region between Lizard Island and Green Island (**Figure 2**) and then progress southward at a rate of 60 kilometres per year, over a 15-year period.[19] From this initiation region COTS larvae are predominantly carried southward by the prevailing ocean currents, but can also be carried northwards by inner shelf counter currents[20], thus contributing to the high connectivity of reefs in the initiation region. Outbreaks have also been documented in the Far North of the Marine Park; although modelling suggests these may occur at a much lower frequency (i.e. around once every fifty to eighty years) compared to those outbreaks that begin in the initiation region and spread through the northern and central regions of the Great Barrier Reef.[21] Finally, separate outbreaks have also been observed in the Swain Reefs at the southern extent of the Marine Park[22,23], though the dynamics and drivers of these outbreaks are not well understood.[14]

2.3 What causes outbreaks?

While the exact combination of factors that lead to primary COTS outbreaks are not fully understood, research suggests that a combination of factors may be involved, including the biological traits of the starfish themselves, as well as environmental factors such as nutrient run-off, fishing pressure, coral prey availability, and hydrodynamic circulation patterns (**Figure 3**). Indeed, the geography, connectivity and hydrodynamic characteristics of the Great Barrier Reef appear to make it particularly vulnerable to COTS outbreaks.[20,24] Some of the factors that may lead to outbreaks are linked to human activities[2,14,20,21] and may be mitigated through management of the Marine Park and its catchments (e.g. water quality, protection of COTS predators), whereas other factors cannot be influenced through local management intervention (e.g. hydrodynamic circulation patterns).

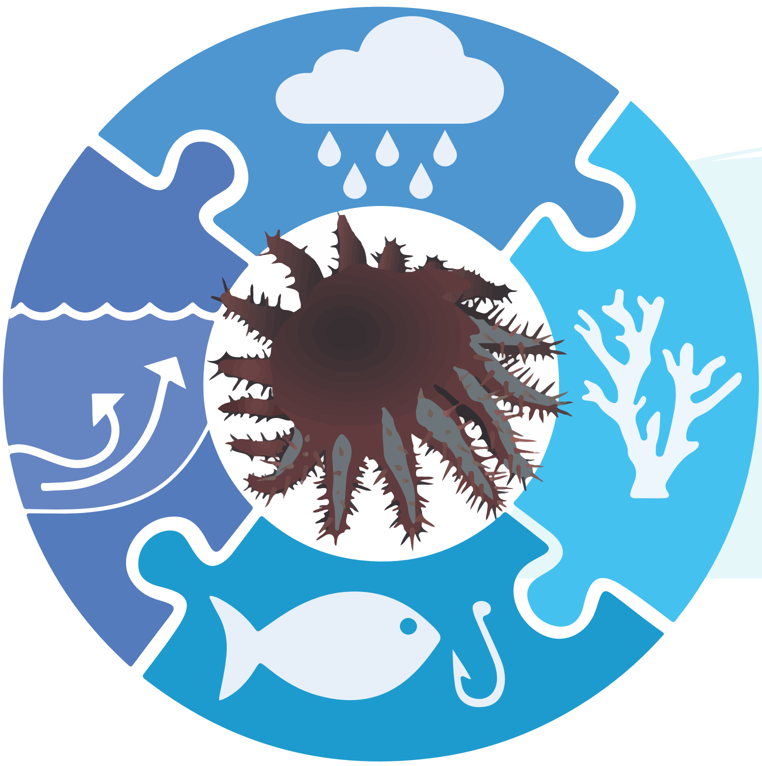

Figure 3: Environmental factors that may contribute to the development of outbreaks of crown-of-thorns starfish on the Great Barrier Reef.

These include nutrient run-off entering the Great Barrier Reef lagoon following storms and flooding events, the availability of sufficient coral prey to support outbreak populations of COTS, reduced numbers of COTS predators due to fishing pressure, and hydrodynamic circulation patterns that distribute COTS larvae.

3

Outbreak management cycle

3.1 Preventative actions

While anecdotal accounts and oral histories suggest that the Great Barrier Reef may have experienced COTS outbreaks prior to the 1960's[25,26], contemporary outbreaks may be linked to human activities that have compromised the resilience of the ecosystem and made it more vulnerable to outbreaks.[14] Consequently, investment in preventative actions aimed at improving water quality and protecting COTS predators are expected to deliver positive management outcomes in the long-term, by enhancing the resilience of the Reef ecosystem. If these preventative actions are successful, the current 15-17 year outbreak cycle may be extended with a longer duration between outbreaks, providing more time for coral communities on the Reef to recover from cumulative impacts.

3.1.1 Water quality improvement

Declining water quality is one factor that has been linked to the development of contemporary COTS outbreaks on the Reef.[20,21,27,28,29,30] Rivers in the central and southern Great Barrier Reef currently carry five to nine-fold higher nutrient and sediment loads compared with pre-European settlement.[2,31] As a consequence, elevated nutrient levels now exceed the thresholds that promote enhanced survival of COTS larvae in most years.[28,29] Concurrently, the effect of climate change on rainfall variability is increasing the likelihood of large-scale flood events that can carry high nutrient loads to the Reef.[32] Although COTS larvae can still survive in low nutrient conditions, exposure to high levels of nutrients enhances COTS larval growth and survival[21,29] and also enhances rates of cloning (i.e. asexual reproduction) in

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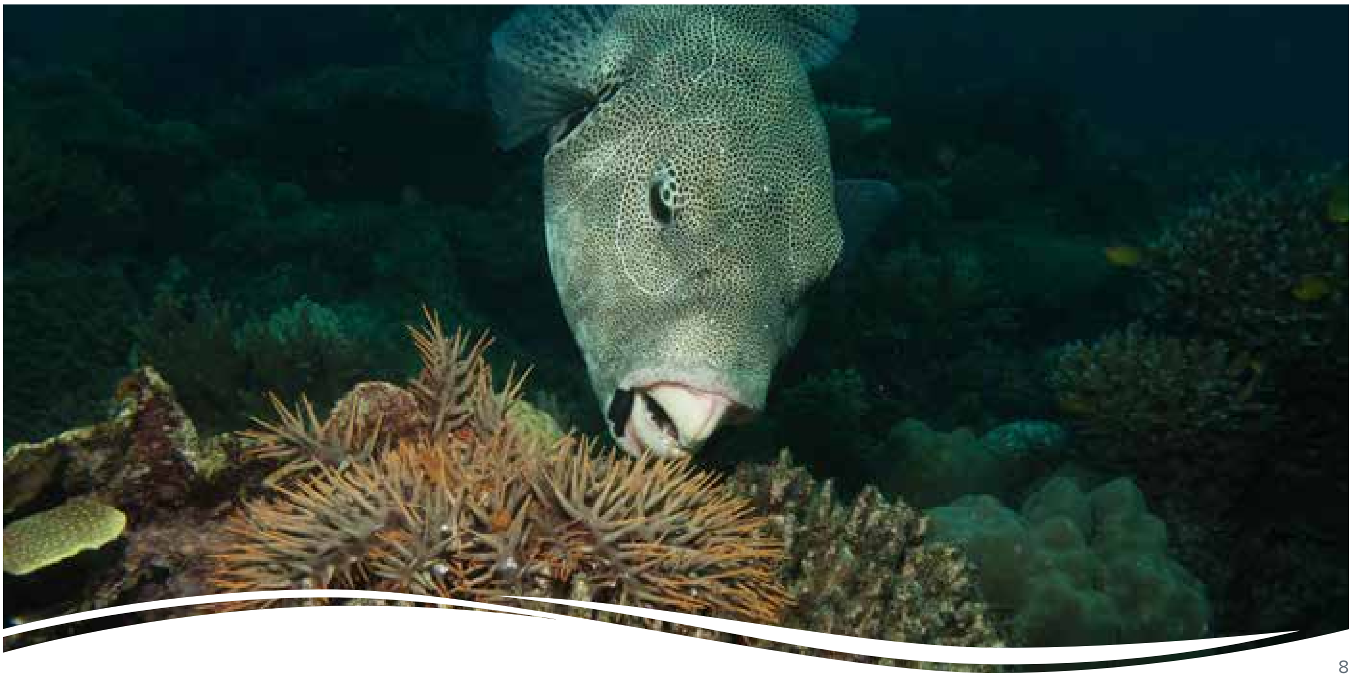

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COTS larvae.[30] Taken together, this evidence suggests that contemporary water quality conditions on the Great Barrier Reef are enhancing the capacity of COTS larvae to survive, multiply and spread.

Given the accumulation of scientific evidence indicating that poor water quality may exacerbate COTS outbreaks, improving water quality is an important long-term strategy to reduce the frequency of COTS outbreaks in the Marine Park. This preventative action will also have the benefit of enhancing the ability of coral communities to recover from cumulative impacts, including damage from COTS outbreaks.[33] These positive outcomes for the Reef may be realised by meeting the targets set by the Australian and Queensland governments Reef 2050 Water Quality Improvement Plan 2017-2022.[34] However, progress towards achieving these water quality targets has slowed[1], and research suggests that current mitigation measures may be inadequate to reach these targets.[35,36] Increasing efforts to improve water quality, particularly in the Wet Tropics catchment adjacent to the primary outbreak initiation region, remains critical for effective COTS management in the long-term.

3.1.2 Protection of the natural predators of COTS

Reductions in the natural predators of COTS is another factor potentially linked to the development of COTS outbreaks on the Great Barrier Reef.[14,19,37,38,39,40] Predators play an important ecological role in regulating the abundance of their prey, and when predator numbers are reduced it can lead to population outbreaks in prey species. Natural predators of juvenile and adult COTS include a diverse range of reef fishes and invertebrates, including the giant triton snail, harlequin shrimp, humphead Maori wrasse, spangled emperor, red throat emperor, starry pufferfish, Queensland grouper, and titan triggerfish.[37] Some of these COTS predators, like the giant triton snail, were historically overfished, and other iconic species, including Maori wrasse and Queensland grouper, are now fully protected species under Great Barrier Reef Marine Park Regulations and Queensland Fisheries Regulations.[41,42,43] In contrast, other COTS predators, such as emperors, are currently fisheries target species. Reefs in the Marine Park that are protected from fishing and collecting through the Great Barrier Reef Marine Park Zoning Plan[44] tend to have lower abundances of COTS and have experienced outbreaks less frequently than those open to fishing and collecting.[19,38,40,45] Consequently, the continued and improved regulation of fishing, and enforcement of compliance with Marine Park Zoning, are important components of the long-term strategy for managing COTS outbreaks in the Marine Park. In the future, the restoration of local populations of keystone COTS predators, such as the giant triton snail, may also be considered.[46]

As with water quality improvement, preventative COTS management actions aimed at protecting the predators that naturally suppress COTS abundance will provide additional benefits to the health and resilience of the Great Barrier Reef. Marine Park Zoning and fisheries management provide benefits for fisheries sustainability[47,48], and reefs that are protected from fishing recover 2-3 years faster from the damage caused by COTS outbreaks compared to reefs where fishing is allowed.[49]

3.2 Tactical responses during an outbreak

Although completely eradicating COTS in the Marine Park is neither possible nor desirable, a tactical response that effectively reduces the ***severity and extent*** of COTS outbreaks on the Great Barrier Reef has the potential to deliver ecosystem resilience benefits.[11] This outbreak response should be dynamic and adaptive, with objectives and strategic targeting of COTS control efforts varying over time depending on the phase of the outbreak cycle (**Figure 4**).

PHASE 1: During the **NON-OUTBREAK** phase, live coral cover may ***RECOVER*** on reefs in the outbreak initiation region, thus providing the prerequisite natural environmental condition for a primary outbreak (i.e. sufficient food availability). As outlined in Section 3.1, a key management goal during this phase is to ***PREVENT*** a primary outbreak through actions to mitigate the anthropogenic factors that contribute to outbreaks. These preventative actions should be ongoing throughout the outbreak cycle. The other critical management actions during this phase are proactive monitoring to provide early warning of the environmental conditions that may lead to the development of a primary outbreak, and proactive surveillance of COTS numbers, particularly in the primary outbreak initiation region. If this monitoring and surveillance reveals any signs of COTS activity in the initiation region, this would indicate the outbreak is entering Phase 2.

PHASE 2: If the right combination of environmental factors occurs (**Figure 2**) and surveillance indicates COTS numbers are beginning to build up, this indicates the potential for a **PRIMARY OUTBREAK** to develop on reefs in the initiation region. The key management actions during this phase in the outbreak cycle are to ***SUPPRESS*** the build up of COTS numbers, and ***CONTAIN*** the primary outbreak to the initiation region. This may be achieved through proactive control to suppress COTS numbers in the initiation region before they reach outbreak thresholds. Strategic targeting of control efforts to focus on reefs that are ecologically important for spreading COTS larvae to other reefs will help to contain the primary outbreak to the initiation region. Control efforts during this phase in the outbreak cycle should aim to reduce COTS densities below threshold levels that reduce the potential for successful reproduction.[50] If successful, this targeted action to suppress and contain a primary outbreak in the initiation region will have the greatest regional scale management

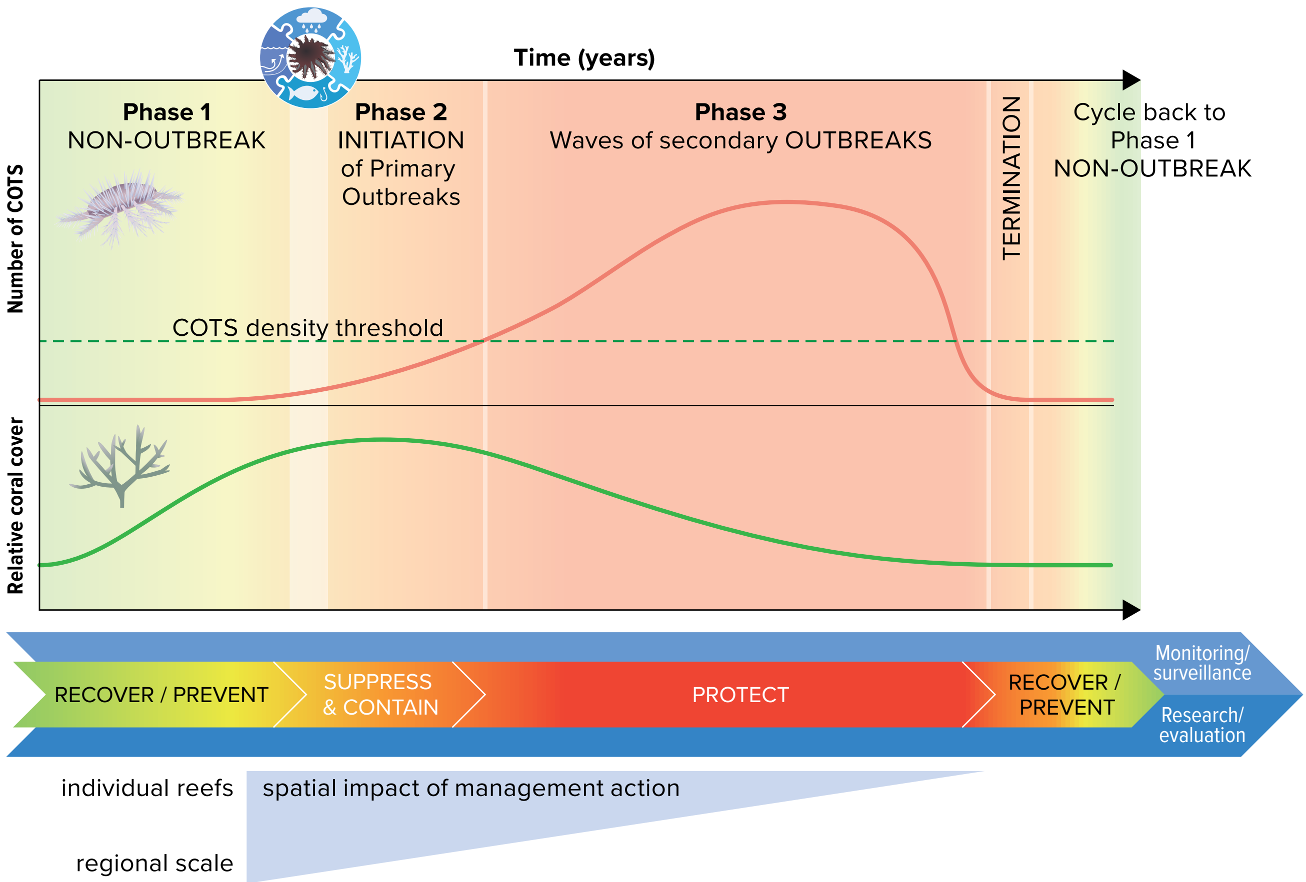

Figure 4: COTS outbreak cycle across the Great Barrier Reef, relative coral cover, and the associated stages of management action.

impact by minimising the spread of the outbreak from the initiation region to other regions of the Marine Park.[51] It is important to note that there is a relatively small window of opportunity to act during this phase of the outbreak cycle, and the development of early warning monitoring is therefore crucial to achieving management goals. Ongoing environmental monitoring and surveillance of COTS numbers remain important during this phase in the outbreak cycle.

PHASE 3: If COTS numbers exceed outbreak thresholds across reefs in the initiation region it will trigger waves of **SECONDARY OUTBREAKS** that spread COTS to other regions of the Marine Park. At this point, the outbreak can no longer be prevented, suppressed or contained. During this phase in the outbreak cycle the key management action is to **PROTECT** coral cover on selected reefs (or reef sites) of high ecological and economic value until the outbreak passes. Control efforts at this phase in the outbreak cycle should therefore aim to mitigate coral decline by reducing COTS densities below threshold levels that allow for coral growth and recovery.[52,53,54] Ongoing monitoring and surveillance during this phase remains important to inform targeted control efforts. The spatial scale of impact of management actions taken during this phase in the outbreak is more limited compared to the previous phase, with control targeted to the protection of individual reefs (or reef sites) of high ecological and economic value. The duration of this protection-focused phase in the outbreak cycle is much longer compared to the previous phase.

This third and final phase of the COTS outbreak cycle ends with outbreak Termination, which is characterised by a sharp decline in COTS numbers (**Figure 4**). The factors contributing to this abrupt decline are not well understood, but may include starvation and the spread of disease amongst outbreaking populations.[8] From a management perspective, it is important to recognise that these three phases in the outbreak cycle may occur simultaneously across different regions of the Great Barrier Reef Marine Park, such that the Termination of one outbreak cycle in the southern region after its southward spread over a 15-17 year period may occur at the same time as the beginnings of the next outbreak cycle in the initiation region. Consequently, the northern region may be in Phase 1-2 while the southern region is in Phase 3.

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3.3 The COTS Control Program

Since 2012 the Marine Park Authority has delivered a broad-scale COTS Control Program on the Great Barrier Reef, with vessel(s) and trained crews dedicated to manually culling starfish using lethal injection. Since its inception, the COTS Control Program has been delivered in close partnership with the Reef tourism industry through the Association of Marine Park Tourism Operators (AMPTO).

The Control Program was established several years into the current COTS outbreak cycle, once the primary outbreak in the initiation region was already well established and the opportunity to **SUPPRESS** and **CONTAIN** (Phase 2) had already passed. Consequently, the goal of the COTS Control Program has primarily been to **PROTECT** (Phase 3) coral in the Marine Park from COTS impacts. Initially the program targeted high value tourism sites on reefs in the initiation region.
As the secondary outbreaks spread, and resources for control increased, the program has expanded to target ecologically and economically valuable reefs within and beyond the initiation region.

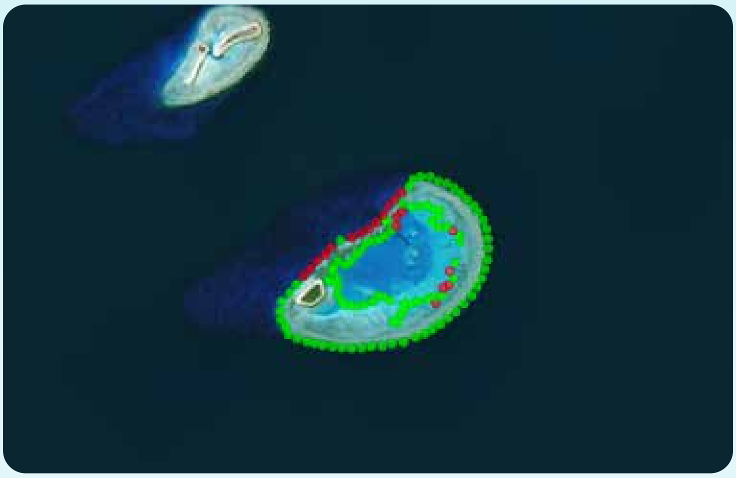
The Control Program applies the best-available science in its approach to tactical COTS response on the Great Barrier Reef, and has a track-record of ongoing adaptive management and improvement through its collaboration with research partners. In 2014, scientific innovation enabled significant improvements in the efficiency of culling operations using a single-shot injection of bile salts.[9] In 2015, the COTS Control Program began transitioning towards operating on modern principals of Integrated Pest Management (IPM) developed in terrestrial agricultural systems.[6,55] In 2018, further improvements to the program were achieved through the introduction of a bespoke decision support tool to guide on-water operations.[7,56]

The contemporary COTS Control Program on the Great Barrier Reef is more strategic in its approach than any previous COTS control efforts on the Great Barrier Reef or globally. Importantly, inherently limited resources are applied based on IPM principles that include strategically controlling key reefs based on systems analysis of connectivity[24,57], use of targeted surveillance to increase the efficiency of cull effort[58], application of culling thresholds designed to ensure COTS are controlled to levels that promote coral growth and recovery[52,53,54], and systematic monitoring of controlled reefs to inform adaptive planning and overall program effectiveness.[45,59] The Control Program will continue to adapt and improve its approach to tactical COTS management based on best available science, and will look to integrate new pest management tools and technologies as they become available.

CASE STUDY 1

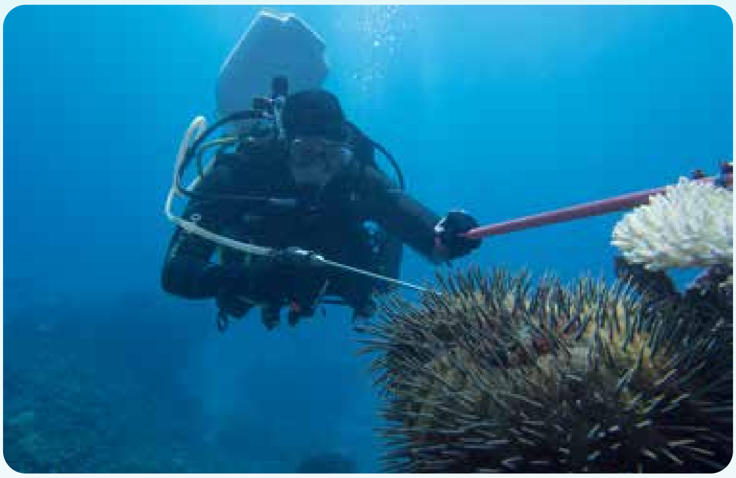
The COTS Control Program

Lady Musgrave Island reef, located in the Capricorn Bunkers in the southern Great Barrier Reef, has high economic and ecological value and is prioritised for pest management in the COTS Control Program. When this reef was first visited by a COTS Control Program vessel in July 2019, initial surveillance revealed it had an '*Established Outbreak*', with an average of 0.35 COTS counted per manta tow



Established Outbreak
July 2019, before culling

Over several months of intensive pest management this outbreak has been culled down, with trained divers thoroughly searching the reef across repeated voyages and culling 4,396 starfish using lethal injection



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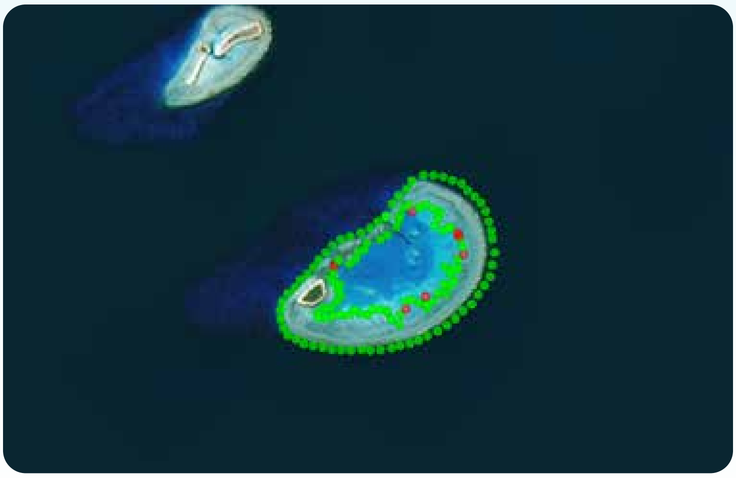
Intensive pest management
4,396 starfish culled

Repeated surveillance in January 2020 showed that the reef has been transitioned to '*No Outbreak*' status, with an average of 0.06 COTS counted per manta tow



No Outbreak
January 2020, after culling

Throughout the pest management process, surveys at this high value reef show that coral cover has remained stable at an average of ~40% hard coral cover. Ongoing monitoring and pest management will continue in order to maintain this positive outcome for coral communities at Lady Musgrave

3.4 The benefits of a holistic approach to COTS management

The most effective management response to the COTS threat is a combination of ongoing preventative actions to reduce the frequency of outbreaks in the long-term, and tactical responses that minimise the severity and extent of an outbreak when they occur. **Figure 5** illustrates and compares the effects of different combinations of preventative and tactical response measures, highlighting the value of a combined approach. If no management action is taken then it is expected that COTS outbreaks will continue to occur at a frequency of 15-17 years and these outbreaks will continue to have a severe impact on the health of the Great Barrier Reef (see **Option A**). Effective tactical response actions (e.g. a COTS Control Program) can reduce the severity of these outbreaks when they occur, but are unlikely to reduce their frequency (**Option B**). Effective preventative actions to manage the environmental factors that contribute to outbreaks (e.g. water quality, natural predators) may help to reduce the frequency of outbreaks, providing more time for coral to recover between outbreaks (**Option C**). Consequently, a sustained effort to address the environmental factors that contribute to outbreaks, as well as tactical response when outbreaks do occur, may reduce both the frequency and severity of outbreaks (**Option D**). This combined management approach to address both long-term drivers and acute pressures, is the most likely path to a future scenario in which coral cover is given the best chance to improve over the long term in accordance with the objectives of the Reef 2050 Plan.

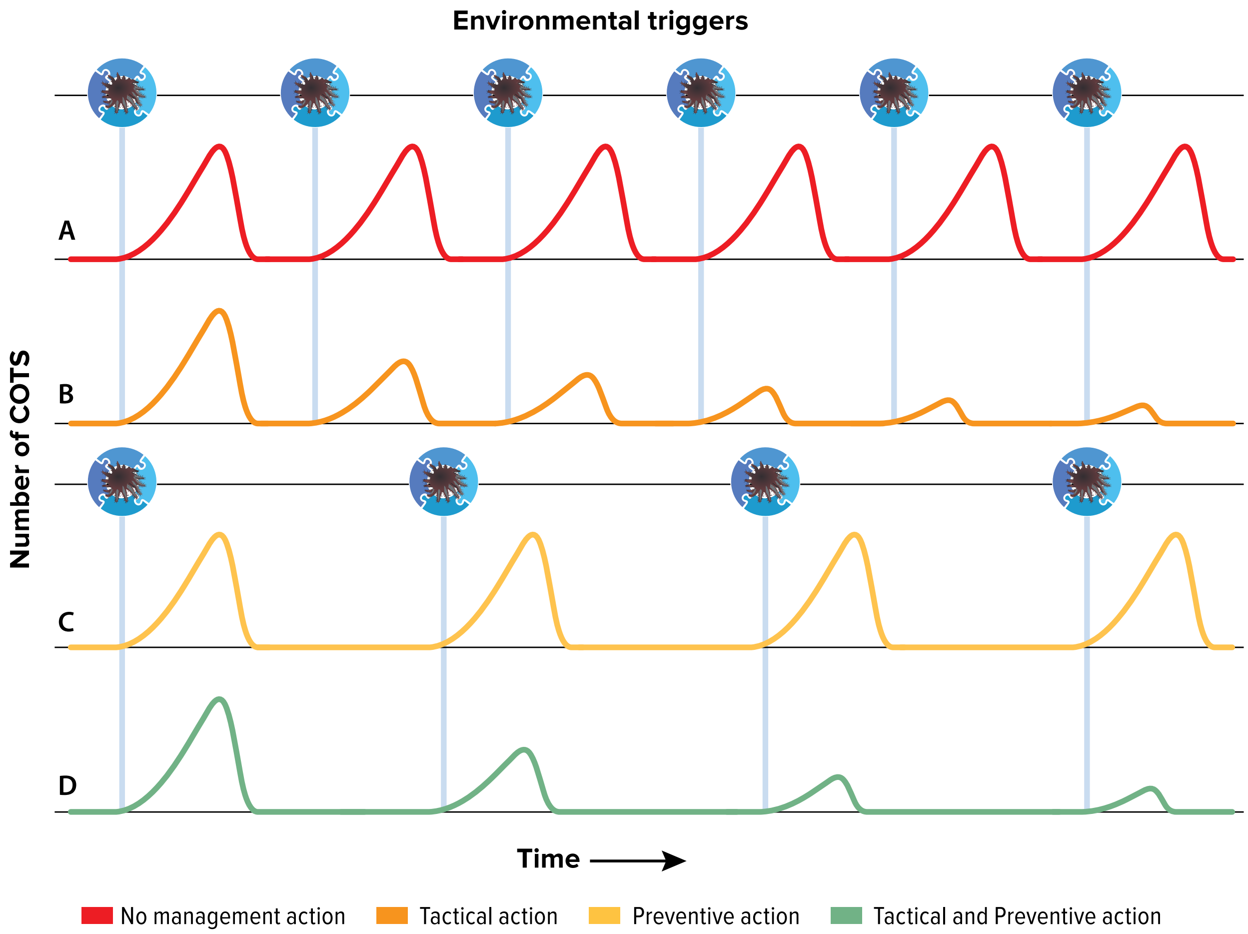


Figure 5: Conceptual model that illustrates the potential outcomes of different management options (**A-D**) on the number of crown-of-thorns starfish outbreaks on the Great Barrier Reef in the long-term.

Option A illustrates a scenario where no preventative or tactical response actions are taken.

Option B illustrates a scenario where tactical response actions (e.g. COTS control) are taken to manage the severity of outbreaks when they occur, and these tactics become more effective over time.

Option C illustrates a scenario where preventative management actions are taken to reduce the frequency of outbreaks.

Option D illustrates a scenario where both preventive and tactical response actions are taken to reduce the frequency and severity of COTS outbreaks on the Great Barrier Reef in the long-term.

4

Outbreak monitoring on the Great Barrier Reef

Monitoring is a critical component of COTS management across all phases in the outbreak cycle, as it provides the information required to efficiently and effectively respond to impending and established outbreaks. This monitoring includes both the environmental factors that may contribute to outbreaks and also changes in the abundance of COTS. Given the immense spatial scale of the Great Barrier Reef Marine Park (~3,000 reefs across 344,440 km^2), it is impossible to know the outbreak status of every individual reef at any one time. However, a combination of modelling predictions, environmental monitoring, and in-water surveys can be used to provide an indication of likely outbreak status of as many individual reefs as possible. The Marine Park Authority engages with a wide network of observers to collect information to monitor the development of outbreaks – including the Queensland Parks and Wildlife Service (QPWS), the Reef Joint Field management Program, the Australian Institute of Marine Science (AIMS), and the Reef tourism industry (including the Association of Marine Park Tourism Operators). The Marine Park Authority also engages the wider community of reef-users (e.g. fishers, tourists, local community members) through the Eye on the Reef Program to submit Sightings reports that help provide an early warning to inform more intensive monitoring efforts.

This monitoring information is being built into the Reef 2050 Integrated Monitoring and Reporting Program (RIMReP). Once operational, RIMReP will integrate the environmental, biological, and management information required for decision support and delivery of the Marine Park Authority's holistic approach to COTS management.

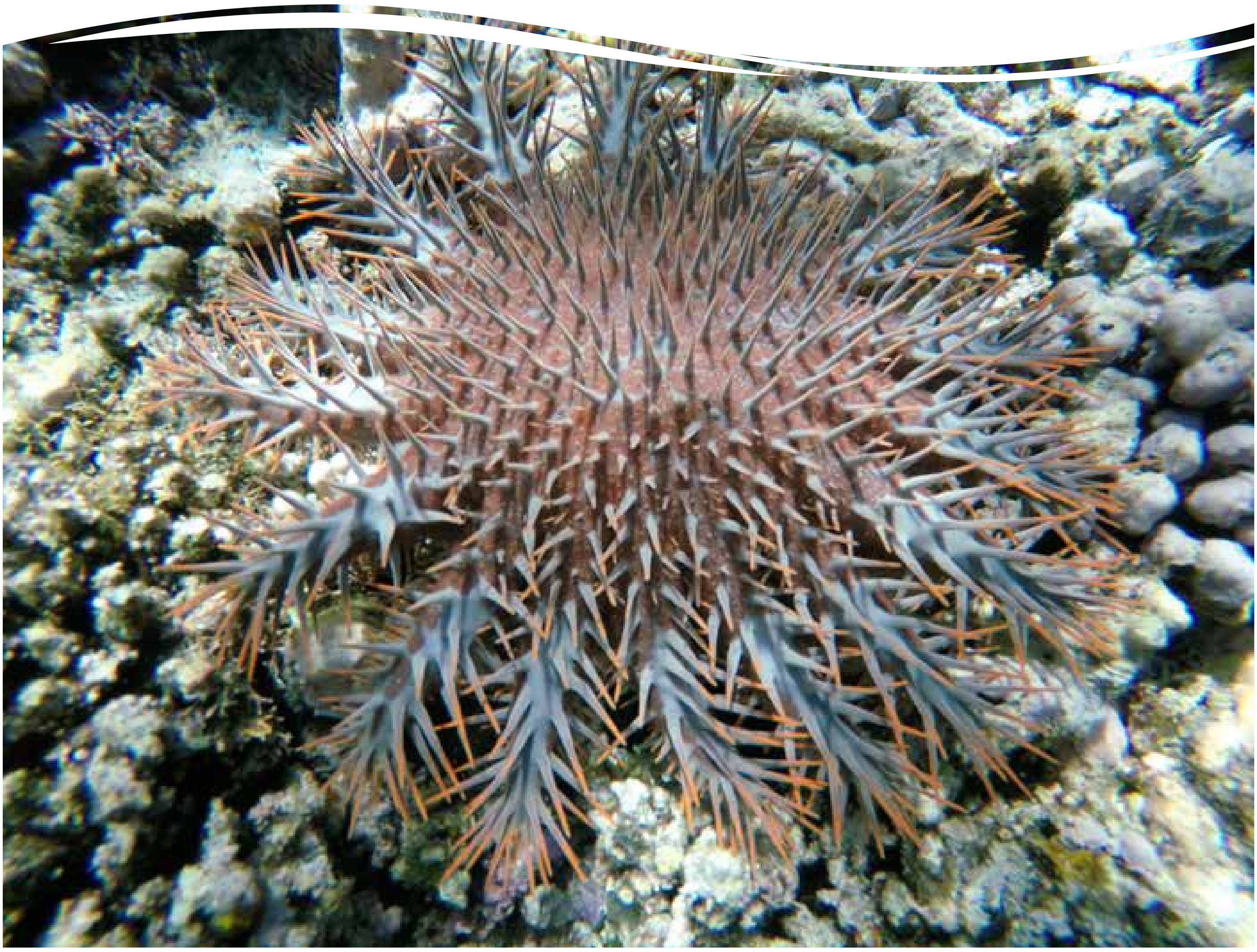
4.1 Environmental Monitoring

During the non-outbreak phase, the focus of monitoring should be on the suite of environmental factors that may combine to trigger primary outbreaks, including coral cover, water quality, and hydrodynamic circulation patterns. Monitoring these environmental factors, particularly in the outbreak initiation region, will provide an ***early warning*** of a potential impending primary outbreak and enable a rapid and efficient tactical response. This environmental monitoring should be ongoing through the outbreak cycle, though it is a particularly important focus of management effort in the non-outbreak phase leading up to a primary outbreak.

Coral cover. Monitoring live coral cover is critical across the outbreak cycle in order to inform management. During Phase 1 of the outbreak cycle, coral cover monitoring across reefs in the initiation region will indicate whether sufficient coral is available to sustain a primary outbreak. Preliminary modelling suggests that when coral cover is approximately 14 per cent, this could provide enough food availability for COTS populations to increase to outbreak densities.[52] Therefore, for the purposes of COTS management, if monitoring shows that average live coral cover has recovered to approximately 10-15 per cent across reefs in the initiation region there may be sufficient coral available to support a primary outbreak. Monitoring coral cover beyond the primary outbreak initiation region is also important to guide tactical control efforts during Phases 2-3 of the outbreak cycle, as it may inform strategic targeting of reefs for control and assessment of the effectiveness of management actions.

Water quality. Monitoring water quality in the initiation region, particularly during and after major flooding events, can provide an early warning of conditions that would enhance the development of a primary outbreak. In the northern and central sections of the Great Barrier Reef Marine Park, major COTS outbreaks have sometimes been preceded by large-scale flood events.[2,21,60] Nutrient enriched terrestrial runoff is linked to elevated phytoplankton bloom concentrations, which leads to enhanced COTS larval survival.[29] Therefore, floodwater exposure may be used to assess the probability of an outbreak occurring. Remote sensing and modelling of water quality conditions (particularly phytoplankton/chlorophyll-a concentrations) may also provide insight into which reefs are directly exposed to floodwaters (and subsequent increased phytoplankton densities) during the COTS spawning period. Successive years of exposure to nutrient-rich floodwaters may increase the likelihood of increased larval supply, and enable multiple generations of COTS larvae to survive and settle across reefs in the initiation region, creating the conditions for a primary outbreak. In the future, water quality monitoring could be integrated with biophysical modelling to identify reefs at risk of initiating primary outbreaks and thereby guide management efforts, particularly after major flood events.

Hydrodynamics. Monitoring variation in hydrodynamic circulation patterns could also provide early warning of impending primary outbreaks. This is because ocean currents are responsible for distributing COTS larvae across reefs within and beyond the initiation region, and the strength and direction of these currents affect local reef interconnectedness. Biophysical models that consider these hydrodynamic circulation patterns alongside the biological characteristics of COTS larvae could be used to estimate connectivity amongst reefs and assess the likely build up of COTS in the primary outbreak initiation region. These models could be used to identify reefs for monitoring in the initiation region that are most likely to initiate and spread COTS outbreaks.[24,61] These biophysical models are being extended to include explicit estimates of COTS numbers and coral cover[12] which may further help to predict the conditions that are conducive to the development of a primary outbreak. Combining these model predictions with regular in-water monitoring of COTS and coral cover in the initiation region may provide the greatest opportunity to suppress a primary outbreak and/or reduce the severity of subsequent secondary outbreaks.



[12]

CASE STUDY 2

The RJFMP COTS Response Project

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The Reef Joint Field Management Program (RJFMP) is a partnership between the Australian and Queensland governments to work together for the long-term protection of the Great Barrier Reef World Heritage Area. The RJFMP has a COTS Response Project, which delivers 30-60 days per year of in-water field surveillance of COTS numbers and coral cover across the Marine Park. This project fills gaps in knowledge about the severity and extent of outbreaks across the Marine Park, and ground-truths reports of COTS outbreaks from stakeholders and the community. This information is critical to inform the strategic planning and adaptive management of the COTS Control Program, with survey data from the COTS Response Project integrated into regional planning and reef prioritisation schedules for targeted pest management by COTS Control Program vessels.

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4.2 COTS Monitoring

When environmental monitoring suggests an increased risk of a primary outbreak developing in the initiation region, efforts to conduct targeted in-water assessment of COTS numbers should intensify. Given the large spatial extent of the Marine Park, gathering information on COTS from a range of different survey techniques and Marine Park users is vital to provide managers with an early warning of a developing primary outbreak (Phases 1-2) in the initiation region, and also to fill knowledge gaps on the severity and extent of COTS outbreaks across the Marine Park during secondary outbreak (Phase 3).

Eye on the Reef, Sightings Network reports. These reports provide information on the approximate number and spatial location of COTS observed in the Marine Park. No survey equipment or specialised training is required. These opportunistic surveys provide a quick and easy way for all users of the Marine Park to share information on COTS with Marine Park managers. This information may then be used to guide more in-depth assessments. COTS sightings information can be submitted via smartphone to the Marine Park Authority using the Eye on the Reef Sightings app.

Manta tow surveys. These surveys provide assessments of adult COTS abundance and also provide an indication of COTS activity through the presence of scars. Manta tow surveys are carried out by towing a trained observer behind a small vessel at a constant speed, and are therefore able to collect information over a broad spatial scale (e.g. 100's to 1000's of metres of reef habitat) relatively quickly. Surveys are conducted using snorkel, and some equipment and training is required. This survey technique is commonly used by reef managers, marine parks rangers and scientists to assess the outbreak status of reefs in the Marine Park.

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Eye on the Reef, Reef Health and Impact Surveys (RHIS). These surveys provide assessments of the abundance of both adult and juvenile COTS and their impacts on coral. The technique involves intensive searches of a 5-metre radius survey area.[62] RHIS are conducted using either snorkel or scuba, and some equipment and training is required. This survey technique is commonly used by reef managers, marine parks rangers and tourism industry stakeholders, and can be used to assess the outbreak status of reefs in the Marine Park.

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Scuba transect surveys. These surveys can provide highly detailed assessments of the densities and body sizes of both adult and juvenile COTS. This technique involves intensive searches in a pre-defined or known survey area (e.g. 100 m^2). Scuba transects are relatively time-intensive and require the most specialised knowledge and expertise. This survey technique is typically conducted by highly trained observers (e.g. scientists, reef managers)

4.3 Outbreak status assessment of reefs in the Marine Park

Individual reefs may experience varying severity of COTS outbreak, and some reefs may not be impacted by COTS at all, during Phases 2 and 3 of the outbreak cycle on the Great Barrier Reef. This spatial and temporal variability in the impact of COTS across reefs in the Marine Park poses a challenge to managers, and makes the information from in-water surveys from all Marine Park users valuable to inform where and when management action may be required.

An individual reef in the Marine Park is considered to have an outbreak when adult starfish reach densities where the impact of their feeding becomes unsustainable for coral growth and recovery, and will therefore cause decline in coral cover on that reef. The outbreak status thresholds used by the Marine Park Authority are derived from scientific research[40,63,64], and are tailored to the particular survey technique (e.g. manta tow or RHIS) that is used to estimate COTS density on a reef.

Information on the outbreak status of individual reefs across the Marine Park over time is stored in the Marine Park Authority's Eye on the Reef database, and can be visualised to provide an overview of known COTS impacts across the Marine Park (**Figure 6**).

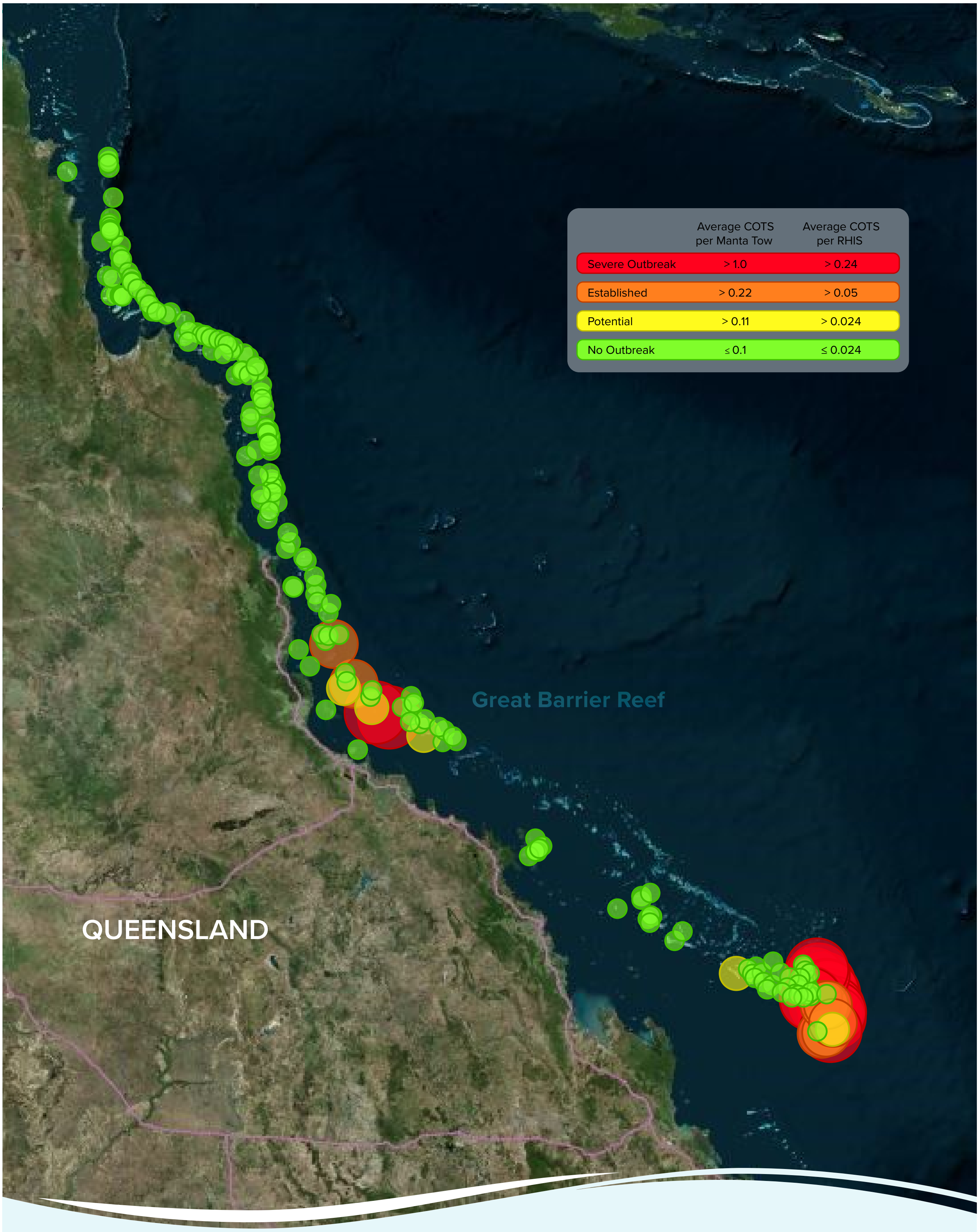

Figure 6: Monitoring the outbreak status of individual reefs across the Great Barrier Reef Marine Park. Manta tow surveys and Reef Health Impact Surveys are the primary in-water survey techniques used to assess outbreak status. Specific thresholds are used for each survey technique to provide information on the degree of outbreak (i.e. No Outbreak, Potential, Established, or Severe). The combined information from these two types of surveys provides managers with broad spatial coverage of reefs across the Marine Park.

5

Research and innovation to inform management

Effective adaptive management of COTS outbreaks on the Great Barrier Reef requires a coordinated, long-term research strategy that prioritises efforts to address key knowledge gaps across all phases of the COTS outbreak cycle. The Marine Park Authority works in close partnership with scientific experts to identify these knowledge gaps and support the science that underpins innovative approaches to managing COTS outbreaks in the Great Barrier Reef Marine Park, now and into the future.

5.1 Addressing priority knowledge gaps

The Marine Park Authority's *Science Strategy and Information Needs 2014-2019* provide guidance on research critical to the management of the Great Barrier Reef, including management of COTS outbreaks.[65] Priority knowledge gaps related to COTS management should be addressed within the appropriate time-critical research window for each phase of the outbreak cycle (**Figure 7**). This ensures that any new tools or understanding (including value adding to existing programs) can be effectively trialled and utilised. Failure to address knowledge gaps in the appropriate time window will result in the need to wait until a particular outbreak phase returns, which prolongs the impacts of outbreaks and the long-term costs for the health of the Great Barrier Reef.

While there is no doubt that key knowledge gaps remain unresolved[8,14], considerable advances in understanding COTS outbreaks and strategies for their management have been made in recent years under the National Environmental Science Program's Integrated Pest Management projects (2015-2021). These projects, which are administered through the Reef and Rainforest Research Centre's Tropical Water Quality Hub, bring together COTS experts from key research organisations including the Commonwealth Scientific and Industrial Research Organisation (CSIRO), the Australian Institute of Marine Science, James Cook University, University of Queensland, Central Queensland University, and Griffith University.

Integrated pest management **(IPM)** considers a pest's lifecycle, ecology and dispersal characteristics in order to identify its strengths and weaknesses. This information is then used to develop and implement management actions that will maximise pest control outcomes and minimise impacts on the pests' desired food source. IPM was initially developed for use in terrestrial environments, and is now used regularly in agriculture and native vegetation management.[66,67] The development and application of pest management approaches in marine environments is relatively new, and has primarily focused on the eradication of invasive pests in temperate marine environments. To date, the only successful eradication of an introduced marine pest in tropical Australian waters occurred in 1999, when the Northern Territory and Australian governments eradicated the black striped mussel from Darwin Harbour by quarantining and treating infected sites with chlorine and copper sulphate.[68] Although such a drastic action would not be viable for control of COTS in the Great Barrier Reef Marine Park due to the risks to non-target organisms including corals, there are relevant learnings from this success story. In this case, pre-emptive surveillance, coordinated government and industry action, and timely decision making provided the foundations for successful management of a marine pest.

The NESP Integrated Pest Management projects are focused on filling critical knowledge gaps regarding COTS biology and ecology to inform the management of this native pest in the Great Barrier Reef Marine Park. The NESP IPM delivers a coordinated research program that underpins the Marine Park Authority's ***COTS Strategic Management Framework***.

5.2 Emerging tools for COTS management

The Marine Park Authority anticipates that the COTS Control Program's tactical response to COTS outbreaks on the Great Barrier Reef will continue to be an important component of its ***Strategic Management Framework*** for the foreseeable future. Although culling by lethal injection is currently the primary method employed to directly mitigate the severity and extent of COTS outbreaks, the COTS Control Program will trial and implement new tools and methods for controlling COTS outbreaks as they become available. Several promising tools and methods that may be applied in COTS management in the Marine Park are highlighted below.

Biophysical and system modelling. Biophysical models are useful tools for the strategic targeting of COTS monitoring and control efforts in the Great Barrier Reef Marine Park. These models combine the biological characteristics of COTS or coral larvae with physical hydrodynamics in order to simulate the dispersal of larvae across reefs in the Marine Park. These models are useful for generating predicted connectivity networks, which may reveal areas that pose greatest risk of spreading COTS larvae, areas that are at greatest risk of receiving COTS larvae, or areas that have potential to spread coral larvae to aid reef recovery. These models can therefore assist in identifying the possible points of origin for outbreaks and guiding in-water monitoring and control efforts to target reefs at highest risk during Phases 2 and 3 of the outbreak cycle. Predictions from these models are already being considered in the COTS Control program, and further development and validation of these biophysical models is an important area of current research.[24,57,69,70,71] These biophysical models are now being extended into system models that can be used to test and compare the effectiveness of alternative COTS management strategies to protect coral across the Great Barrier Reef.[12]

Decision Support Tools. These tools harness ecological knowledge of COTS populations to support on-water decision-making in the COTS Control Program at multiple spatial scales. They assist operational planning across voyages and dives in order to increase the efficiency of the program's operations, and analyse control program data in order to inform decisions about when and where to cull to achieve maximum gains for coral on the Great Barrier Reef. Early versions of these tools are already being used to guide COTS Control Program operations[7,56] and further development of these tools is an important area of current research.[7] In addition to these tools focused on improving the effectiveness

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of integrated pest management once an outbreak is underway, there are also decision support tools being developed to prioritise reefs for resilience-based management actions, including COTS control, across the Marine Park.[72,73,74]

Environmental DNA (eDNA). The detection of COTS eDNA in water samples may be used to provide an early warning of developing outbreaks and assist in their timely intervention.[75] The methodology for eDNA detection of COTS is now well advanced, with trials demonstrating the capacity to detect the presence of adult COTS on reefs through collection of surface water samples[76], and estimate the abundance of larval COTS using plankton tows.[77,78] Further development of these methods is underway to improve and automate the collection and analysis of eDNA samples for both larvae and adult lifestages of COTS. These methods could be used in an early warning monitoring program to detect the precursors to a primary outbreak.

Genetic technologies. The sequencing of the COTS genome has opened the door for the development of a number of new biocontrol methods.[79] These methods may include the synthesis and release of chemical cues to attract or deter COTS, or genetic engineering to modify their reproductive biology. While development of these genetic tools are still in their infancy and not yet available for management application, they hold promise for enhancing COTS control into the future. The safety and social acceptability of these methods will also need to be considered.

Non-Outbreak

AIM: In order to understand and prevent outbreaks we need to understand what drives non-outbreak populations.

Identify **demographics of outbreak versus no-outbreak populations** – what factors control densities?

Identify **drivers and patters of outbreaks in adjacent reef systems** and determine connectivity relationship to GBR (Includes determining COTS speciation)

Explore the feasibility of a **Giant Triton breeding program** – aim to increase predation pressure in non-outbreak periods and provide pheromone deterrents in outbreak periods.

Determine level of **genetic connectivity** in GBR COTS population

Determine role of **sapponins** in predator deterrence.

Implement **pre-emptive monitoring** to identify build-up of an outbreak. This could include passive sampling of the plankton to identify COTS larvae (research needed to design and test the feasibility of this technology)

Initiation of Primary Outbreak

AIM: Identify factors that may contribute to and exacerbate primary outbreaks, including where they initiate, to facilitate targeted management (both direct and indirect).

Identify initiation region(s) and factors that influence the build-up of outbreaks (e.g. water quality, hydrodynamic circulation patterns & larval connectivity, upwelling, coral availability, predation)

Population structure of primary outbreak populations: age structure, genetics, growth and fecundity

Fine-scale **reproductive** studies - determine spawning frequency, timing and cues

Develop a **COTS focussed ecosystem model** to integrate knowledge from the entire research program and evaluate the probability and relative influence of multiple causal factors

Waves of Secondary Outbreaks

AIM: Fill ecological knowledge gaps while COTS are abundant, test and refine both new and existing surveillance and intervention tools.

Larval tolerances and capabilities - determine environmental tolerances, sensory capabilities and behaviour.

Test and strengthen **connectivity and predictive models** to better inform surveillance and control

Predation: Identify keystone predators of all COTS life stages and their relative abundance, and measure their functional responses to changes in COTS densities – does Zoning play a role?

Advance and test **pheromone 'pull and push technologies'** to improve control effectiveness and decrease fertilisation success

Explore and test more accessible and effective **control methods**

Develop a **Primary Outbreak Response Plan** to pre-emptively detect the build-up of a primary outbreak and trigger action to supress and contain it in the initiation region (linked to IPM).

Termination

AIM: Understand processes and conditions responsible for the collapse of an outbreak.

Identify **natural microbial pathogens** (bacteria, virus etc) and symbionts that are responsible or could cause a COTS population collapse

Explore opportunities to safely use natural, **COTS-specific biological control** methods (e.g. bacteriophages, castration).

Design and implement a **public information awareness campaign** to feed into the identification of deteriorating COTS and their locations – to support researcher sampling

Understand **demographics and energetics** of collapsing populations

As part of the response plan - re-survey reefs to **stocktake effect of outbreak** and identify habitat cues that may have contributed to population collapse (e.g. coral cover below x % led to starvation)

Figure 7: Priority knowledge gaps related to COTS management and the corresponding phase of the outbreak cycle during which they should be addressed

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Community involvement in COTS management

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Users of the Marine Park, including community members and industry stakeholders, are encouraged to engage in the Strategic Management of COTS on the Great Barrier Reef. There are two primary ways that Reef users can participate in COTS management. The first option is to report any COTS sightings to the Marine Park Authority through the Eye on the Reef Sightings app. This COTS sightings information may then be used to guide more in-depth assessments by Marine Parks rangers or COTS Control Program vessel crews.

The second option is for Reef users to actively engage in COTS culling in the Marine Park. In April 2019, updated Great Barrier Reef Marine Park Regulations[41] came into effect that removed limitations on the take of COTS in Marine Park Zones where fishing and collecting is allowed (i.e. General Use, Habitat Protection, and Conservation Park Zones). Under these regulations, permits are still required to conduct COTS culling in locations where fishing and collecting activities are restricted (i.e. Marine National Park, Scientific Research, Preservation, and Buffer Zones). Applications for COTS control permits have no assessment fee, and can be submitted through the Permits Online application portal.

Marine Park users interested in undertaking COTS culling in the Marine Park are strongly encouraged to consult the Marine Park Authority's COTS Control Guidelines.[80] These guidelines provide important information on how to conduct this activity safely and effectively. The recommended method currently involves injecting COTS with approved solutions (i.e. bile salts or household vinegar). These solutions can be highly effective at killing COTS in 24-48 hours, as long as the dosage and injection technique is delivered correctly.[9,10] When used for COTS culling, these solutions are harmless to non-target reef organisms.[9,81] Culling through lethal injection is safer than collection and burial onshore because it does not require handling starfish, which have venomous spines. It is also significantly more effective than cutting the starfish into pieces, a practice that may actually make the problem worse because pieces of a single animal may regenerate into multiple starfish.

More broadly, users of the Great Barrier Reef Marine Park can contribute to COTS management and Reef 2050 goals by practicing good stewardship when in the Marine Park. Responsible reef practices contribute to maintaining Reef health, and ensure that efforts to enhance the resilience of the Reef through targeted management actions, such as COTS control, are not undermined through poor reef stewardship practices. Examples of such practices include compliance with zoning, the responsible disposal of waste, chemicals and litter, as well as taking precautions not to damage corals when anchoring a boat or when diving and snorkelling.

7

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