Tropical Water Quality Hub

National **Environmental Science** Programme

Synthesis Report

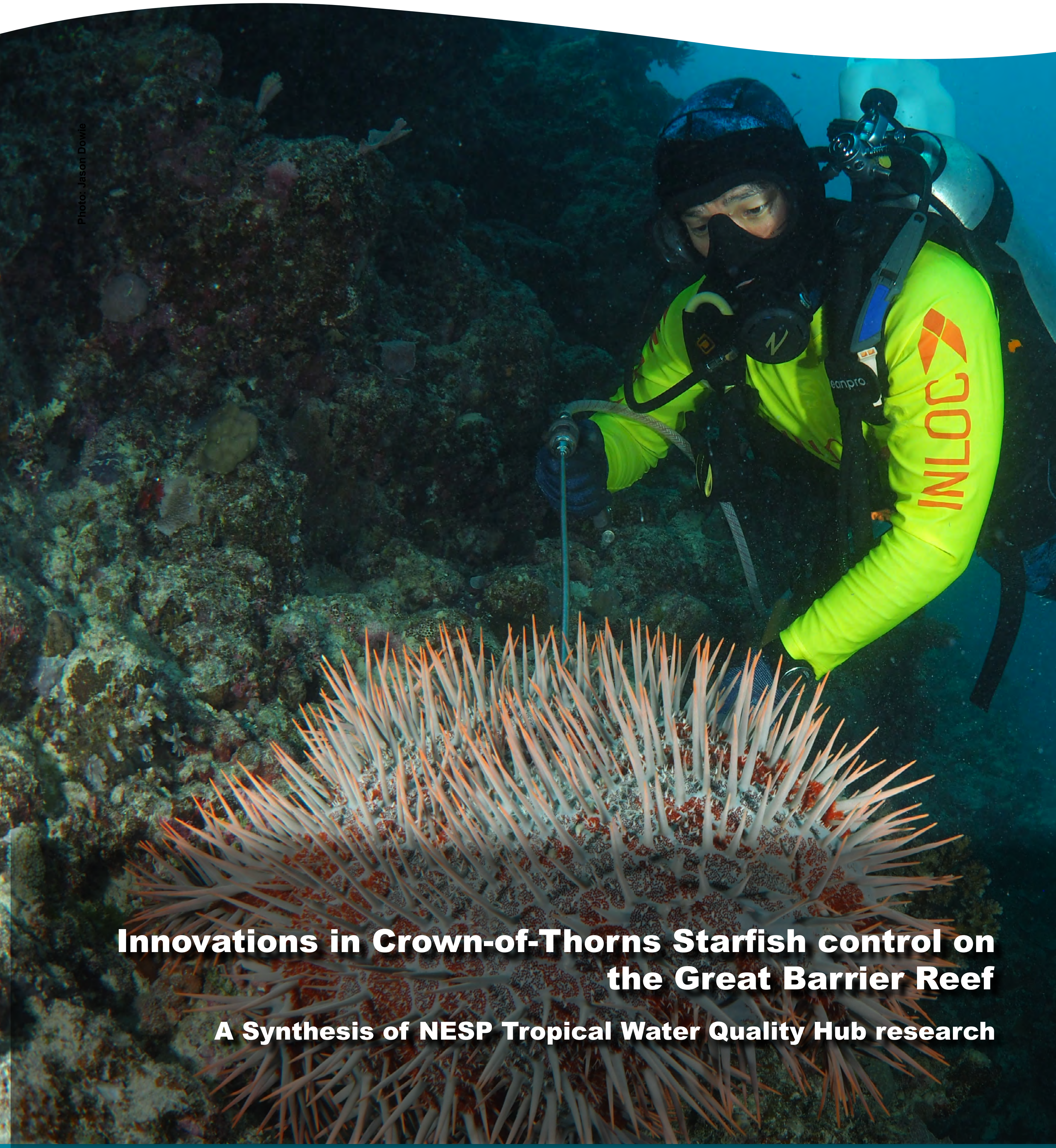

Photo: Jason Dowie

Innovations in Crown-of-Thorns Starfish control on the Great Barrier Reef

A Synthesis of NESP Tropical Water Quality Hub research

The Tropical Water Quality Hub is funded by the Australian Government's National Environmental Science Program

Innovations in Crown-of-Thorns Starfish control on the Great Barrier Reef: A Synthesis of NESP Tropical Water Quality Hub research

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Cover photographs: (front) Crown-of-thorns starfish Control Program diver in action. (back) Crown-of-thorns starfish and a Giant Triton snail on the Great Barrier Reef. Images: Rickard Abom.

This report is available for download from the NESP Tropical Water Quality Hub website:
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ACRONYMS AND ABBREVIATIONS

ACCSP .... Australian Climate Change Science Programme
AIMS .... Australian Institute of Marine Science
AMPTO .... Association of Marine Park Tourism Operators
CCA .... Coralline Crustose Algae
CCIP .... COTS Control Innovation Program
CERF .... Commonwealth Environment Research Facilities
COTS .... Crown-of-thorns starfish (*Acanthaster cf. solaris*)
CPUE .... Catch per unit effort (COTS per minute bottom dive time)
CRC Reef .... Cooperative Research Centre for the Great Barrier Reef World Heritage Area
CQU .... Central Queensland University
CSIRO .... Commonwealth Scientific and Industrial Research Organisation
DPSIR .... Driver–Pressure–State–Impact–Response
DST .... Decision Support Tool
eDNA .... environmental DNA
GBR .... Great Barrier Reef
GBRF .... Great Barrier Reef Foundation
GBRMPA .... Great Barrier Reef Marine Park Authority
GU .... Griffith University
IPM....................................... Integrated Pest Management
JCU .... James Cook University
LTMP .... AIMS Long-term Monitoring Program
MMP .... Marine Monitoring Program
MPA .... Marine Protected Area
MTSRF .... Marine and Tropical Sciences Research Facility
NERP .... National Environmental Research Program
NESP .... National Environmental Science Program
Reef 2050 Plan .... Reef 2050 Long-Term Sustainability Plan
RHIS .... Reef Health Impact Surveys
RIMRep …………………… Reef 2050 Integrated Monitoring and Reporting Program
RRMMP .... Reef Rescue Marine Monitoring Program
RRRC .... Reef and Rainforest Research Centre
TWQ Hub .... Tropical Water Quality Hub
UQ .... University of Queensland
WQ .... Water quality

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The authors acknowledge the Australian Government National Environmental Science Programme (NESP) Tropical Water Quality Hub for providing funding for the research projects reported here. We also acknowledge the researchers and their research institutions and universities who have delivered innovative and applied science under the NESP Tropical Water Quality Hub with the goal of informing and improving management. These include the Commonwealth Scientific and Industrial Research Organisation (CSIRO), James Cook University (JCU), the Australian Institute of Marine Science (AIMS) and the University of Queensland (UQ). We would also like to thank researchers who provided input to this report, in particular Morgan Pratchett (JCU), Frederieke Kroon (AIMS) and Cherie Mottie (AIMS), and Russ Babcock and David Westcott (CSIRO) who reviewed the report.

EXECUTIVE SUMMARY

The Pacific Crown-of-thorns starfish (COTS) *Acanthaster cf. solaris* is a notorious predator of live hard coral and when in outbreak numbers, causes significant coral loss across its range. The Great Barrier Reef is facing cumulative risks from climate change, ocean acidification and other anthropogenic activities, such as land-based run-off, coastal development and commercial fishing. Along with tropical cyclones and coral bleaching, crown-of-thorns starfish (COTS) are recognised as a major threat to corals and associated Great Barrier Reef resilience.

Protecting the Great Barrier Reef from COTS outbreaks is an important management response amenable to intervention, but it requires a strategic approach. Earlier research programs established by the COTS ARC and COTS Research Committee delivered foundational science that increased understanding of COTS biology and ecology. The suspected link between land-based nutrient inputs and COTS outbreaks derived from this past research has been a significant driver in the definition of land-based water quality targets to reduce pollutant transfer from agricultural lands into the Great Barrier Reef. However, progress towards the targets has been slow and there are likely to be significant time-lags between management changes in the catchment and marine ecosystem response. Therefore, it is recognised that water quality management alone is unlikely to prevent future outbreaks of COTS in a timely manner and that multiple innovative approaches are required to manage COTS populations on the Great Barrier Reef in the short and longer-term.

This technical report synthesises the National Environmental Science Program (NESP) TWQ Hub funded research that has informed the COTS control decision support tools and strategies for the Great Barrier Reef (GBR). This synthesis provides a summary of the current state of knowledge of COTS, how the science has been applied to the COTS control program and summarises recommended future research directions. It captures the process by which this complex and multi-disciplinary research program has achieved its impact and brings together the learnings from various COTS related research projects (including non-NESP projects, where relevant).

The NESP TWQ Hub identified COTS control as a priority for urgent management action to improve the state of the GBR World Heritage Area. Six projects were funded over the life of the 6-year program, including the operationalisation of an integrated pest management (IPM) approach and improvement of manual COTS control methods by incorporating new knowledge from current research. Associated research investigated the potential link between COTS outbreaks and water quality, the ecology, life-history and distribution of COTS, and the potential for biological control of the species. Modelling and development work was also undertaken that enabled optimisation of on-going field-based COTS control operations including cost-benefit guidance on preferred strategies to minimise the impact of future COTS outbreaks.

The recent research has shown that while many environmental factors are likely to contribute to the prevalence of COTS, larval connectivity and sea surface temperature had the highest impact, and (modelled) chlorophyll concentrations and river derived pollutant inputs were also important. In particular, COTS larval survivorship and growth was directly linked to nutrients and subsequent food availability. Research has also highlighted the benefits of marine protected areas, with COTS living in no-take zones exhibiting significantly higher levels of predator injury which is likely to have a significant impact on their individual fitness and the species population dynamics, potentially reducing outbreak potential in areas protected from fishing in the GBR. Innovative techniques analysing for the presence of COTS DNA in water samples have provided a promising new tool for detection of the starfish. This use of genetic screening in identification and detection of juvenile and cryptic adult COTS can inform spatial targeting of surveillance and control efforts as pre-outbreak strategies to prevent larger moving COTS outbreaks. Assessment of potential biological control methods for COTS control have been completed and recommended that artificially increasing densities of the giant triton (*Charonia tritonis*) in reef waters should be investigated further. The NESP TWQ Hub research also concluded that significant research is still required to identify appropriate candidate semio-chemicals to understand their performance under field conditions, and to develop deployment technologies and strategies to potentially control future COTS outbreaks. Semio-chemicals are involved in regulating COTS foraging, metamorphosis, growth, spawning, reproduction, larval settlement, chemical defence, dispersal and predator avoidance and can potentially disrupt COTS populations when applied artificially into local marine environments.

In 2016, a 2-year collaborative COTS Integrated Pest Management (IPM) programme was established between the NESP TWQ Hub and CSIRO to integrate ecological principles into the existing COTS Control Program. This strategy was adapted from terrestrial research and tailored to the marine environment and was developed based on current understanding of how COTS outbreaks initiate and spread. It was designed to achieve efficient and effective solutions for COTS management using diver-based manual control methods.

Early management experiences had led to the perception that manual control of starfish numbers by manual removal by divers was neither effective nor affordable given the spatial scale of the GBR, despite some clear examples of success. However, over the past five years, NESP TWQ Hub research has informed an improved approach to identifying priority reefs for culling and an improvement in culling methods, contributing to a notable reduction in COTS abundances at many reefs and a reduction of reefs requiring ‘intensive’ culling.

The NESP TWQ Hub has analysed the performance of the collaborative IPM COTS Control Program over the first 20-months of its operations. Adoption of the new IPM approach in 2018 by the COTS Control Program administered by the Great Barrier Reef Marine Park Authority (GBRMPA) and more recently the GBR Foundation, has demonstrated successful outcomes.

One of the largest improvements to (manual) COTS control occurred with the introduction of the single-injection method, which significantly reduced individual COTS culling time. Another significant shift in management focus was the introduction of monitoring of non-outbreak phases at reefs likely to experience future population outbreaks based on their location and hydrodynamic models. The performance analysis found that the IPM program was twice as likely to reduce a site requiring COTS control to below the three COTS ha^{-1} threshold compared with the pre-IPM programme and did so in 63% of the time of the pre-IPM program. Critically, the IPM Control Program was found to have achieved its management objectives at a reef scale at 89% of the 103 reefs targeted, while the pre-IPM program achieved this objective at 0% of 102 reefs. These results confirm that the IPM COTS Control Program has turned an effective culling method developed in the pre-IPM program into a potent tool for achieving COTS control objectives and protecting coral at the scale of sites, reefs, and hundreds of reefs.

Research conducted under the NESP Tropical Water Quality (TWQ) Hub by the extended CoCoNet and ReefMod-GBR models highlight that regional-scale reduction of the proportion of reefs across the GBR experiencing outbreaks is possible with a manual Control Program. Importantly, modelling predicted that the only regional strategy considered to be likely to provide significant increases in control performance during the current outbreak is to increase the number of vessels in the COTS control fleet. The current ecologically-informed IPM COTS Control Program is working, both at the scale of individual reefs and regionally and it should be continued, and effort increased where funding is available. Minor investment in the development and integration of new technology, such as GPS trackers or other devices to record diving depth and visibility underwater, has the potential to improve operational efficiency and deliver more detailed data regarding the distribution of COTS in the GBR.

The program determined that it is critical that future investment in on-water monitoring of COTS should be guided by a rigorous statistical design to maximise the value and the utility of the data. The development of this sampling design must, along with the refinement and operationalisation of new monitoring tools (including Towed Underwater Vehicles and collection and analysis of COTS Environmental DNA), be a research and development priority. In addition, development of information management systems, tools that improve in-water data collection by cull divers to improve accuracy of monitoring data and automated collection of data on vessel movements and patterns of operation would improve monitoring program efficiencies and also maximise value of collected data. Specifically, the following priorities were recommended:

1) Development of shallow water Towed Underwater Vehicles (TUVs) with appropriate sensors, operational capabilities and piloting methods;
2) Development of deep-water Remotely Operated Vehicles (ROVs) with appropriate sensors, operational capabilities (e.g. culling) and piloting methods;
3) Development of data management regimes that enable real time feedback to vessels;
4) Development of data management regimes that optimize information, storage and handling requirements;
5) Improved Artificial Intelligence for detection of key COTS and coral thresholds;
   Development of data recording tools for control divers; and
   Development of spatial sampling strategies for each activity during each phase of the outbreak cycle.

In summary, research conducted under the NESP Tropical Water Quality Hub focused on providing scientifically robust strategic and operational information to support effective manual control of COTS on the GBR. The research has been collaborative and targeted and has been able to demonstrate major achievements in COTS population control and deliver a greater understanding of COTS behaviour and biology that informed IPM activities.

1 INTRODUCTION

1.1 NESP Tropical Water Quality Hub and research priorities

The Australian Government, through the National Environmental Science Program (NESP), has been funding research in environmental and climate science since 2015, with a budget of $145 million over six years. Specifically, the NESP targeted research in marine, coastal and freshwater ecosystems, sustainable communities and waste, threatened species, climate systems and other key environmental issues. All NESP-funded projects focused on practical and applied research to deliver accessible results and improve decision-making processes. The program, which builds on its predecessors (the National Environment Research Program – NERP – and the Australian Climate Change Science Program) aimed at facilitating delivery of the best available information in order to support better understanding, management and conservation of Australia's environment (Department of Agriculture Water and the Environment (DAWE), 2020). The Tropical Water Quality (TWQ) Hub was one of six multi-disciplinary research hubs within NESP, investing AU$31.98 million on delivering innovative research to maintain and improve tropical water quality from catchment to reef (NESP, 2020), mainly in the Great Barrier Reef (GBR) and adjacent tropical waters. It was structured into three main themes:

- Theme 1: Improved understanding of the impacts, including cumulative impacts, and pressures on priority freshwater, coastal and marine ecosystems and species;
- Theme 2: Maximise the resilience of vulnerable species to the impacts of climate change and climate variability by reducing other pressures, including poor water quality; and
- Theme 3: Natural resource management improvements based on sound understanding of the status and long-term trends of priority species and systems.

Research projects within the TWQ Hub covered a wide spectrum of fields, from genes to ecosystems, including a better understanding of controversial species such as the invasive crown-of-thorns starfish (COTS), iconic organisms such as dugongs and marine turtles, seagrass, coral reef resilience, water quality (including impacts of sediments and nutrients in the marine environment, their sources and management responses), and wetland restoration science that maximises values and services. The TWQ Hub also had an overall strong focus on cumulative impacts and climate resilience, while building Indigenous connections and capacity in management of Queensland land and sea country.

The NESP TWQ Hub was delivered through a collaborative, multi-disciplinary research network composed of six leading Australian universities and research institutions. The institutions were the Australian Institute of Marine Science (AIMS), James Cook University (JCU), Commonwealth Scientific and Industrial Research Organisation (CSIRO), Central Queensland University (CQU), University of Queensland (UQ) and Griffith University (GU), with coordination of the network by the Reef and Rainforest Research Centre (RRRC). These partner institutions have collaborated for over 20 years and have established an extensive network of research end-users, including government, industry, NGO's, Indigenous and other community groups. The partners contributed to the success of the Hub through co-funded research programs (e.g. in-kind contributions to specific projects through staff expertise or research facilities and resources), while also fostering partnerships across the other Hubs and with a wide range of relevant stakeholders. Researchers in the NESP TWQ Hub have worked collaboratively with a number of research organisations, industry bodies, stakeholder groups and landholders. Examples relevant to this report include Canegrowers, Sugar Research Australia, Burdekin Productivity Services, Farmacist, Queensland Department of Environment and Science and Queensland Department of Agriculture and Fisheries and many individual sugarcane farmers. This collaboration has been an extremely valuable feature of the research.

This report is one in a series of technical reports synthesising the findings of NESP research on topical issues most relevant to policy and stakeholder groups. These include: Improving coral reef condition through better informed resilience-based management (Pineda & Johnson, 2021), **innovations in crown of thorns starfish control on the GBR** (this report; Erdmann et al. 2021), reducing end of catchment fine sediment loads and ecosystem impacts (Pineda & Waterhouse, 2021), overcoming barriers to reducing nitrogen losses to the GBR (Waterhouse and Pineda 2021), restoring ecosystems from catchment to reef (Pineda et al., 2021), principles for establishing greater trust between scientists and farmers (James, 2021), and learnings from applied environmental research programs (Long, 2021). The reports are supported by individual project research publications, in addition to several targeted case studies and fact sheets accessible through a dedicated website (linked through the NESP TWQ Hub website[1]).

This report synthesises innovative research findings in Crown-of-thorns starfish (COTS) control management undertaken in the GBR. Five COTS projects were funded under the Theme 1 research priority,

> Project 1.1: Establishing the future NESP COTS research framework including and ecologically-based approach to the management of COTS at multiple scales.
> Project 2.1.1: Integrated pest management of crown-of-thorns starfish.
> Project 3.1.1: Implementation of the crown-of-thorns starfish research strategy: regional strategies.
> Project 4.1: Crown-of-thorns starfish: surveillance and life history.
> Project 5.1: Matching the COTS IPM to the scale of the new control program.

These projects were designed to:

- Further develop a systematic approach to COTS control;
- Identify and trial risk abatement, and prioritisation strategies in response to COTS outbreaks, extreme events and biosecurity threats; and
- Develop and implement a plan to reduce COTS numbers by two million.

A summary of the research projects is presented in Appendix A, Table A1.

1.2 Current policy and management direction for COTS outbreak control

The Australian and Queensland Governments' Reef 2050 Long-Term Sustainability Plan (Commonwealth of Australia, 2018a, 2018c) plays a key role in addressing major threats to the GBR, by directly promoting the health and resilience of the GBR. The Plan aims to "*ensure*

[1] https://nesptropical.edu.au/

the Great Barrier Reef continues to improve on its Outstanding Universal Value every decade between now and 2050 to be a natural wonder for each successive generation to come" (Commonwealth of Australia, 2015). Protecting the values and health of the GBR will be accomplished by developing and strengthening initiatives that build reef resilience.

Management of the GBR is a collective endeavour engaging governments, industry, research, management, traditional communities and social science. The Reef 2050 Plan is underpinned by a range of programs, such as the COTS control program, established by the Great Barrier Reef Marine Park Authority (GBRPMA) and the Reef Trust and supported by the Australian Institute of Marine Science's (AIMS) Long-term Monitoring Program (LTMP). Furthermore, the Reef 2050 Plan aims to integrate research and management with leading agencies and partners, including the Australian and Queensland Governments, GBRMPA and the Association of Marine Park Tourism Operators (AMPTO) to enhance the success of the Reef 2050 Plan.

Underpinning the Reef 2050 Plan, the Reef 2050 Integrated Monitoring and Reporting Program (RIMReP) includes monitoring, modelling and reporting undertaken to direct management actions to improve reef condition over seven themes: ecosystem health; biodiversity; water quality; heritage; community benefits; economic benefits and governance (GBRMPA, 2015). The RIMRep plans to integrate COTS indicators as a significant driver of coral cover decline into short- to medium-term response monitoring (GBRMPA, 2015, 2018). The Australian Government's Reef Trust initiative contributes to the Reef 2050 Plan through funding water quality improvements, habitat restoration and species recovery. These management initiatives have a strong focus on the control of outbreaks of COTS, under the theme *"Improve and protect marine biodiversity, including the reduction of crown-of-thorns starfish"*. In collaboration with the Great Barrier Reef Foundation (GBRF), the Reef Trust Partnership was formed in 2019 and established the COTS Control Innovation Program (CCIP) which has built on the Integrated Pest Management (IPM) approach for the control and management of COTS pioneered by NESP research.

Reducing nutrient inputs to the GBR has been a major priority of the Australian and Queensland governments in the implementation of the GBR water quality policies since 2003 (Australian and Queensland Governments, 2003). Significant investment has been directed towards reducing nitrogen losses from sugar cane areas, the primary contributing land use to dissolved inorganic nitrogen in the GBR (Waterhouse et al., 2017). This has involved the development of management practice frameworks, now formally incorporated as part of the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (P2R program), for minimising nutrient losses to the GBR. Ambitious management practice adoption targets to be achieved by 2025 are defined for all land uses. Targets of 90% of land in priority areas under grazing, horticulture, bananas, sugarcane and other broad-acre cropping are managed using best management practice systems for water quality outcomes and targets for end of catchment load reductions are defined for all basins (Australian Government and Queensland Government, 2018). The link between land-based nutrient inputs and COTS outbreaks has been a significant driver in the definition of these targets (Brodie et al., 2017a) and in the assessment of the relative risk of pollutants to the GBR (e.g. Waterhouse et al., 2017a). However, progress towards the targets has been slow (Great Barrier Reef Water Science Taskforce, 2016) and there are likely to be significant time-lags between management changes in the catchment and marine ecosystem response (Brodie et al., 2012; Eberhard et al., 2017). Therefore, it is recognised that water quality management alone is unlikely to prevent future outbreaks of COTS in a timely manner (Westcott & Fletcher, 2018). Multiple innovative approaches are required to manage COTS populations in the short and longer term.

2 NESP TWQ HUB RESEARCH HIGHLIGHTS

2.1 State of the GBR and COTS outbreaks as a driver of change

The Great Barrier Reef (GBR) is the largest coral reef ecosystem in the world and was listed as a World Heritage Area in 1981 due to its Outstanding Universal Value including its diversity and uniqueness as a vast ecosystem (Day & Dobbs, 2013). The GBR is facing cumulative risks from climate change, ocean acidification and other anthropogenic activities, such as land-based run-off, coastal development and commercial fishing (GBRMPA, 2019). Along with tropical cyclones and coral bleaching, crown-of-thorns starfish (COTS) are recognised as a major threat to corals and associated Great Barrier Reef resilience (De'ath et al., 2012).

The Pacific COTS, *Acanthaster cf. solaris* is native to coral reefs in the Pacific region (Haszprunar et al., 2017). They are a notorious predator of hard corals, feeding on reef building corals and in particularly *Acropora spp.* (Pratchett et al. 2014). Damage caused by COTS predation significantly reduces hard coral cover at invaded reefs with risks to overall reef health and resilience. When COTS populations increase to a point where the quantity of coral being consumed exceeds coral growth, there can be significant declines in coral cover. This is referred to as a COTS 'outbreak'. COTS outbreaks have been recorded on the GBR for decades, with the first documented observations in 1962, 1979, and 1993-94 (Brodie et al., 2005; Fabricius et al., 2010). COTS outbreaks are a major driver of coral reef decline and are thought to be responsible for 42% of coral loss in the GBR between 1985 and 2012 (De'ath et al., 2012) with (major) consequences for reef resilience and recovery (Mellin et al., 2019; Vercelloni et al., 2017). It has been determined that 1,000 COTS per km^2 can be classified as an outbreak. This intensity of outbreak can result in approximately 0.18% loss of hard coral cover per day (Westcott et al., 2016).

The COTS life cycle has four phases (Figure 1), which can be used to focus management efforts on the prevention of COTS outbreaks rather than to concentrate solely on control during an active outbreak. Subsequent control measures can take effect when COTS populations are still small and further measures are likely to maximise effectiveness and support greater coral protection. In this way, corals are assisted to recover due to reduced predation by COTS, provided that COTS densities remain below outbreak levels and an 'Ecological Threshold' is not exceeded. The 'Ecological Threshold' is a measure calculated based on COTS density that result from COTS removal catch-per-unit-effort (CPUE) and current observation rates (Babcock et al., 2014). Hence, CPUE is a useful proxy to quantify COTS population status.

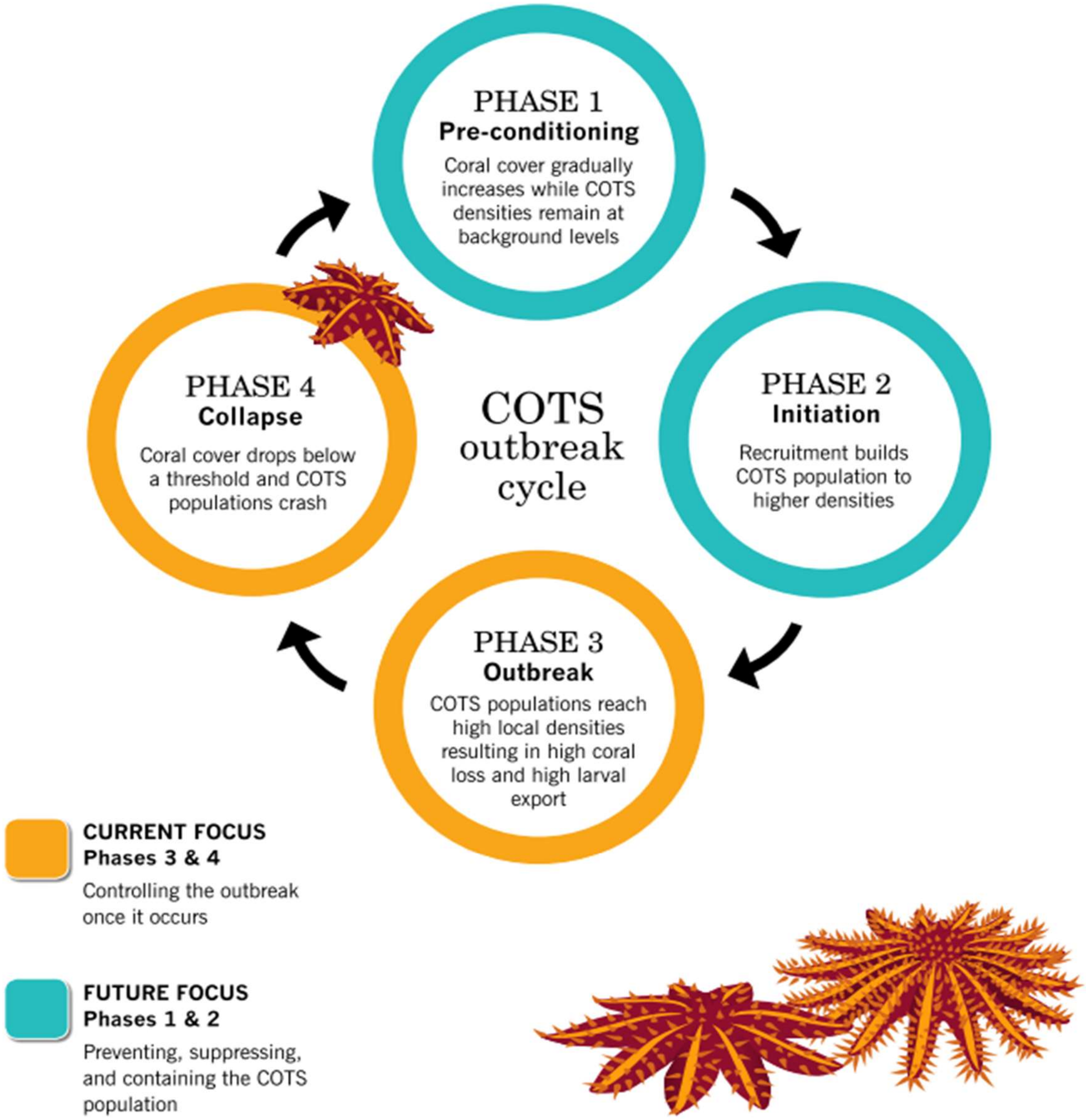

Figure 1. Crown-of-thorns starfish outbreak cycle and control. In the lead up to an outbreak, as coral cover increases, COTS densities remain low (pre-conditioning). In sites referred to as initiation zones, coral cover and local conditions become favourable to COTS and their densities increase progressively (initiation). As COTS numbers and size increase, they start affecting coral cover and produce high numbers of larvae that can move with water currents to other sites (outbreak). Ultimately coral cover at this initial site will be so low that COTS will run out of food and starve (collapse). Once a primary outbreak is established, a similar sequence of events is then repeated along the reef as secondary outbreaks occur (Source: GBRF, 2019).

COTS control relies upon advances in research to efficiently identify outbreaks by monitoring population sizes and distribution ranges. For the last three decades, ongoing COTS research was able to fill many of the knowledge gaps identified by Moran (1986) on COTS biology, ecology, outbreaks and management (Pratchett et al., 2017a), basic information on the distribution of COTS and corresponding information on the distribution of habitat preference as well as coral communities and their condition is still incomplete in the GBR (Westcott et al., 2021). However, there remains a lack of consensus among experts about the processes driving COTS population dynamics in the GBR (Babcock et al., 2016, 2020; Pratchett & Cumming, 2019; Westcott et al., 2020).

Protecting the GBR from COTS outbreaks is an important management response amenable to intervention but it requires a strategic approach. The COTS Control Program started in 2012 and supported by the Association of Marine Park Tourism Operators (AMPTO) in partnership with GBR marine tourism operators, primarily focused on COTS control at tourism sites. Over 30 years of COTS research effort has provided an important platform for the NESP TWQ Hub Integrated Pest Management (IPM) research program; a collaborative and targeted approach that has harnessed research efforts and enabled delivery of significant improvements in effectiveness and efficiency of COTS control.

An ecological analysis of hard coral cover and the associated density of COTS (based on a conversion of catch per unit effort) developed a CPUE-COTS density relationship (Plagányi et al., 2020). The estimated threshold levels of COTS that prevent net growth of hard corals is when 0.04 (hard coral cover < 40%) to 0.08 (hard coral cover > 40%) COTS are culled per minute (Plagányi et al., 2020). This new definition was incorporated into the GBR COTS Control Program as an ecological threshold not to be exceeded in order to ensure that COTS densities remained low enough to enable (regenerative) hard coral growth.

Ongoing reef surveillance increases understanding of the location and movement of COTS outbreaks and is an important component of the current Integrated Pest Management (IPM) COTS control methodology. Similarly, the AIMS Long-Term Monitoring Program (LTMP) also monitors reef conditions and COTS abundance among approximately 86 reefs each year. Manta tow surveys in 2019-2020 found that the number of reefs with COTS outbreaks had reduced in the Northern and Central GBR but remained constant in the Southern GBR compared with the previous monitoring period (AIMS, 2019). The Northern and Central GBR had one potential outbreak (defined as 0.1-0.22 COTS/two-minute manta tow), and the Southern GBR one incipient outbreak (defined as 0.22-1 COTS/ two-minute manta tow) and four active outbreaks (defined as >1 COTS/ two-minute manta tow) (Figure 2). However, the picture for the entire GBR is incomplete for this time as few surveys covered the reefs in the southern Central GBR, where active outbreaks are potentially ongoing (Pratchett, pers. comm).

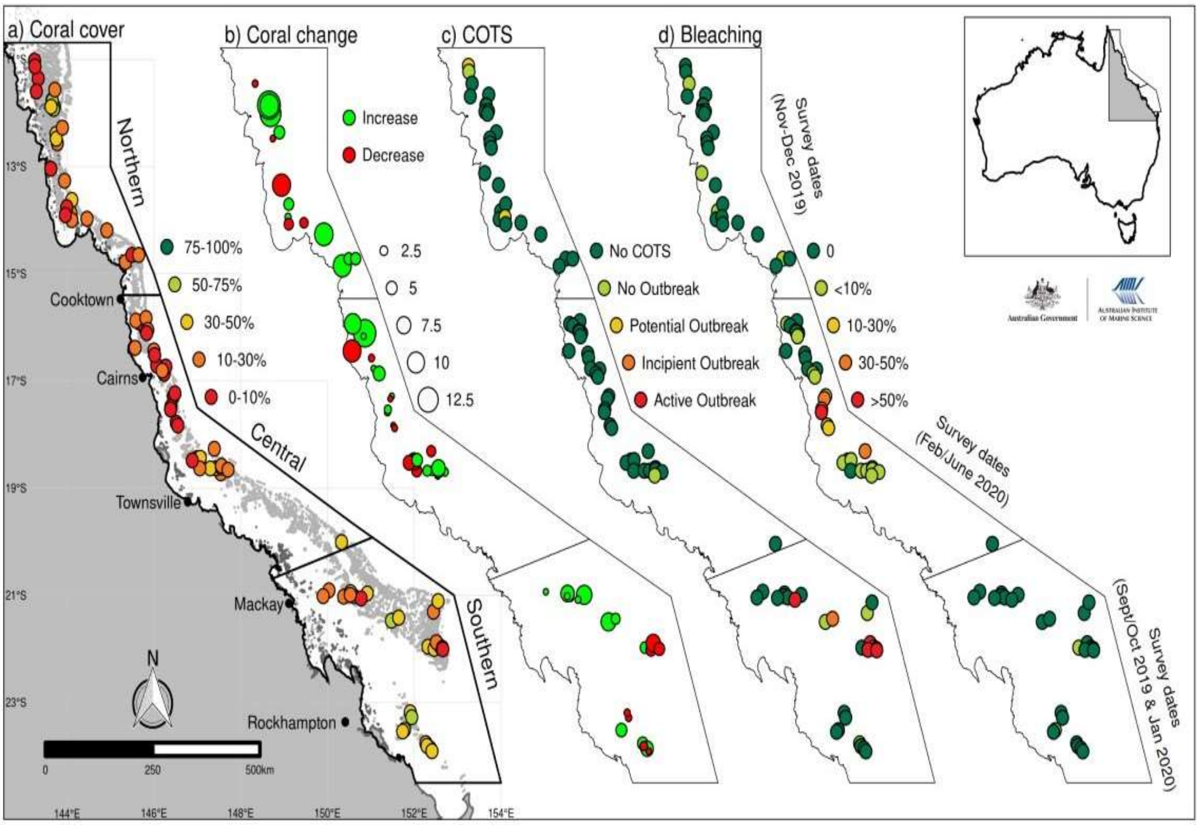

Figure 2. Manta tow surveys (Sept 2019 - June 2020) of 86 reefs in the Northern, Central and Southern GBR showing a) the hard coral cover (%), b) the change of hard coral cover (%), c) the COTS outbreak status (COTS/2 min: No outbreak = <0.1, potential = 0.1-0.22, incipient = 0.22-1 and active = >1) and d) the coral bleaching severity (%) (Source: AIMS, 2019).

One of the largest improvements to (manual) COTS control occurred with the introduction of the single-injection method which significantly reduced individual COTS culling time (Pratchett et al., 2017a). Another significant shift in management focus was the introduction of monitoring of non-outbreak phases at reefs likely to experience future population outbreaks based on their location and hydrodynamic models (Pratchett et al., 2017a).

Over the past five years, NESP TWQ Hub research has informed an improved approach to identifying priority reefs for culling and a change in culling methods, contributing to a notable reduction in COTS abundances at many reefs (Figure 2) and a reduction of reefs requiring ‘intensive’ culling (GBRMPA, 2020; Figure 3). Adoption of the new IPM approach in 2018 by the Crown-of-thorns starfish (COTS) Control Program administered by the Great Barrier Reef Marine Park Authority (GBRMPA) and more recently the GBR Foundation, has demonstrated successful outcomes.

The 2020 annual report from GBRMPA for the COTS Control Program highlighted an improvement compared with previous years despite continued damage caused by COTS; 32,516 COTS were culled from 3,290 ha of the GBR Marine Park, which resulted in 94 of the 103 priority reefs being maintained at or returned to “no-outbreak” status (GBRMPA, 2020). All priority reefs and selected non-priority reefs between Lizard Island and Airlie Beach were monitored throughout the year. The COTS control activities recorded Reef Health and Impact

Surveys (RHIS) and Catch-Per-Unit-Effort (CPUE) along with COTS densities and hard coral cover from manta tow surveillance activities. Depending on individual management modes, priority reefs were revisited at regular intervals to suppress COTS outbreaks (See Figure 3; GBRMPA, 2020). This systematic approach in COTS control efforts returned five priority reefs from intensive (culling underway) to maintenance (culled below threshold) management mode within one year.

However, there is currently no coordinated means of reliably detecting new (primary) COTS outbreaks, or of efficiently monitoring their subsequent spread (secondary outbreaks), beyond *ad hoc* observations, the limited surveying conducted under GBRMPA's Field Management Program and AIMS's Long-Term Monitoring Program (LTMP), and the culling activities of the COTS Control Program itself. Ultimately, the capability to:

i) predict and detect incipient outbreaks,
ii) detect breaches of key ecological thresholds, and
iii) monitor the spread of existing outbreaks,

will be an essential component of any efficient and successful COTS control program. The most effective management response will most likely rely on anticipating and preventing outbreaks rather than responding to their presence.

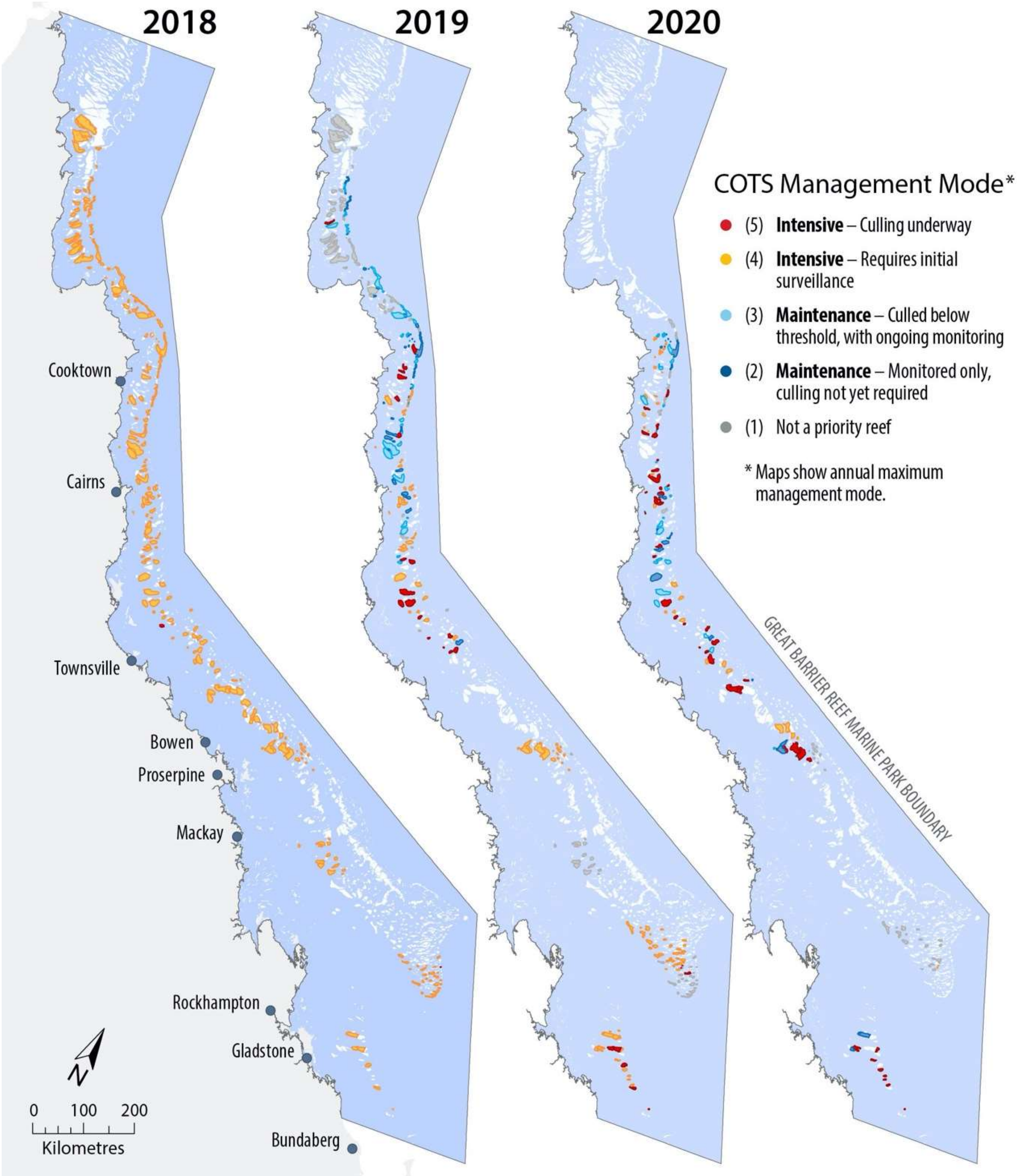

Figure 3. Changes in reef management modes across the GBR from 2018 to 2020 when the innovative Integrated Pest Management approach was applied.

2.2 Previous knowledge about COTS outbreaks and control effectiveness

Earlier research programs established by collaborating institutions and organisations, the COTS ARC and COTS Research Committee, delivered foundational science that increased understanding of COTS biology and ecology. These programs ultimately informed the development of the NESP TWQ Hub IPM research program that have identified innovative management practices to better protect, conserve and restore coral reefs on the GBR.

Brodie (2021) reviewed the history of COTS population outbreak hypotheses. One view postulates that COTS population outbreaks are a natural phenomenon caused by the inherently unstable population sizes of the highly fecund starfish (Potts, 1981). An alternative view links COTS population outbreaks to anthropogenic induced changes to the environment of the starfish. These induced enhancement of COTS larval food supply (phytoplankton) by nutrient-enriched terrestrial runoff (Bell & Gabric, 1991; Brodie, 1992; Brodie et al., 2005; Fabricius et al., 2010; Lucas, 1982); removal of predators of adult starfish (particularly fish and large gastropods) (Mendonga et al., 2010; Sweatman, 1995) and/or destruction of potential predators of COTS larvae, particularly plankton feeding corals; and other environmental induced changes (including climate change induced changes) to the population structure of predators of larval and juvenile COTS (Chesher, 1969; Randall, 1972).

2.2.1 Enhanced nutrients

Elevated nutrient concentrations on inshore and mid-shore reefs are postulated to promote outbreaks of COTS on the GBR due to nutrient-driven enhanced survival of COTS larvae (Fabricius et al., 2010). This ‘nutrient hypothesis’ was first proposed 40 years ago in relation to land-based nutrient runoff from high islands (Birkeland, 1982). Nutrients contained in runoff in river discharge can provide the conditions needed for phytoplankton to bloom and provide increased food availability to larval COTS (Birkeland, 1982; Brodie, 1992). This is in contrast to larvae growing in “normal” nutrient conditions that have insufficient phytoplankton food to reach competence (Lucas, 1982). Recent research has further supported this hypothesis (Uthicke et al., 2015; Wolfe et al., 2015). COTS outbreaks can also occur at sites with natural nutrient enrichment from ocean upwelling such as the Chagos archipelago (Roche et al., 2015), at oceanic nutrient/productivity fronts (Houk et al., 2007; Houk & Raubani, 2010) or at sites without any apparent nutrient enrichment (Miller et al., 2015) where upwelling may be present but not clearly documented.

In the GBR, elevated nutrients and thus increased dissolved inorganic nitrogen availability in land-based run-off has led to poor water quality in inshore habitats and increased phytoplankton biomass (Waterhouse et al., 2017b; Gruber et al., 2020). This may have directly enhance COTS larval survival (Fabricius et al., 2010). Timing of nutrient inputs is also important. During the wet season, river nutrients can influence COTS outbreak dynamics when large discharges (approximately more than 10 km^3) occur during the early wet season (November–February) in the region between Hinchinbrook and Lizard Islands from the Wet Tropics and the Burdekin Rivers (Brodie et al., 2005; Brodie et al., 2017a; Fabricius et al., 2010). The COTS spawning period is mainly from November to February (Babcock et al., 2014), which coincides with this period. The strongest correlation between water quality and COTS outbreaks has been found in the COTS initiation area, also called the ‘initiation box’ between Cairns and Lizard Island (Logan et al., 2014; Wooldridge & Brodie, 2015; Figure 4). This area of periodic nutrient enrichment linked to river discharge from the Wet Tropics rivers is believed to be the initiation point of the four historic waves of COTS outbreaks in the GBR (Wooldridge & Brodie, 2015). It has recently been suggested that nutrient levels on mid-shelf reefs are sufficiently elevated during flood plumes to also promote the spread of secondary outbreaks (Brodie et al., 2017b). Longevity of a COTS outbreak, however, depends on there being sufficient live coral cover to sustain adult populations.

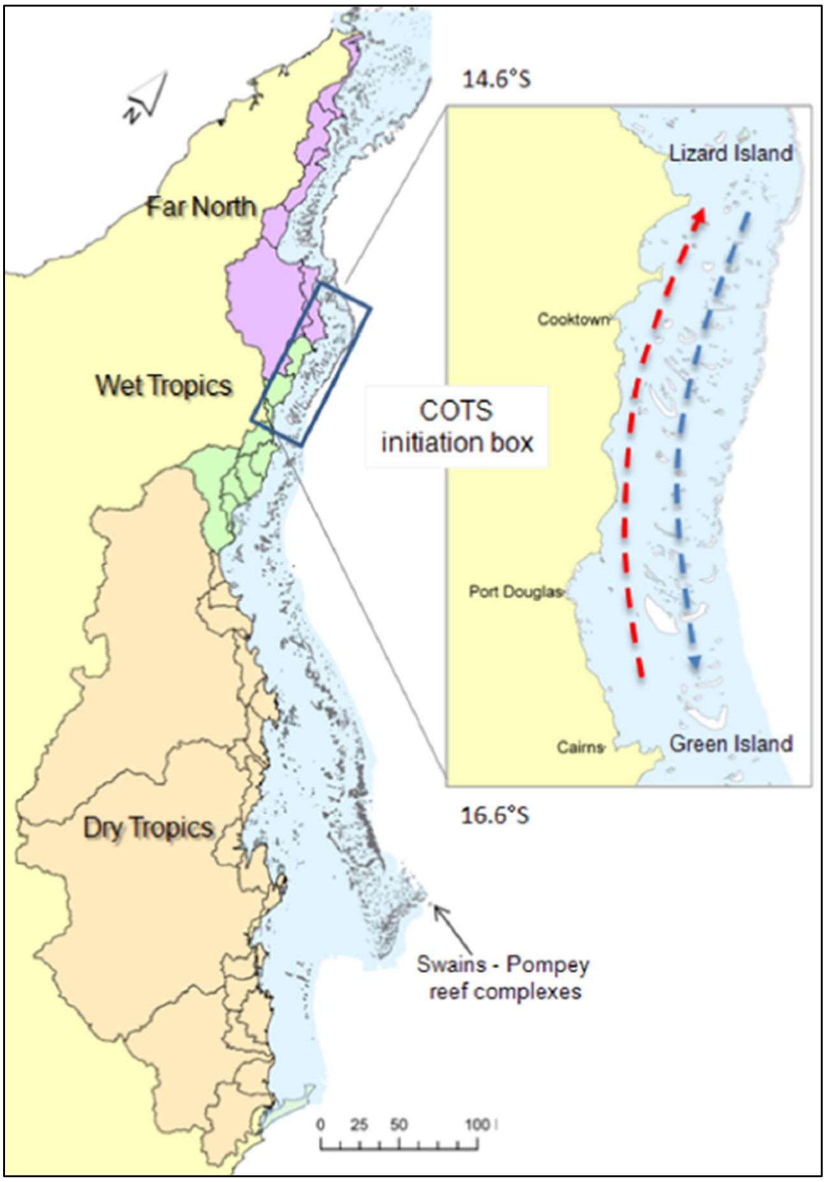

Figure 4. COTS initiation box in Far Northern GBR. (Source: Wooldridge & Brodie, 2015).

The debate over whether more frequent COTS outbreaks in the central GBR are partially caused by nutrient runoff from agricultural activities in the Wet Tropics and Burdekin regions is unresolved (Pratchett et al., 2014; Wooldridge & Brodie, 2015) and other factors including the loss of the predators on various life stages of COTS may also influence outbreaks. It has been demonstrated that oceanographic conditions associated with the ENSO cycle (Hock et al., 2014) may also play a part in this region, and Wooldridge & Brodie (2015) have also confirmed that both nutrient enrichment from river runoff and connectivity due to ENSO conditions are important in initiating outbreaks. Pratchett et al. (2014) suggested that primary outbreaks in the Far Northern Management Area (near Lizard Island) are initiated through a slow population build-up, and nutrients imported during flood events promote larval survivorship and thus (southward) COTS spread and secondary outbreaks.

The survival of COTS larvae is likely to be also strongly affected by other factors including their dispersal patterns, which influence the likelihood of larvae finding a suitable habitat for settlement (Westcott et al., 2016).

2.2.2 Predator-prey relationships

A shift in predator-prey densities is another potential factor related to COTS outbreaks. Based on models using historical data, abundance of invertebrates, such as the giant triton (*Charonia tritonis*) and fish species are suspected to affect COTS abundances (Morello et al., 2014). Overfishing of key predators is assumed to reduce predation pressure on COTS (Cowan et al., 2017; Endean, 1969; Westcott & Fletcher, 2018). There is some evidence that the increase in the area of no-take zones in the Great Barrier Reef Marine Park in 2004 has reduced COTS numbers on closed reefs (McCook et al., 2010; Sweatman, 2008; Vanhatalo et al., 2017). It is postulated that this is a consequence of increased numbers of fish predators of juvenile starfish. However, both processes, the ‘nutrient and the predator hypothesis’, interact at reef scales, contributing to COTS outbreaks (Westcott et al., 2016).

2.2.3 Other potential stressors

Additional environmental and anthropogenic stressors and their cumulative effects can further impair the health and resilience of the entire marine ecosystem in a dynamic and interconnected system such as the GBR. Corals previously stressed by partial COTS predation invest energy in recovery and therefore may be more susceptible to stresses caused by elevated sea surface temperatures, reduced water quality, pesticides and cyclones (De’ath et al., 2012; Mellin et al., 2019). Both COTS larval survival and juvenile growth increases with higher sea surface temperatures and acidification (Kamya et al., 2018; Uthicke et al., 2015). It is also postulated that COTS grazing and damage of coral coupled with higher than normal sea surface temperatures increases the risk of brown band coral disease (Kamya et al., 2018; Katz et al., 2014).

2.2.4 Monitoring

Monitoring plays a major role in contemporary COTS management. Monitoring was the foundation of early efforts to understand COTS outbreaks and support the sustainable management of the GBR. The Australian Institute of Marine Science (AIMS) established the Long-term Monitoring Program (LTMP) in 1983. Manta tow surveillance data from the LTMP helped to document COTS densities and variability throughout the GBR (refer to this example of an online animation of outbreaks from 1985 to 2020).

COTS monitoring funded by the CRC Reef, AIMS and associates (GBRF, GBRMPA, AMPTO) have helped to provide a better understanding of outbreaks by tracking the spread of COTS The development of an early warning system due to concerns of COTS outbreaks at Moore Reef in 2009 prompted AIMS to alert tourism operators (Australian Government and

Queensland Government, 2009). COTS Alert operates in parallel with the Marine Monitoring Program (MMP) (2005-current), which is designed to monitor inshore water quality, and coral reef and seagrass health in the GBR.

2.2.5 Research

The Cooperative Research Centre for the Great Barrier Reef World Heritage Area (CRC Reef, 1999-2006) and the Marine and Tropical Sciences Research Facility (MTSRF, 2006-2010) both identified COTS outbreaks at important tourism sites as a focal issue, and provided further knowledge on the links between healthy reefs and a strong tourism industry (Australian Government and Queensland Government, 2009; Woodley et al., 2006). The CRC Reef focused on the sustainability of industry and management actions, and the maintenance of ecosystem quality. Their research suggested that COTS outbreaks are linked to land run-off and overfishing (Brodie et al., 2005).

The National Environmental Research Program Tropical Ecosystem Hub (NERP, 2011-2015), a predecessor of the NESP, similarly focused on environmental research in the GBR and decision-making support with an emphasis on reef biodiversity, management and conservation. The NERP contributed to new knowledge on COTS, finding that the likelihood of outbreaks of COTS was higher on reefs open to fishing pressure (RRRC, 2014). Research also documented a southward movement of three waves of COTS outbreaks over the past 30 years. Models simulations assessing corals' response to environmental pressures indicated that reductions in nutrient and sediment inputs could lead to higher resilience of the GBR when combined with effective control of COTS at important reefs (RRRC, 2014). At this time, water quality decline was assessed as the greatest single factor contributing to coral loss on the GBR compared to any other disturbances, including cyclones and COTS (RRRC, 2014).

2.3 NESP research to develop an improved COTS control strategy

Climate change is now universally acknowledged as the greatest threat to coral reefs globally (Hughes et al., 2018). However, the occurrence of COTS outbreaks still remains a major cause of coral loss on the GBR, necessitating investment in innovative research and management to protect the GBR. NESP TWQ Hub research has actively addressed this issue over the last five years. The NESP TWQ Hub identified COTS control as a priority for urgent management action to improve the state of the GBR World Heritage Area. Six projects were funded over the life of the 6-year program, including the operationalisation of an integrated pest management (IPM) approach and improvement of manual COTS control methods by incorporating new knowledge from current research. Associated research investigated the potential link between COTS outbreaks and water quality, and the ecology, life-history and distribution of COTS, the potential for biological control of the species. Modelling and development work was also undertaken that enabled optimisation of on-going field-based COTS control operations including cost-benefit guidance on preferred strategies to minimise the impact of future COTS outbreaks. Implementation of the NESP COTS IPM research program is illustrated in Figure 5, and the key findings of each of the primary research areas are summarised below.

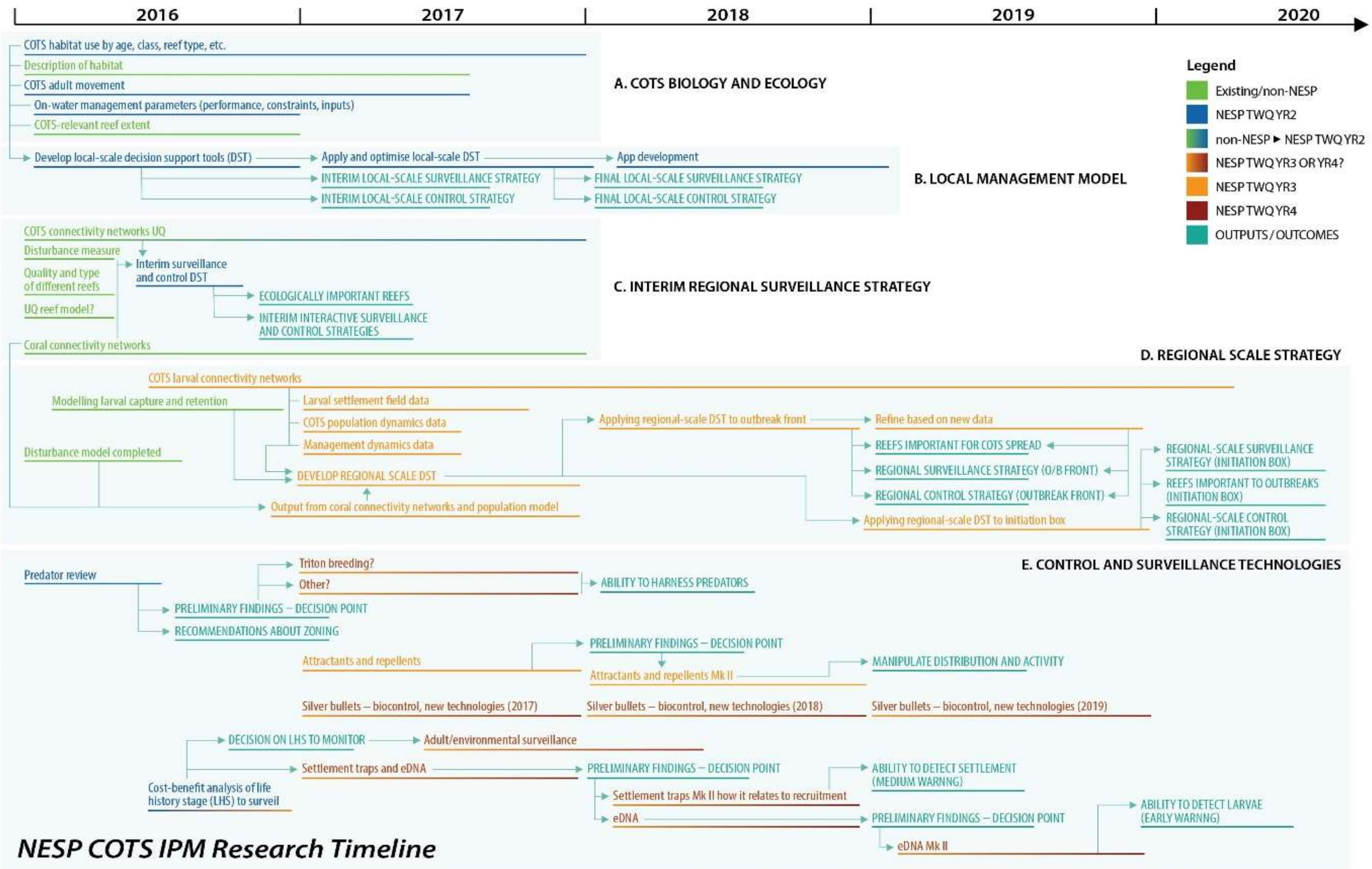

Figure 5. How the NESP COTS IPM research program has been implemented over time, through local, regional, and new technological strategies.

2.3.1 Links to water quality and associated management

Brodie (2021) summarised the potential links of water quality to anthropogenic induced changes to COTS population dynamics and new research has assessed the relative importance of nutrient enrichment compared to other factors in driving COTS outbreaks. Matthews et al. (2020) tested the effects of multiple factors influencing COTS abundances in the GBR. The study showed that while many factors contributed to the predicted prevalence of COTS, larval connectivity and sea surface temperature had the highest impact, and that (modelled) chlorophyll concentrations and particularly river derived inputs were also important.

2.3.2 Larval COTS development

Fundamental studies on the ecology, behaviour and life-history of COTS have been completed over many decades, however only limited information on the early life history processes including settlement, and survival rates that could further improve management of COTS as a pest species have been available until now. The NESP TWQ Hub research programme and structured management programs have improved our understanding of COTS biology and ecology and been incorporated into the design of an ongoing Integrated Pest Management (IPM) programme for the starfish.

Research on early life stages, body size and growth has found that survival of juvenile starfish is inherently linked to an ontogenetic diet shift from crustose coralline algae (CCA) to coral (Deaker et al., 2020; Wilmes et al., 2020). Juvenile starfish with a body size of ≤ 8 mm feed on coralline algae (Wilmes et al., 2020), but exhibit a flexible diet starting at 6 months post-settlement and can endure periods of herbivory when deprived of coral as a food source (Deaker et al., 2020). The early food preference for CCA and *Amphiroa sp*., in contrast to a low preference for biofilm promotes fast growth and increased body size in juvenile starfish (Deaker et al., 2020). When COTS juveniles reach a body size of 20mm at around 8 months post-settlement, they shift their main diet towards corals if locally available, which accelerates their growth (Wilmes et al., 2020). This diet shift enhances replenishment success through growth "boost", maturity and survival success, consequently increasing individual fitness and therefore initiating potential population irruptions (Wilmes et al., 2020). An optimal diet results in an early maturity, usually within two years due to faster grow rates (Wilmes et al., 2020). This research has reduced the age estimation at which ontogenetic shift occurs from 9-15 months (Zann et al., 1987) to 6-8 months (Wilmes et al., 2020). The research highlights the need for earlier interventions in COTS control and also indicates an increased risk of coral mortalities if these early interventions are absent (Deaker et al., 2020).

2.3.3 Larval COTS predation

Field studies were conducted in 2018 and 2019 at five mid-shelf reefs to explore variation in recruitment and survival of early-stage juvenile COTS between reefs where fishing was permitted (Habitat Protection Zone) compared with those where fishing was prohibited (Marine National Park Zone) (Pratchett et al., 2020b). Most (>90%) early-stage juvenile COTS were found to have evidence of injuries, with no apparent effect of management zone. Similarly, the severity of injuries did not vary between juveniles that were sampled from reefs where restricted fishing was permitted compared with no-take areas. The severity of injuries was, however, negatively correlated to body size. Zoning was also determined to have no impact on juvenile starfish densities or on juvenile survivorship (Pratchett et al., 2020b).

2.3.4 Adult COTS predation

A total of 5,238 COTS (ranging in size from 50-600mm diameter) were sampled across 70 reefs in the Great Barrier Reef Marine Park between 2013 and 2018 and examined for injury (Pratchett et al., 2020b). Variation in the incidence and severity were compared among the three different management zones; 1) Marine National Park Zones (green); ii) Conservation Park Zones (yellow); and iii) Habitat Protection Zones (blue), while also accounting for variation in the size (maximum diameter) of individual starfish. Forty-three percent of adult crown-of-thorns starfish sampled from across the GBR had evidence of injuries. Overall, zoning had a significant effect on the prevalence of injuries, with the overall prevalence of injuries significantly higher for starfish sampled from reefs within Marine National Park Zone (Green Zones) compared to those sampled from Conservation Park Zones (Yellow Zones) and Habitat Protection Zones (Blue Zones). The severity (proportion of injured arms) of injury also increased with increasing levels of fisheries protection. Higher prevalence and severity of sub-lethal predation is likely to have a significant impact on the individual fitness and population dynamics of COTS, potentially reducing outbreak potential in areas protected from fishing in the Marine Park (Budden et al., 2019; Harris, 1989; Wilmes et al., 2019; Zajac, 1995).

2.3.5 COTS distribution

Understanding the distribution (home ranges and movement patterns) of COTS is critical for management strategy development. Using innovative technologies, such as tracking devices, research has found that adult starfish generally have a small home range of 50-100 m in areas with moderate to high hard coral cover (Ling et al., 2020). Research has found that COTS may move 250-520 m per day in search of live hard coral (Pratchett et al., 2017b), although inter-reef movements are thought to occur only rarely. A high-resolution bathymetry grid which incorporates spatial datasets on topography and hydrodynamics was used to assess the potential spatial distribution of COTS in deep water reefs within the GBR (Beaman, 2018). Permanent COTS study sites were overlayed with the information from the grid to detect any suitable deep-water banks as a COTS habitat. Deep-water habitats located on emergent reefs below the zone of highest coral cover were found to be unsuitable habitat for COTS larvae or COTS adult foraging based on starfish distribution patterns.

At larger spatial scales, emerging genetic technologies were able to support the investigation of distribution patterns and abundances of adult and juvenile COTS. Water samples were screened for environmental COTS DNA (eDNA) and compared to transect data recording COTS densities. Even at low COTS densities, eDNA concentrations were able to confirm the presence of COTS in the field within 500 km of the sample site (Uthicke et al., 2018). Similarly, lateral flow analysis successfully detected eDNA of COTS at densities below outbreak levels from field samples collected from two locations on the GBR (Doyle & Uthicke, 2020). Genetic screening was also able to detect the presence of larval COTS, using previous knowledge about spawning periods of COTS in the northern GBR (Uthicke et al., 2019). Using quantitative PCR assays, a 3-year time series of plankton samples, settlement assays and benthic surveys were analysed to determine COTS larval abundances (Uthicke et al., 2019) This research showed that larval abundances were correlated with settlement densities, demonstrating that larval abundance estimates can be used to predict variations in settlement at interannual and inter-reef scales (Uthicke et al., 2019). Computational models were applied to define larval dispersion via currents expanding the distribution range of COTS (Hock et al., 2014, 2017). The identification and detection of juvenile and cryptic adult COTS informs spatial targeting of surveillance and control efforts as pre-outbreak strategies to prevent larger moving COTS outbreaks.

Statistical modelling of previously collected data sets using a parametric generalized linear mixed model (GLMM) at reef and site scales and using a non-parametric statistical random forest model at the reef scale were used to determine the potential influence of environmental factors on the distribution of COTS (Gladish et al., 2020). Data sets (2012-2020) from several monitoring programs were included in the analysis. These included the Australian Institute of Marine Science (AIMS) Long Term Monitoring Program (LTMP), Great Barrier Reef Marine Park Authority's (GBRMPA) Eye on the Reef (EotR) surveys, and Queensland Parks and Wildlife Service (QPWS), GBRMPA's Marine Bioregions of the Great Barrier Reef, GBRMPA joint Field Management Program (FMP), and the COTS control program.

The results of this analysis concluded that environmental, spatial, and temporal factors influence the observation of COTS on the GBR. Critically, this study confirmed that the observed abundance of COTS is positively related to hard coral cover, and provides an important insight for management, namely control effort should be targeted at reefs and reef sites with high hard coral cover, independent of their bleaching history. The analysis also indicated that observed COTS abundance tended to be higher on the southern aspects of individual reefs, relative to the north-eastern aspect (noting that COTS would prefer regions of the GBR less exposed to open ocean influences).

2.3.6 Biocontrol

Biocontrol methods provide a potential opportunity to naturally suppress and control COTS populations, even when they are at low densities (McCallum, 1987; McCallum et al., 1989). NESP TWQ Hub research investigated a range of possible approaches incorporating direct biocontrol, including the use of predators such as the giant triton (*Charonia tritonis*), microbes and parasites, semio-chemicals (compounds that are involved in COTS chemical communication and signalling) and genetic methods (Høj et al., 2020), and indirect biocontrols, such as the establishment of no-fishing zones that can protect species that are known predators of adult COTS such as humphead Maori wrasse, starry pufferfish and titan trigger fish (Cowan et al., 2017).

Predation control

A potential biocontrol investigated was based on a hypothesis developed in 1970s that the presence of giant triton (*Charonia tritonis*) can disperse COTS spawning aggregations and thus disrupt reproduction (Dana et al., 1972). Adult COTS react with a flight response to the presence of this benthic predator and the chemical compounds they exude (Hall et al., 2017). The presence of even one adult giant triton can disperse many adult COTS with the potential to disturb the formation of pre-spawning aggregations, ultimately reducing reproductive success and future outbreaks (Hall et al., 2017). Theoretically, increased densities of giant triton on reefs may therefore delay or minimize the size of future outbreaks, even if these predators do not significantly reduce the number of COTS through predation. Their role as a disruptor of COTS reproduction and a direct predator of COTS has been supported by acoustic tracking defining the spatial ecology of giant triton snails (Schlaff et al., 2020). Acoustic tracking confirmed that the movement patterns of this natural COTS predator was greater at night, where on average individuals travel 1,923 m per night, generally in concentric patterns reflecting foraging and hunting. This behaviour aligns well with COTS behaviour, that are also nocturnal organisms. Additionally, the home range of the giant triton of 659.4 m^2 is greater than that of their COTS prey, and therefore re-stocking giant triton has COTS control potential over reef areas (Schlaff et al., 2020).

Biocontrol can also be achieved by increasing predator pressure on COTS larvae and adults. A number of reef fish are known to feed on adult and juvenile stages of COTS (e.g Titan Triggerfish (*Balistoides viridescens*) and Starry Pufferfish (*Arothron stellatus*)), and a number of fish species feed on the pelagic larval stage, e.g. Ambon Damselfish (*Pomacentrus amboinensis*) and Lemon Damselfish (*Pomacentrus moluccensis*) (Cowan et al., 2017; Kroon et al., 2020). Eighteen reef fish species were identified to feed directly on COTS, or on species feeding on COTS using new DNA technologies analysing coral reef fish faecal and gut content, suggesting that fish predation on COTS larvae, and therefore its natural biocontrol by fish may be more common than previously understood (Kroon et al., 2020). This is significant as biocontrol of COTS populations by reef fish through direct predation on the pelagic stage could directly regulate the settlement of COTS larvae and influence future population densities (Kroon et al., 2020). Significantly, associated NESP TWQ Hub research concluded that fishing pressure zoning had a significant effect on the prevalence and severity of COTS injuries, and that the higher prevalence and severity of sub-lethal predation is likely to have a significant impact on the individual fitness and population dynamics of COTS, potentially reducing outbreak potential in areas protected from fishing in the Marine Park (Budden et al., 2019; Harris, 1989; Wilmes et al., 2019; Zajac, 1995).

No-take marine reserves that protect predator fish species could potentially increase predation pressure on COTS larvae. Sweatman & Cappo (2018) found that these no-take zones reduce the likelihood of COTS outbreaks at a low threshold of 0.12 starfish per two-minute manta tow. However, the effects are inconsistent and weak. Further, they acknowledge that lower densities of starfish, i.e. below the ecological threshold, can still result in net loss of coral cover and areas with higher hard coral cover can attract COTS that lead to higher COTS grazing rates. Zoning was also determined to have no impact on juvenile starfish densities or on juvenile survivorship in complimentary research (Pratchett et al., 2020b).

2.3.7 Identification and targeting effort on ‘Priority’ Reefs

The COTS Control Program previously led by the GBRMPA and currently led by the GBR Foundation identifies priority reefs to determine where culling and surveillance activities should focus. Priority Reefs in the GBR are identified based on attributes (measured or modelled) that indicated high ecological and economic value. Ecological value is based on an estimation of coral condition and the reef’s capacity to contribute to coral population dynamics and resilience through their role as a source of coral larvae, and their connectivity to other reefs. Economic value is based on a reef’s value as a tourism destination. These values are updated when new information becomes available (Westcott et al., 2021).

NESP TWQ Hub research has facilitated decision-making for identifying these priority reefs through development of decision trees. Decision trees assist in determining the best strategy to manage high COTS densities and to identify low COTS density reefs while allocating resources most effectively (Fletcher et al., 2020). These consider fundamental ecological information, surveillance data and reef health survey data in locating high priority reefs.

Three decision trees have been proposed and tested. The first decision tree is for simplified on-water decisions for culling prioritising reefs in 'Maintenance Mode' and that need initial assessment. It is based on manta tow surveys and these assessments are completed before new reefs are surveyed. The second tree is an advanced on-water tool, which combines detailed data analysis and ecological modelling with data generated by culling activities and surveillance. The selection and revisitation to sites are based on computed COTS densities and 'Ecological Thresholds' (See Section 2.1). The final decision tree includes adaptive actions to be taken in response to weather changes, distances between reefs, resource allocation and the most effective execution of multiple tasks. This approach improves efficient controlling of COTS densities and in identifying high priority reefs by accounting for current COTS abundances via reefs surveys and the inclusion of variable and more complex factors such as weather or logistics, and also ecological processes, including the distribution of COTS.

2.3.8 The COTS Control Centre Decision Support Tool

Early work in the NESP COTS Integrated Pest Management (IPM) Research Program demonstrated that data collected by the Control Program could be used to improve efficiency by targeting control actions within a reef (Fletcher & Westcott, 2016). Building on this, in 2018 CSIRO developed, with input from reef managers at GBRMPA and on-water control staff, a fully ecologically-informed framework for the expanded National COTS Control Program (Fletcher et al., 2021). The COTS Control Centre Decision Support Tool (CCC-DST) is a combined hardware and software solution developed by CSIRO to help guide on-water decision making and implement an ecologically-informed management program. The COTS Control Centre DSS is built around a fleet of 32 ruggedised Samsung Galaxy Tab Active2 Android tablets, along with a suite of three data collection apps, developed for the Great Barrier Reef Marine Park Authority (GBRMPA) by *ThinkSpatial*, and three decision support components developed by CSIRO as part of the NESP COTS IPM Research Program. The fleet of tablets can be managed remotely, including locating hardware and updating software, and run a custom kiosk launcher. Data is shared between the apps that make up the CCC-DSS within a tablet using the Android file system, between tablets on a vessel independent of cellular connectivity with the Android Nearby Communications protocol, and with GBRMPA's Eye on the Reef Database when cellular networking is available. In addition to designing and implementing the overarching CCC-DSS system, CSIRO has developed a suite of three software components, consisting of the main Decision Support Tool (CCC-DST), a Data Explorer functionality, which is currently implemented as part of the CCC-DST but may, in future, be separated into a second app, and a utility Data Sync Tool for sharing data between tablets when internet connectivity is not available.

2.3.9 Monitoring and surveillance requirements

Monitoring is a critical component of any strategic ecological COTS control program, as it provides foundation data on the distribution of the abundance of COTS across the region of interest and over time. An effective COTS monitoring program should be:

- tailored to the attributes of COTS and COTS control;
- specific to the needs of the COTS control program;
- conducted on temporal and spatial scales relevant to COTS outbreaks and control;
- sufficiently accurate and precise for the needs of the program;
- cost-effective;

- capable of being consistently applied across different phases of the outbreak and by different operators; and
- able to produce information that is readily interrogated.

The monitoring and surveillance requirements of an Integrated Pest Management COTS Control Program were analysed by a NESP TWQ Hub research subprogram in the context of management of existing and new COTS outbreaks. The most immediate needs for the present Control Program are detection and delimitation of initiating and established outbreaks. These data provide the information necessary to make on-water control decisions that can enable effective control actions to protect individual high value reefs. Better monitoring will lead to better decisions, and more reefs will be able to be protected with the resources available. Within the next few years, however, ability to leverage this manual control capability to dramatically minimize the impact of the next outbreak on the GBR will depend on early detection of events leading to outbreak initiation, and potentially pre-outbreak or baseline monitoring of COTS abundance, density, coral, reef condition across the GBR.

Monitoring of pre-outbreak conditions (Initiation and Establishment)

NESP TWQ Hub research identified that the use of both Cull monitoring and Towed Underwater Vehicle (TUV-tow) monitoring methods in combination with eDNA monitoring (See Box 1) was the preferred monitoring methodology to develop a predictive understanding of the drivers of COTS outbreak initiation and spread. Exclusion of eDNA monitoring was only recommended if monitoring resources are limited. Using this approach, Towed Underwater Vehicles (TUV-tow) monitoring provides a broad range of detailed monitoring data on COTS and coral condition. Where indicated, these estimates can be refined by cull (monitoring). eDNA methods would contribute to this task, particularly in terms of early warning, and would be fundamentally important in 'sentinel' and validation roles.

Box 1: Recommended monitoring practices for detection and delimitation of initiating and established outbreaks

Culling: Cull divers swimming through a site systematically culling COTS record information on the size and numbers of COTS culled. This approach is slow but reliable (though this could be improved with automated data recording), allowing divers the freedom of movement to detect COTS underneath plate corals and potentially those hidden in the coral matrix. This is the current standard used in the control program for estimating COTS densities and size distributions. Culls provide good data at the site and reef scales, and even at regional scales, and at GBR scales over longer time periods. However, as the spatial scale increases, the temporal resolution decreases. Culls, by definition, measure the population density and size of COTS removed from the population, and the COTS remaining after management must be inferred by estimating age-size class detectability, thus confidence in the estimate increases with more dives at a site or reef. It is a high-cost approach with depth limited sampling, however, as culling of COTS is the fundamental management activity, its data comes at little additional cost to a monitoring program.

Towed Underwater Vehicles (TUVs): TUV tows are similar to manta tows but humans are replaced with a remotely operated TUV that collects high-resolution images of the substrate from an angle, and above across a swathe that varies with height from the substrate but is generally 10+ m. These images are then analysed using AI approaches to provide estimates of COTS sizes & number, coral cover and assemblages and reef condition. They have a vastly improved COTS detection capability compared with manta tows and early indications suggest that they will allow for reliable and precise estimation of COTS density and size (Kettle, B., pers. comm.). Because the cameras capture vision at angles oblique to the direction of travel, as well as from directly above, and because machine learning-based algorithms can interrogate multiple frames, they are far better than humans at detecting partially obscured COTS and those that are visible for only a fraction of a second. They are faster (1.5 – 2 times), more comprehensive, and cheaper to implement than manta tows and capable of monitoring at all relevant depths. While work on development and operationalising of TUVs is ongoing (with programs at AIMS, Babel/CSIRO, and QUT), TUVs are a replacement for manta tows and will do so in the very near future.

eDNA: Based on detection of sloughed-off cells, gametes or larvae of COTS are detected in water samples using eDNA methods (Uthicke et al. 2015, Doyle et al. 2017, Uthicke et al. 2018, Doyle and Uthicke 2020). This method is highly sensitive in detecting COTS DNA in water samples and appears to provide a reasonable index of COTS abundance (Doyle et al. 2017, Uthicke et al. 2018). These tools should be able to detect COTS regardless of their position in the coral matrix. Dipstick methods (Doyle and Uthicke 2020) provide a rapid sampling approach. The method requires pumping and filtration of water on the vessel and laboratory processing and analysis (dipstick methods aside) once the samples are returned to shore. Currents and vertical mixing mean that the source location remains unknown, although eDNA detected at a reef appears to come from that reef (S. Uthicke, unpubl. data), hence locational accuracy is poor but could be improved with appropriate spatial sampling strategies. With adequate samples, the technique would perform well at larger scales and when sampling timeframes are longer. This means that it would also perform particularly well in a sentinel role or as a validation method for other sampling. eDNA larval detection based on plankton tows is the only feasible method for detecting larvae. This method is well established, and water samples are currently collected as part of some COTS culling and other monitoring activities.

The concept of the sentinel role is that while TUV-based monitoring can cover the Initiation and Dispersal Boxes adequately over time, at any given point in time, its sampling is sparsely distributed, and although capable of detecting the majority of the COTS population at a given site, inevitably will miss some individuals. eDNA methods can plug this gap by sampling water flows over longer time periods that represent a much broader sampling of a region and, at a reef, detect individuals not otherwise monitored almost regardless of their location in the coral matrix. Any eDNA trigger would allow a re-focusing of TUV-based monitoring and its associated culling capability. A key objective of this approach would be to detect and prevent spawning events that might lead to outbreak initiation. Combining Culling, TUV tows and eDNA provides a comprehensive and ultimately more reliable program for monitoring and decision making.

Outbreak and post-outbreak monitoring

Monitoring during other phases would be as per the tow-based strategy but would use eDNA monitoring to validate tow monitoring of areas that have been successfully controlled and are now in maintenance mode and sites assessed as not requiring culling, and to monitor spread ahead of the outbreak. Tows and eDNA (larvae and post-settlement) are used to delimit and monitor outbreak progress, assess asset condition, inform design of the control response at the regional scale.

2.3.10 Evaluation of biologically based technologies to support IPM

The NESP TWQ Hub evaluated biologically based technologies that could be developed for COTS as part of an integrated pest management strategy (Høj et al., 2020). The evaluation considered the following control strategies:

- Biological control using predators or coral epi-fauna;
- Biological control using microbial agents;
- Semiochemicals; and
- Genetic biocontrol.

For each strategy, the current state of the technology was considered, drawing on work in terrestrial, aquatic and marine environments, and the potential application of each strategy for COTS control summarised based on current knowledge of key biological and ecological traits of COTS. Knowledge and technology gaps, associated risks, and the possible role of each approach in an integrated pest management strategy including the scale and frequency of their application was determined. None of the technologies considered were considered to represent a ‘silver bullet’, and the challenge identified was to optimise the combination of tools to develop and strategically apply them to maximise the level of control that can be achieved.

One potential biocontrol investigated was based on a hypothesis developed in 1970s that the presence of giant triton (*Charonia tritonis*) can disperse COTS spawning aggregations and thus disrupt reproduction (Dana et al., 1972). Adult COTS react with a flight response to the presence of this benthic predator and the chemical compounds they exude (Hall et al., 2017). The presence of even one adult giant triton can disperse many adult COTS with the potential to disturb the formation of pre-spawning aggregations, ultimately reducing reproductive success and future outbreaks (Hall et al., 2017). Theoretically, increased densities of giant triton on reefs may therefore delay or minimize the size of future outbreaks, even if these predators do not significantly reduce the number of COTS through predation. Their role as a disruptor of COTS reproduction and a direct predator of COTS has been supported by acoustic tracking defining the spatial ecology of giant triton (Schlaff et al., 2020). The NESP TWQ Hub research concluded that there remain significant challenges in developing species-specific technologies required for COTS control, for building infrastructure and operationalizing the process.

Corals symbionts such as polychaetes, shrimps, crabs, and fish could potentially be used as an alternative biocontrol strategy as they are grazers of early COTS life stages and coral host defenders (Høj et al., 2020). The NESP TWQ Hub research concluded investigation of the potential of the feeding behaviour of the peppermint shrimp (*Lysmata spp.*) on juvenile COTS warranted future research.

The introduction of pathogens, such as bacteria, viruses, fungi, ciliates and endoparasites, represent another possible biocontrol strategy that can control COTS populations through mortality or infertility (Høj et al., 2020). The contagious ‘sea star wasting disease’ (SSWD) affects many species of sea stars causing tissue breakdown and ultimately death, an may be an effective biocontrol for COTS populations, (Miner et al., 2018). However, there are significant risks associated with the application of microbial agents, since they are often not species-specific thus impacting many more species than just COTS and their effect on COTS is still unknown. The NESP TWQ Hub research concluded this strategy was deemed unsafe and unsuitable for COTS control at present.

Semio-chemicals are secondary metabolites that can be used for COTS control either as repellents or attractants (Høj et al., 2020). These semio-chemicals are involved in COTS related ecological processes, such as foraging, metamorphosis, growth, spawning, reproduction, larval settlement, chemical defence, dispersal and predator avoidance (Høj et al., 2020). Attracting agents can assist in detecting cryptic individuals in the field, while repellents can protect high-value areas on reefs by deterring COTS or disrupting the formation of spawning aggregations (Høj et al., 2020). The NESP TWQ Hub research concluded that significant research is still required to identify appropriate candidate semiochemicals, to understand their performance under field conditions, and to develop deployment technologies and strategies.

Genetic modification of DNA entails genetic alteration of processes involved in reproduction and ecological behaviour and may have application for COTS control (Høj et al., 2020). The release of sterile individuals can bias the sex ratio and reduce reproductive success of populations. However, these approaches have not been applied to COTS and require further research investment since COTS they do not appear to have sex chromosomes and the cellular and genetic basis for sex determination in starfish is not known. Genetic modification generally causes a reduction in organism fitness and is selected against by natural selection (Høj et al., 2020). The NESP TWQ Hub research concluded that genetic biocontrol strategies present unknown environmental risks to the ecosystem and other species and are therefore not suitable for COTS control at present.

Overall, manual control was considered to represent an (and the only) immediately available approach that has been shown to be effective at the site and reef scale and which is currently being scaled up to the regional scales. It can and should be further refined, including through the integration of some of the other technologies considered here. Other technologies would be unlikely to be in use within the next 10 years (Høj et al., 2020; Figure 6).

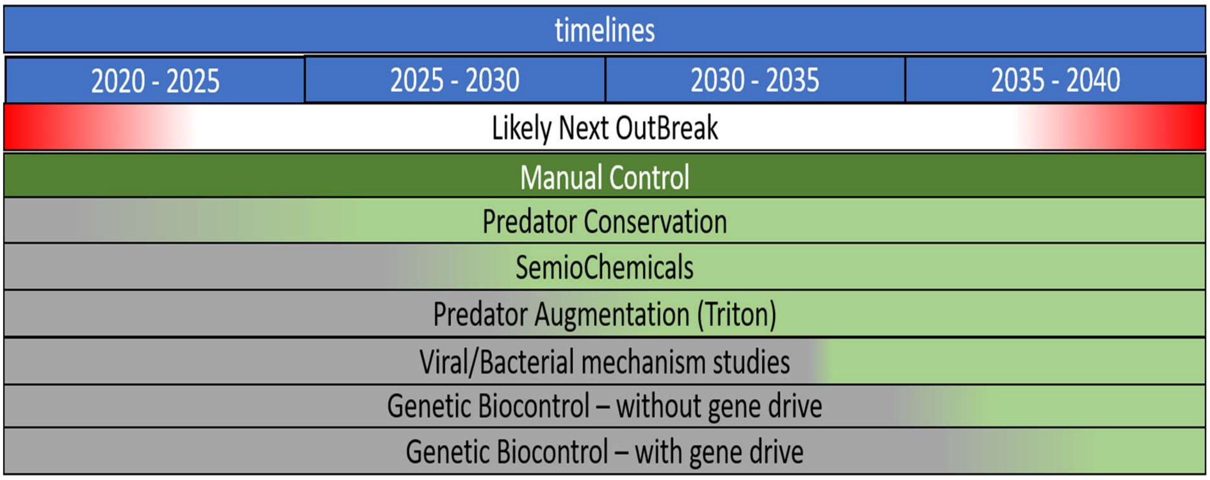

Figure 6. Likely timelines for development and implementation of alternative control techniques. Grey areas represent the period for research, development and consultation prior to implementation of technology. Coloured periods represent implementation period. The likely period of the next outbreak is shown in white as an indicator of the timeliness of each potential technology. (Source: Høj et al. 2020)

2.3.11 COTS Integrated Pest Management (IPM) programme

In 2016, a 2-year collaborative COTS Integrated Pest Management (IPM) programme was established between the NESP TWQ Hub and CSIRO to integrate ecological principles into the COTS Control Program (Figure 5, Westcott et al., 2016). This strategy has been adapted from terrestrial research and tailored to the marine environment. It was developed based on current understanding of how COTS outbreaks arise and spread and designed to achieve efficient and effective management solutions for COTS management using diver based manual control methods (Westcott et al., 2016). The COTS Control Program strategically targets priority reefs in the (current) outbreak region to achieve the following goals:

1. Protect coral cover at reefs that are critical sources of coral larvae to facilitate reef recovery and resilience;
2. Protect coral cover at reefs of high value for the tourism industry; and
3. Reduce the spread of the outbreak by culling at reefs that have greatest risk of spreading COTS larvae.

During the period 3 November 2018 to 30 July 2020, the IPM COTS Control Program conducted management activities at 202 reefs between latitudes 12.9°S and 24.1°S. At each of these reefs: 1) surveillance manta tows were conducted around the entire reef perimeter; and 2) control operations were conducted where this initial surveillance indicated it was necessary based on the decision rules of the control program. Of these 202 reefs, surveillance indicated that cull dives were not required at 81. At 18 reefs, surveillance had been conducted but control had not begun by 30 July 2020, while at the remaining 103 reefs, cull dives were conducted at 884 sites where COTS or feeding scars were detected. By 30 July 2020, control activities had successfully achieved the management objective along the entire perimeter of 92 (89%) of these 103 reefs, with COTS densities being reduced to below the conservative threshold density of 3 COTS ha^{-1}.

The NESP TWQ Hub has analysed the performance of the collaborative IPM COTS Control Program over the first 20 months of its operations. The performance analysis found that the IPM program was twice as likely to reduce a site requiring control to below the three COTS ha^{-1} threshold compared with the pre-IPM programme and did so in 63% of the time of the pre-IPM program. The final mean COTS density at an IPM site was one sixth that of a Pre-IPM site, meaning that lower on-going rates of coral loss and lower contribution to downstream COTS recruitment would be expected. Critically, the IPM Control Program achieved its management objectives at a reef scale at 89% of the 103 reefs it targeted, while the Pre-IPM program achieved this objective at 0% of 102 reefs. These results confirm that the IPM COTS Control Program has turned an effective culling method developed in the Pre-IPM program into a potent tool for achieving COTS control objectives and protecting coral at the scales of sites, reefs, and hundreds of reefs.

2.4 Innovations in COTS control strategy and delivery

Managing the impacts of COTS outbreaks is a major objective of management strategies and investment on the GBR. For most of its history, COTS control in Australia has focused on protecting individual reef sites of tourism importance and the majority of COTS management effort has involved manual control at small (sub-reef) scales, either in the form of the physical removal of the COTS onto land or by lethal injection (Pratchett & Cumming, 2019). Until the recent development of single-shot lethal injections (Boström-Einarsson & Rivera-Posada, 2016; Moutardier et al., 2015; Rivera-Posada et al., 2013) these methods were labour intensive, time consuming and, consequently, spatially constrained. As a consequence, and despite the huge investment, past COTS control has had limited success.

2.4.1 Improved COTS control

Changes introduced in COTS control management during the current outbreak (2010-present) have revolutionized the way COTS control is conducted (Westcott et al., 2021; Box 2). The IPM Crown-of-Thorns Starfish Control Program is the product of a 5-year and on-going collaboration between GBR managers, researchers and on-water control operators conducted under the auspices of the National Environmental Science Program's Tropical Water Quality Hub. The IPM COTS Control Program is funded by the Australian Government and was administered by the Great Barrier Reef Marine Park Authority and more recently by the GBRF.

Box 2: How a significant improvement in defending live coral cover from COTS outbreaks on the GBR was achieved

Outbreaks of coral-eating crown-of-thorns starfish (COTS) are responsible for substantial losses of live coral cover on the GBR (De'ath et al., 2012). Coral loss poses a substantial threat to the ecosystem function and integrity of the GBR, highlighting the need to minimise or prevent major causes of coral mortality. The inclusion of the IPM (Integrated Pest Management) approach is a promising strategy to improve the efficiency and effectiveness of COTS management control on the GBR, thereby reducing coral loss caused by COTS outbreaks.

The adaptation of IPM concepts from land-based programs to the marine environment requires a deep understanding of ecological processes and dynamics of the target species and a multidisciplinary research strategy (Westcott et al., 2016). Collaborating institutions such as AMPTO, GBRMPA, CSIRO, AIMS, JCU and UQ identified research needs (Figure 4) and integrated new knowledge on COTS annually throughout the NESP TWQ Hub's five-year program supporting the protection of coral cover during active COTS outbreaks. Since the program identified manual single shot injection as the most effective control method, more research vessels were deployed initiating the Queensland Government's Skilling Queenslanders for Work program to train young locals in boating, SCUBA and COTS control activities (Jarvis et al., 2020).

The innovative strategy resulted in restoring starfish densities below the Ecological Threshold at 90% of the 103 priority reefs (GBRMPA, 2020), thereby helping to protect hard coral cover. Furthermore, new genetic tools and technologies including eDNA that can be useful for future management activities and collaboration between research and management were developed. Finally, this program also improved socio-cultural aspects with the inclusion of Indigenous and non-Indigenous young adults through the Skilling Queenslanders for Work program (Jarvis et al., 2020).

Pre-IPM Control Program

The first of the COTS control management changes was introduced in 2013. The program established was based on two dedicated control vessels staffed by trained and experienced COTS control divers (the Pre-Integrated Pest Management Control Program). This coordinated effort was enhanced by the introduction of single-shot injections for COTS culling (Boström-Einarsson & Rivera-Posada, 2016; Moutardier et al., 2015; Rivera-Posada et al., 2013), which dramatically reduced the time and effort required to kill each starfish, vastly improving the efficiency of individual divers and the program. The program was funded by the Australian Government through the Great Barrier Reef Marine Park Authority (GBRMPA) and on water operations were conducted by the Association of Marine Park Tourism Operators (AMPTO). Over the first five years of the program (2013-2017), control efforts were nominally focused on 56 sites at 21 'high value' reefs in the Cairns region. These were considered high value because they were economically important tourism sites or because they were considered ecologically important due to their location or attributes. Each site where control was conducted was mapped as geolocated polygons. During a voyage, each polygon was searched, and COTS culled until no more COTS were available to cull. Depending on the size of the polygon and the density of COTS encountered, reducing COTS sometimes required multiple dives over a period of days by a team of divers. The Pre-IPM control program was highly effective in targeting sites with high densities of COTS and, as a result, of achieving a high cull count. However, it was far less efficient at achieving meaningful COTS control objectives, particularly at the scale of entire reefs. No reef's perimeter was controlled in its entirety under this program.

IPM Control Program

The move to the IPM COTS Control Program strategy involved a transition phase (2016 to mid-2018), during which elements of the IPM approach were trialled or implemented on some or all control vessels. The transition to the IPM COTS Control Program has required significant modification to how the control fleet is deployed and operates and has been supported by additional oversight and research input and has resulted in a structured IPM approach to COTS control (Fletcher et al., 2020; Westcott et al., 2016). The transition to the IPM COTS Control Program was completed in November 2018 with five vessels operating along the full length of the GBR. While the strategic underpinnings of the IPM Control Program (Fletcher et al., 2020) are fundamentally different to those of the Pre-IPM program, the Pre-IPM program provided the operational foundation on which the IPM program was developed. A key difference between the two programs is that in the IPM COTS Control Program sites are not managed in isolation. Rather, in the IPM COTS Control Program the goal is to manage entire reefs because they represent discrete management and population units. Consequently, geo-located and standardised 500x200m (10 ha) sites are established to encompass the entire perimeter of each reef. Where surveillance indicates the need, cull sites are also established at other accessible locations on each reef. All sites at a reef are managed to below the desired threshold density before culling is diverted to a new reef.

The IPM approach integrated an understanding of the underlying processes driving the spatial and temporal dynamics of COTS populations, with control operations to support the program's strategy and decision-making processes. A key to the development of this IPM strategy has been a close collaboration with reef managers, control vessel operators and researchers, along with developments in understanding of the key processes and thresholds in population dynamics and control operations (Westcott et al., 2016). These developments have included: incorporation of surveillance to target control actions (Fletcher & Westcott, 2016); the application of connectivity to prioritise reefs for control (Hock et al., 2017); the implementation of repeated visits on short timeframes (Fletcher et al., 2020); and the use of ecological and reproductive thresholds to gauge stopping points and performance (Fletcher et al., 2020; Plagányi et al., 2020; Rogers et al., 2017).

With insufficient resources available to manage all reefs, the IPM program must identify a suite of Priority Reefs at which culling will be invested. In total, between November 2018 – late 2020, 289 reefs distributed across the GBR were identified as Priority Reefs and targeted for COTS control. Priority Reefs are identified based on attributes (measured or modelled) that indicated high ecological and economic value. Ecological value is based on an estimation of coral condition and the reef's capacity to contribute to coral population dynamics and resilience through their role as a source of coral larvae, and their connectivity to other reefs. Economic value is based on a reef's value as a tourism destination. These values are updated when new information becomes available. Approximately 48% of priority reefs are identified as such because of their ecological values alone, 20% for their economic values, and 32% for both ecological and economic values.

The outcomes of the Integrated Pest Management (IPM) approach used in the COTS Control Program have improved the program efficiency and accomplishments. The control-only approach employed by AMPTO in 2013-2015 focussed on high-value tourism reefs and conducted limited surveillance to identify sites with high densities of COTS. The new IPM approach introduced a structured surveillance-and-control strategy with a selective reef prioritisation system. A computational model based on the ecology of COTS populations compared these two management approaches and showed that the combined surveillance-and-control strategy resulted in 33% more COTS being removed compared to control-only strategies (Fletcher & Westcott, 2016). According to the latest annual report, the IPM methodology contributed to the shift from an “established” to a “no outbreak” status at five reefs (Bramble, Davies, Fore & Aft, Fork and Lynchs Reef) because of intensive culling (GBRMPA, 2020).

2.4.2 Scaling up and optimising improved COTS control

Despite the demonstrated success of the new expanded COTS Control Program in reducing COTS densities and coral impacts across entire reefs with a fleet of five vessels, scaling this approach up to the GBR is a daunting prospect. The GBR consists of over 3800 reefs, and the current control program depends on repeated voyages to each controlled reef, with dives and manual removal implemented anywhere COTS are detected. Efficiently achieving significant COTS impact reduction at larger scale requires intelligent selection of the reefs where control will be implemented. Ideally, the location of management actions should be based on an understanding of the complex ecological processes driving the growth and spread of the pest population (Fletcher et al., 2021; Fletcher & Westcott, 2016).

The solution reached under the NESP Programme to better understand these complex processes was to leverage two established coral-COTS reef community simulation models of the GBR, CoCoNet (Condie et al., 2018, 2021) and ReefMod-GBR (Anthony et al., 2019; Bozec et al., 2020), which incorporate both key ecological processes and management actions. The most important outcome of this research was the development of a new regional-scale ensemble modelling capability for COTS management across the scale of the GBR. The two complementary coral-COTS reef community models (the extended CoCoNet and ReefMod-GBR models) have been harmonised and extended with detailed descriptions of control actions matching those currently employed in the Expanded IPM COTS Control Program, providing ensemble predictions of regional scale outcomes of different control program strategies to most effectively reduce the proportion of reefs across the GBR experiencing COTS outbreaks. This represents important new capability that will underpin both the refinement of the IPM Control Program for the current outbreak, and the development of a coordinated response to the next outbreak.

The models were used to compare a range of different regional scale management strategies, including variations in total resourcing, spatial distribution of effort over both fixed and varying regions, and strategies that aimed to preserve resources by temporarily pausing control when COTS densities dropped. A key outcome of this analysis is that the regional strategies currently being implemented by the Expanded IPM COTS Control Program are likely to be generating ecologically meaningful regional scale reductions in COTS outbreaks across a significant proportion of reefs on the GBR, and most, if not all, of GBRMPA’s identified Priority Reefs. Other than increasing the number of vessels in the fleet, none of the alternative strategies for regional distribution of effort considered are likely to provide significant improvements during the current outbreak. However, strategies that pause the Control Program near the end of an outbreak as average COTS densities fall lead to significantly worse performance as the next Outbreak begins. Moreover, the model scenarios considered in this work made conservative assumptions compared to what has been implemented on-water since 2012, and what could be implemented if the current Control Program is maintained until the next outbreak begins. This suggests both that: 1) the current Control Program is likely to be generating greater outcomes than those reported; and 2) that the ability to reduce the regional impacts of COTS during the next outbreak will significantly exceed the outcomes presented by this modelling study. This potential should be investigated further using the regional-scale modelling capability developed as part of this work.

The NESP research has also advanced the on-water decision-making process by creating a decision tree structure using COTS surveillance data. This supports a more effective decision-making process by prioritising the start of cull activities at sites with the highest number of COTS (Fletcher et al., 2020). To support the IPM decision tree, GBRMPA created the Crown-of-Thorns Starfish Control Program operations manual (GBRMPA, unpublished). Despite the demonstrated effectiveness of intensive culling at individual reefs, the effective management of COTS outbreaks will, in the longer-term, require alternative approaches (Westcott & Fletcher, 2018). For instance, the ideal tool to achieve effective management outcomes should be applied once, does not require ongoing monitoring, is effective at large scales, is based on the ‘COTS Ecological Threshold’, specific to GBR COTS species, reversible, self-propagating, and reduces abundance rather than eradicates COTS (Westcott et al., 2016). Since no such tool exists that combines all these traits despite a variety of approaches (Høj et al., 2020), a strategy employing multiple tools is the best option to confront these inter-connected processes into the future (Figure 7).

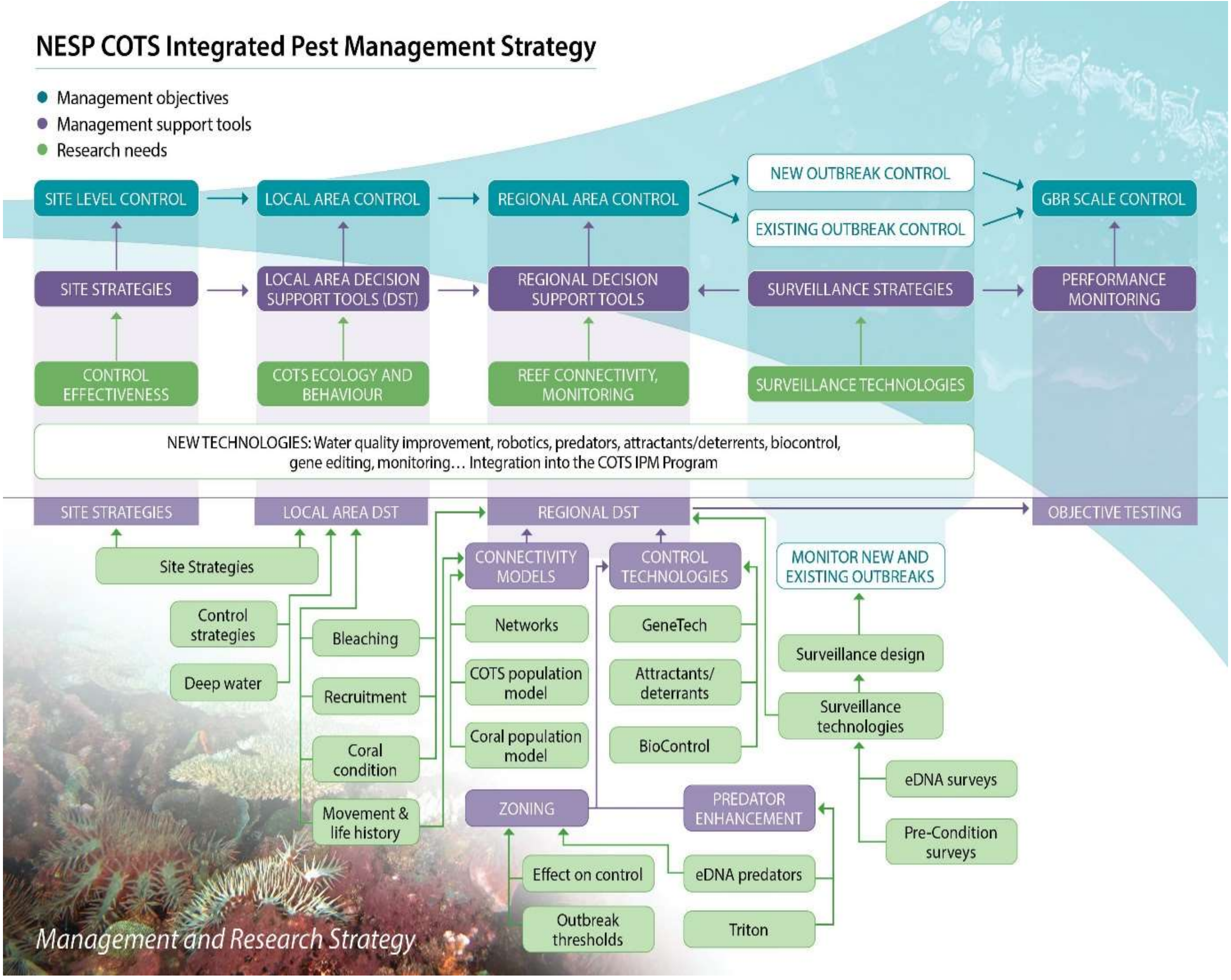

Figure 7. Management objectives, management support tools, and research needs for the NESP COTS IPM research strategy, established by Westcott et al. (2016).

3 RESEARCH INFORMING POLICY & MANAGEMENT

3.1 Application of NESP COTS research for policy & management

The NESP TWQ Hub research project “Innovations in COTS control on the GBR” have filled many knowledge gaps in the ecology of COTS. The program has also led to a successful transformation of the COTS control program resulted in a 33% increase in the number of COTS removed when compared to earlier control methods.

3.2 Policy applications

NESP TWQ Hub COTS research outcomes are being incorporated in current management plans and policies for the GBR, including the Reef 2050 Plan coordinated by GBRMPA (Commonwealth of Australia, 2018a, Commonwealth of Australia, 2018b), the Reef 2050 Water Quality Improvement Plan lead by the OGBR (Australian Government and Queensland Government, 2018), the Blueprint for Resilience Plan by GBRMPA (GBRMPA, 2017) and the latest GBR Outlook Report (GBRMPA, 2019). Results will also contribute to the development of the updated Reef 2050 Water Quality Improvement Plan and the next Scientific Consensus Statement which is due in 2022.

3.3 Management applications

Previous management approaches have focused on controlling COTS outbreaks at either local-scales along the GBR using resource intensive methodologies or concentrated on managing external drivers such as water quality. Neither of these approaches has resulted in effective control of COTS outbreaks across the entire GBR (Westcott et al., 2016). NESP TWQ Hub COTS research outcomes have resulted in the identification of a range of potential management applications that, if implemented, will improve COTS control over the long-term.

3.3.1 Manual Control Technology

Manual control, such as single-shot injection with a chemical reagent, has proven to be the most successful approach in supressing COTS densities at individual sites and reefs, and remains as the main management tool (Westcott et al., 2020).

3.3.2 Alternative management practices (Biocontrol)

The giant triton (Charonia tritonis)

The giant triton (*Charonia tritonis*) has several traits that elevate its potential as a stand-alone COTS biocontrol agent. Not only does it actively hunt and consume adult COTS, its habitat preference and home range overlap that of COTS (Schlaff et al., 2020), and its odour can interrupt and disperse COTS spawning aggregations, potentially reducing reproductive success (Høj et al., 2020). Strategic deployment of giant tritons to support manual control activities is recommended to be further investigated. The general technologies and processes necessary exist in the aquaculture industry, however, there remain significant challenges in developing species-specific technologies required for the task, for building infrastructure and operationalizing the process. Testing to assess the biosafety risk and risk of unwanted flow-on effects would also have to be performed. It is unlikely that this approach could be implemented before the late 2020s. It is estimated that it is a low to medium risk for the environment to artificially deploy the giant triton on priority reefs (Høj et al., 2020).

Semio-chemicals

The use of semio-chemicals as a COTS control mechanism could either facilitate the detection of cryptic COTS by attracting them for culling or avoid future reproductive success by the use of repelling chemicals, which can inhibit spawning events (Høj et al., 2020). Attractants can assist culling activities to protect priority reefs, because lower COTS densities are likely achieved, and culling is still effective at low densities. Repellents can also be used to disperse COTS before spawning events, if manual control is still pending, to inhibit the formation of potential pre-spawning aggregations. Based on previous studies on COTS chemosensation, the use of these chemicals is recommended despite the financial risk associated with the high quantity of semio-chemicals needed to be effective, because decreased revisitation rates and faster culling activities reduce operation costs and semio-chemicals demonstrate a low environmental risk on local scales at the same time (Høj et al., 2020). Significant research is still required to identify appropriate candidate semiochemicals, to understand their performance under field conditions, and to develop deployment technologies and strategies. Implementation would be unlikely before the mid to late 2020s.

3.3.3 IPM Control Evolution

The IPM COTS Control Program is an effective and efficient tool for achieving COTS control objectives and protecting coral on the GBR. It has the potential to play a foundational role in efforts to enhance coral cover and reef condition and resilience into the coming decades. Given the escalating pressures currently impacting the economic and biodiversity values of the Marine Park, manual control of COTS populations is one of the few currently available, effective, scalable, and targetable management tools for reducing coral loss on high-value priority reefs. It can only achieve this outcome with reliable and sustained investment. To ensure that the IPM COTS Control Program and its operating strategy continue to evolve and improve in achieving COTS control objectives, the following priority steps are recommended by NESP WQ Hub research (Fletcher et al., 2020, 2021; Westcott et al., 2020, 2021).

- A standing COTS control fleet must be maintained through all outbreak phases to ensure a timely and adequate control response can be mounted at the time and place where a successful outcome is most likely. This will require long-term and sustainable funding throughout the entire COTS outbreak cycle.
- A COTS control specific monitoring program must be implemented as an integral component of the IPM COTS Control Program to ensure detection of initiating outbreaks and to enable a targeted, effective and efficient management response.
- New monitoring technologies (including new Towed Underwater Vehicles to replace manta tows and also eDNA techniques) must be developed to improve the scope and sensitivity of the monitoring data informing the program and to improve geographic coverage of monitoring. This is vital for informed and timely decision making.
- COTS control must operate under an ecologically informed and adaptive strategy such as the IPM COTS Control Program and that program should maintain a focus on refinement and improvement.
- The prioritization process on which reefs are selected must continue to evolve in response to improved monitoring data and program capabilities and needs.
- COTS control will inevitably be a long-term investment and consequently alternative and improved control technologies must be investigated and deployed where feasible. This should include approaches that could contribute in the short term, e.g. strategic implementation of zoning to reflect patterns of connectivity, and in the longer term, e.g. new technologies such as the application of semio-chemicals and gene-editing (Hoj et al. 2020).

3.3.4 Timely Management Intervention

If a COTS Control Program is to be successful in achieving ecologically relevant objectives, and is to do so in an efficient manner, then management interventions must be conducted at the times and places that will produce the greatest gain in terms of the program's objectives (Westcott et al., 2016, 2021). This can only be done if management decisions, at all stages of the outbreak cycle and at all scales of operation, are based on reliable and current information on the distribution of COTS abundance and density across both individual reefs, regions, and the GBR, and on reliable information on the distribution and condition of the coral assets that are to be protected. The NESP WQ Hub research has highlighted the critical need for contemporary information, collected at the scales relevant to COTS control objectives for timely management intervention. This requires ongoing effective monitoring and surveillance designed to address the specific information needs of the COTS control program.

3.3.5 Increased spatial management

Effective fisheries protection via marine reserves may help ensure the abundance and function of potential predators to help regulate populations of COTS (Sweatman, 2008). This approach is likely to be most effective in the initiation box, i.e. the mid-shelf reefs between Lizard Island and Cairns (Kroon et al., 2020). Therefore, the implementation of either temporary fishing restrictions at reefs when environmental conditions are prone to outbreaks, or species restrictions (i.e. no-take of known predator fish) in the outbreak initiation box and on highly connected reefs further south may provide an innovative management approach to COTS control. The implementation of fishing restrictions at specific locations to increase populations of fish that are known to feed on COTS (e.g. triggerfish) is another control approach that has been recommended (Vanhatalo et al., 2017) and are regarded as a "no regrets" strategy (Pratchett et al., 2020). Significantly, associated NESP TWQ Hub research concluded that fishing pressure zoning had a significant effect on the prevalence and severity of COTS injuries, and that the higher prevalence and severity of sub-lethal predation is likely to have a significant impact on the individual fitness and population dynamics of COTS, potentially reducing outbreak potential in areas protected from fishing in the Marine Park (Budden et al., 2019; Harris, 1989; Wilmes et al., 2019; Zajac, 1995).

3.3.6 Facilitated reporting

As identified in the 2017 Scientific Consensus Statement, there is a need for improved communication and collaboration on many levels in all aspects of reef management and protection. Improved implementation of economic and social aspects when addressing and reporting COTS related issues, and the application of modelling tools to improve understanding will also have program benefits (Waterhouse et al., 2017b). Reporting by a range of government agencies and regional bodies responsible for GBR management, such as GBRMPA, has led to the availability of a range of tools able to access spatial and resilience data, including the eAtlas and eReefs initiatives. These online tools offer open-access data, ecosystem models and predictions that enable the integration of information to provide potential future scenarios for the reef, which will be valuable for future GBR Outlook Reports.

3.3.7 Effective field operations and monitoring

Improvements in on-water COTS control programmes includes a range of management measures that have benefited from the research on COTS ecology completed through the NESP TWQ Hub. This includes operational decisions connected with the timing, scheduling and staffing of COTS control voyages. The efficacy of field operations has been significantly enhanced by improvements in the management of marine vessels and voyage scheduling through adoption of clearly defined team sizes and roles, single manta tows at each reef site (Fletcher & Westcott, 2016), and visits to more sites but with less dive time completed at each (Fletcher et al., 2020). For example, as a result of these innovations, one reef site can now be culled to reduce COTS numbers to below ecological thresholds in one voyage unless the outbreak population is particularly high or the reef very large (Fletcher et al., 2020).

3.3.8 Improved support for decision-making

Location of priority reefs for monitoring and culling activities

Key economic, ecological and tourism reef sites are prioritised for COTS removal under the IPM program (Fletcher et al., 2020, Fletcher & Westcott, 2016), and culling is typically undertaken on priority reefs with a threshold control CPUE of higher than 0.1 COTS per minute bottom-time. Prior to implementation of the IPM program, control did not focus on high COTS density reefs (Westcott et al., 2016) and this has improved in 2019 and 2020 control activities. In particular, the use of broad-scale (manta tow) and fine-scale coral cover monitoring (Reef Health and Impact Surveys; RHIS) determines the 'Ecological Threshold' and CPUE (Fletcher et al., 2020). The use of RHIS to assess coral reef status has improved the efficacy of the cull program by identifying healthy reefs during bleaching events. This information allows control efforts to preferentially continue targeting reefs with 'active' outbreaks but avoiding reefs that have suffered significant coral losses to make control effort more effective.

Expansion of control activities to include reef flats and reef margins can be achieved if monitoring is also undertaken in these reef areas (Fletcher & Westcott, 2016). Investigating and control of reef areas beyond the current management polygons helps to prevent recolonization and provides a broader picture of the current situation when capturing entire reefs (Fletcher et al., 2020). This up-scaling of manual control can assist in maintaining hard coral cover at regional scales on the GBR (Westcott & Fletcher, 2018). NESP TWQ Hub research has highlighted the importance of control efforts in the relatively shallow waters of emergent reefs and that valuable resources should not be expended searching for COTS outbreaks in deeper waters significantly below the zone of highest coral cover (Beaman, 2018). Development of eDNA monitoring may lead to routine detection of larval and juvenile stages before an outbreak (Doyle & Uthicke, 2020; Uthicke et al., 2018, 2019) and could be used as a complementary method to identify reefs at high risk of future outbreaks.

Intervals of interactions

Decision tree support systems help to manage high density COTS reefs and identify low density ones, thereby enabling the effective allocation of resources. Effective control at a site is dependent on intensive and repeat site visits which can be scheduled with the assistance of decision trees (Fletcher et al., 2020). Typically, intensive Control Reefs should be manta towed every 42 days and Maintenance Reefs every 6 months. Good understanding of patterns and rates of adult COTS movements to recolonise cleared areas after culling activities is critical for planning site revisitation after culling activities for effective COTS control management (Pratchett et al., 2020).

4 FUTURE DIRECTIONS FOR COTS RESEARCH AND MANAGEMENT

4.1 Investment priorities for on-water control activities

The results of the scenarios assessed by the extended CoCoNet and ReefMod-GBR models highlight that regional-scale reduction of the proportion of reefs across the GBR experiencing outbreaks is possible with a manual Control Program. Importantly, the only regional strategy considered to be likely to provide significant increases in control performance during the current outbreak is to increase the number of vessels in the COTS control fleet. The current ecologically-informed IPM COTS Control Program is working, both at the scale of individual reefs and regionally (Fletcher et al., 2020; Westcott et al., 2021) and it should be continued and effort increased where funding is available. Minor investment in the development and integration of new technology, such as GPS trackers or other devices to record diving depth and visibility underwater, has the potential to improve operational efficiency and deliver more detailed data regarding the distribution of COTS on the GBR (Fletcher et al., 2020).

Non-COTS benefits derived from investment in COTS management have also resulted in positive social and economic outcomes. Young unemployed trainees, of which 50% were from Indigenous origin participated in a six-month training on AMPTO run COTS control vessels acquiring useful job qualifications, such as diving certificates, first aid provider and certificates for the operation of marine vessels (Jarvis et al., 2020). This training had significant and positive impacts on both the life satisfaction with an improvement from 59% up to 86% on average. The employment prospects of the trainees showing that they were 26.5 times more likely to gain a full-time employment. Trainees were 43% more likely to move into part-time to full-time positions and were employed shortly after completing the training. This improvement reflects the direct economic benefits to those individuals and their households. When addressing youth unemployment in the future the main focus should lie on the participants' capabilities, which are their personal identity, aspirations, literacy and numeracy, employability skills and career management, as well as it should be tailored to a young persons' endeavour to gain and retain meaningful employment (Jarvis et al., 2020).

4.2 Investment priorities for research to address knowledge gaps

COTS control relies upon advances in research to efficiently identify outbreaks by monitoring population sizes and distribution ranges. For the last three decades, ongoing COTS research was able to fill many of the knowledge gaps identified by Moran (1986) on COTS biology, ecology, outbreaks and management (Pratchett et al., 2017a). However, basic information on the distribution of COTS and corresponding information on the distribution of habitat preference as well as coral communities and their condition is still incomplete in the GBR (Westcott et al., 2021). Just as concerning is the lack of consensus among experts about the processes driving COTS population dynamics in the GBR (Babcock et al., 2016, 2020; Pratchett & Cumming, 2019; Westcott et al., 2020). Priorities for future research include research to improve monitoring efficacy, improve understanding of COTS biology and ecology, implement recommended biocontrol strategies and improve understanding and management of climate change and catchment-based drivers of COTS outbreaks.

4.2.1 Monitoring

Monitoring is the critical component of any strategic ecological (COTS) control program, as it provides the foundational data on the distribution of the abundance of the focal entity across the region of interest and over time. This information becomes central to all decisions made in the design and implementation of a species management program, and without it such programs cannot be assessed for their effectiveness in meeting objectives or outcomes. The Expanded COTS Control Program must have a dedicated monitoring program to ensure that it delivers effective and high value for money protection of coral on the GBR (Westcott et al., 2021). This program, along with COTS control, must be maintained throughout the outbreak cycle. In the absence of certainty about which drivers are responsible for COTS outbreaks, a logical approach is to monitor as many of the candidate drivers as possible while simultaneously monitoring COTS demography, distribution and abundance (Babcock et al. 2016a), and to do so on a regular basis, focussing on the section of the reef where primary outbreaks are hypothesised to begin and spread to, but also including other regions (to account for the possibility that outbreaks can initiate elsewhere). This approach would allow:

- detection of hypothesized outbreak conditions;
- timely detection of and response to primary outbreaks;
- testing and development of hypotheses for outbreaks; and
- ultimately their control through addressing their root causes over the long term.

Incorporation of monitoring of biophysical and ecological drivers of COTS outbreaks with culling, TUV and eDNA technologies (Box 1) represents the ideal (and most expensive) approach to COTS monitoring, providing optimal surveillance to inform direct management decisions while simultaneously testing key hypotheses about the causes of outbreaks and potentially informing indirect management action. Specifically, incorporation of eDNA technologies, particularly those focused on adult COTS, would allow for tow and cull validation thereby providing enhanced confidence in decision making in the control program while larval eDNA tools offer the potential of an early-warning (c. 2 years in advance) capability. This combination of culls, TUVs and eDNA is the recommended strategy.

The minimum recommended monitoring program would be based on current culling and next generation TUV technologies. New TUV technologies will revolutionize COTS monitoring data collection, vastly improving decision making and enabling a timely, precise and informed management response. Furthermore, this program would contribute currently unrivalled data to a range of other monitoring and reef management activities.

Innovation Needs

It is critical that investment in on-water monitoring of COTS should be guided by a rigorous statistical design to maximize the value and the utility of the data. The development of this sampling design must, along with the refinement and operationalization of new monitoring tools (TUVs and eDNA), be an R&D priority. In addition, development of information management systems, tools that improve in-water data collection by cull divers to improve accuracy of monitoring data and automated collection of data on vessel movements and patterns of operation would improve monitoring programme efficiencies and also maximise value of collected data. Specifically, a focus on the following priorities is recommended:

- Development of shallow-water TUVs with appropriate sensors, operational capabilities and piloting methods;
- Development of deep-water ROVs with appropriate sensors, operational capabilities (e.g. culling) and piloting methods;
- Development of data management regimes that enable real time feedback to vessels;
- Development of data management regimes that optimize information, storage and handling requirements;
- Improved Artificial Intelligence for detection of key COTS and coral thresholds;
- Development of data recording tools for control divers; and Development of spatial sampling strategies for each activity during each phase of the outbreak cycle.

4.2.2 COTS biocontrol

None of the biocontrol technologies assessed as part of the NESP TWQ Hub are likely to represent a 'silver bullet', and the challenge is to optimise the combination of tools to develop and strategically apply them to maximise the level of control that can be achieved (Høj et al., 2020). Of the methods considered, only two were considered to have realistic potential in the next 10 years: the use of natural predators and semiochemicals. Both still need significant research to be completed before they could be confidently implemented as COTS control measures.

Native predators of COTS include fish that could be protected by fisheries management (conservation), and the giant triton, which could possibly be produced via aquaculture or sea-ranching, followed by deployment on priority reefs (augmentation). The value of coral macro-symbionts (crabs, polychaetes, shrimp, fish) as grazers of early COTS life stages and defenders of their coral host is also considered. Although reef predators are rarely species specific, the environmental risk of these approaches is deemed to be low (conservation) to medium (augmentative). The time lag until implementation would likely be shorter for conservation approaches (depending on the legislative/management process), as considerable knowledge gaps exist for aquaculture production of these species, in particular for the giant triton. Further investment is recommended to establish larval dietary requirements of triton snails and develop genomic methodologies to identify the physical and chemical factors that drive their early lifecycle transition. Accordingly, research investment should focus on confirming feeding and foraging behaviours of *C. tritonis* by conducting eDNA surveys, exploring the feeding spectrum and preference of the giant triton, determining the impact on the behaviour and mortality of other prey species, elucidating the chemosensory machinery that facilitates hunting and capture, and establishing capture and consumption rates of adult COTS *in situ* (Hall et al., 2017). Investment is needed to expand on the tagging and monitoring method reported by Schlaff *et al.*, (2020) to simultaneously track COTS movements in the presence of the giant triton in situ (Hall et al., 2017) and reveal predator-prey interactions. This information could then be used to determine the potential for directed deployment of giant tritons on COTS infested reefs (Hall et al., 2017) to assist manual control at local scales. We estimate that the earliest possible implementation of these approaches will be in the mid-2020s and late 2020s, respectively, assuming immediate start and no financing constrains.

Semiochemicals are defined as compounds that are involved in COTS chemical communication and signalling and hold potential for use as attractants or repellents for CTS. Significant research is however still needed to develop efficient compound(s) mixtures, their large-scale production, and deployment ready devices. The efficiency of these approaches in an open water system also must be confirmed. Attractants could be employed in conjunction with manual control to pull out cryptic COTS from hiding places, thereby increasing culling efficiencies and reducing revisitation rates. Repellents could potentially be used to delay spawning aggregations, thereby providing increased time for culling before spawning occurs. There is also scope for using repellents for protection of priority sites. These approaches are regarded as having low environmental risk as they are applied at a local scale, any unspecific effects can be relatively easily assessed, and the treatment can be discontinued if unwanted consequences are observed. The approaches carry a financial risk and implementation could be expected in the late 2020s at the earliest.

4.2.3 COTS demographics

Initial research on COTS demographics (Pratchett et al., 2020b) has explicitly tested for inter-reef differences in the demography of crown-of-thorns starfish with respect to contrasting management zones to provide important insights into the role of predators, and also alternative spatial management arrangements, in regulating populations and reducing the incidence and severity of COTS population irruptions. Collected data describing the incidence and severity of injuries for both juvenile and adult crown-of-thorns starfish adds to the considerable weight of evidence showing that *Acanthaster spp*. are extremely vulnerable to predation (Bos et al., 2008; Cowan et al., 2016, 2017; Endean, 1969; Kroon et al., 2020; McCallum et al., 1989; Ormond et al., 1990; Rivera-Posada et al., 2014; Wilmes et al., 2019). Predation and predators may therefore, play a significant role in regulating local populations of crown-of-thorns, potentially dampening fluctuations in their local abundance and greatly reducing the likelihood of population irruptions (Babcock et al., 2016; Cowan et al., 2016; Messmer et al., 2017; Ormond et al., 1990).

Understanding population dynamics and population irruptions of *Acanthaster spp*. is currently constrained by limited knowledge of early life-history processes and it is critical that further research be undertaken to explicit quantify spatio-temporal variation in demographic rates of crown-of-thorns starfish across all life-stages. This includes further study of age dependent change in food sources of COTS larvae.

Improved quantification of the rates of predation and mortality of crown-of-thorns starfish is also required to better understand the specific role of reef predators on the population regulation of *Acanthaster spp.* Explicit research is required to establish the relative importance of different predatory species and at different life-stages, based on their capacity to regulate larval supply, settlement, and post-settlement survivorship of *Acanthaster spp*.

4.2.4 Water quality and climate-based COTS outbreak drivers

Brodie (2021) summarised the potential links of water quality to anthropogenic induced changes to COTS population dynamics and new research has assessed the relative importance of nutrient enrichment compared to other factors in driving COTS outbreaks. Matthews et al. (2020) tested the effects of multiple factors influencing COTS abundances in the GBR. The study showed that while many factors contributed to the predicted prevalence of COTS, larval connectivity and sea surface temperature had the highest impact, and that (modelled) chlorophyll concentrations and particularly river derived inputs were also important.

The lack of consensus among experts about the processes driving COTS population dynamics in the GBR is of concern (Babcock et al., 2016, 2020; Pratchett & Cumming, 2019; Westcott et al., 2020). Matthews et al. (2020) tested the effects of multiple factors influencing COTS abundances in the GBR. The study showed that while many factors contributed to the predicted prevalence of COTS, larval connectivity and sea surface temperature had the highest impact, and that (modelled) chlorophyll concentrations and particularly river derived inputs were also important. Further research on these key drivers is a critical research priority.

4.3 Integrating research and on-water activities: continuing the IPM approach

The results of the scenarios assessed by the extended CoCoNet and ReefMod-GBR models highlight that ecologically-meaningful regional-scale reduction of the proportion of reefs across the GBR experiencing outbreaks is possible with a manual Control Program similar to the one currently deployed. The results also suggest that the current regional strategies are likely to generate ecologically-meaningful regional scale reductions in the proportion of reefs experiencing COTS outbreaks across the GBR, including most of GBRMPA's identified Priority Reefs. Importantly, the only regional strategy considered to be likely to provide significant increases in control performance during the current outbreak is to increase the number of vessels in the COTS control fleet. Modelling also indicates that the strategies currently being employed in the Expanded COTS Control Program could, if they are maintained, make significant impact on the next outbreak, expected to begin in the mid-2020s.

4.3.1 First recommendations for managers

In the immediate future: continue with the current control strategy. The current ecologically-informed IPM COTS Control Program is working, both at the scale of individual reefs and regionally (Fletcher et al., 2020; Westcott et al., 2021). None of the alternative regional-scale strategies considered in this report meaningfully outperformed the strategies currently being employed.

4.3.2 Second recommendations for managers

In the short-term: leverage our regional modelling capability. The ensemble regional scale modelling capability developed as part of this project should be leveraged to provide:

- an assessment of whether the regional-scale impacts of the next outbreak can be largely avoided through the current strategy, and what level of resources would be required to achieve that outcome;
- if the regional scale impacts of the next outbreak cannot be completely avoided, recommendations on optimal regional strategies when control begins at the start of an outbreak; and
- guidance on which Priority Reefs to target for control within each GBRMPA Operational Region to maximise the accumulative regional-scale benefits of control at specific reefs.

4.3.3 Third recommendations for managers

In the medium-term: don't stop the Control Program between outbreaks. The next outbreak is expected to begin on reefs in the initiation box north of Cairns in the mid-2020s. The results of this analysis show that strategies that attempt to reduce the costs of control by pausing control efforts when COTS densities start to drop at the end of the current outbreak bring with them the risk of a significant reduction in Control Program effectiveness over the next decade compared to strategies that continue targeting high density aggregations of COTS, even when average densities across the GBR are low. Both the costs of COTS impacts, and the benefits of COTS control accumulate over time and pausing the Control Program today will affect how many reefs can be prevented from outbreaking tomorrow.

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APPENDIX A

Table A1. Summary of projects and information relevant to Innovations in COTS control in the NESP TWQ Hub (2015-2021).

Project Title	Report Title	Summary of research outcomes	Innovations	Implications for Management	Future Research Ideas	Reference
1.1.1 Establishing the future NESP COTS research framework including an ecologically-based approach to the management of COTS at multiple scales	Final report: A strategy to link research and management of crown-of-thorns starfish on the Great Barrier Reef: An integrated pest management approach	A research strategy (Integrated Pest Management approach) was developed, based on how COTS outbreaks arise and how they spread in order to achieve efficient and effective management solutions on COTS control.	Introduction to the Integrated Pest Management (IPM) of COTS	Suggested management strategies included: 1) Control at sites and local areas, 2) protection of assets, 3) minimize outbreak's spread, 4) prevention of primary outbreaks, 5) managing ultimate causes and 6) implementation of non-manual controls	Suggested areas of research investment included the optimisation of control at both local and regional scales, addressing ultimate causes to prevent future outbreaks and developing new control technologies	Westcott et al., 2016
2.1.1 Integrated Pest Management of Crown-of-Thorns Starfish	Interim Report: Strategies for Surveillance and Control Using Crown-of-Thorns Starfish management program data to optimally distribute management resources between surveillance and control	A model was constructed to compare management strategies showing that surveillance-and-control strategy resulted in a third more COTS removal than a control-only strategy conducted by AMPTO in 2013-2015	Computational management strategy model	Recommendations for management: 1) conduct surveillance, i.e. manta tow, 2) prioritise potential sites for control activities considering highest COTS densities and key tourism sites, 3) aim for CPUE less than ~ 0.1 COTS/ minute bottom-time in locations with surveillance and control records, 4) maximise control efforts with minimum team sizes and single tows across each site, 5) expand surveillance to reef edge and reef flats and 6) keep good records of surveillance		Fletcher and Westcott, 2016

Project Title	Report Title	Summary of research outcomes	Innovations	Implications for Management	Future Research Ideas	Reference
2.1.1 Integrated Pest Management of Crown-of-Thorns Starfish	Technical Report 2: Do no-take zones reduce the likelihood of outbreaks of the Crown-of-thorns starfish?	Current definition of COTS outbreaks is conservative, meaning that lower densities of starfish do result in net loss of coral cover; however, the more coral cover, the more damage; no-take status reduces the likelihood of starfish outbreaks when 0.12 starfish per two-minute manta tow occur, but shows inconsistent and weak effects		Lower CPUE threshold (0.12) should be adopted and used in reporting research investment should focus on larval and juvenile predation on COTS		Sweatman, and Cappo, 2018
2.1.1 Integrated Pest Management of Crown-of-Thorns Starfish	Technical Report 1b: The potential role of the giant triton snail, *Charonia tritonis* (Gastropoda: Ranellidae) in mitigating populations of the crown-of-thorns starfish	Giant tritons have deterrent effects on COTS, through their chemical exosecretomes, which are able to disrupt COTS forming pre-spawning aggregations. However they are unlikely to significantly reduce number of outbreaks and only delay or minimize size of outbreaks	Advances in genomic techniques to detect chemoreceptors and chemical cues	Biological control programs could apply chemical deterrents (from predators, such as the giant triton) to disrupt spawning aggregations	Research investment should focus on: 1) Feeding and foraging: environmental DNA (eDNA) surveys, feeding spectrum of giant triton, determine water-bourne factors, method for tagging and monitoring giant triton; 2) aquaculture of giant tritons 3) deployment of species as spawning disruptors	Hall et al., 2017

Project Title	Report Title	Summary of research outcomes	Innovations	Implications for Management	Future Research Ideas	Reference
3.1.1 Implementation of the crown of thorns starfish research strategy: regional strategies	Technical Report 3: Movement patterns of Pacific crown-of-thorns starfish (*Acanthaster cf. solaris*) linked to habitat structure and prey availability	starfish generally have small home range of 50-100m in areas with moderate to high coral cover, but could move up to 150-520 m per day within reef environments. Inter-reef movements probably occur only very rarely	Case study to detect movements of COTS using acoustic transmitters	effective scale and rates of adult movement to be considered to understand starfish recolonisation after culling actions and to determine how much and often culling should be applied	periodic and large-scale movements of individuals and populations using acoustic receivers to record incidence and rates of movement when coral sources are depleted	Pratchett, et al., 2020
3.1.1 Implementation of the crown of thorns starfish research strategy: regional strategies	Technical Report 2: An ecologically-based operational strategy for COTS Control - Integrated decision making from the site to the regional scale	Decision trees were reliable and successful in reducing COTS by aiming for an Ecological Threshold; the strategy managed high COTS numbers and identified low COTS reefs to allocate resources most efficiently, with effective control at a site dependent on intensive and repeated revisitation	Three decision trees for voyage operators and managers to make effective decisions; GBRMPA Integrated Pest Management Operations Manual for Crown-of-Thorns Starfish Control Program Vessels (GBRMPA, unpublished) is a companion publication	Priority reefs, i.e. reefs with high density aggregations of COTS, will be culled below Ecological Threshold levels to reduce to Maintenance mode and ensure the density remains low and until CPUE is below the current best estimate of the Ecological Threshold. Intensive Control Reef manta towed every 42 days, Maintenance every 6 months; Site revisitation frequency every Voyage or 12 days is sufficient	Use of broad-scale (manta tow) and fine-scale (RHIS) coral cover surveys to determine Ecological Threshold; sub-Reef scale habitat data for the Reefs being managed, detailed habitat preference data to estimate where COTS are likely to aggregate; movement rate of COTS between sites on outbreak reefs with high densities of COTS over management-relevant timescales	Fletcher et al., 2020

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3.1.1 Implementation of the crown of thorns starfish research strategy: regional strategies	Technical Report 1: Assessment of deep-water habitat for crown-of-thorns starfish (COTS) in the Great Barrier Reef	grid enables to detect deep-water coral reefs potentially suitable for COTS feeding; however, there is low risk of larval COTS to be found in deep-water habitats on emergent reefs below the zone of highest coral cover	CSIRO developed a higher-resolution gbr30 bathymetry grid (~30 m pixel spacing) over the GBR shelf area covering 22 reefs for Integrated Pest Management (http://pid.geoscience.gov.au/dataset/115066)	The recommendation is that COTS control efforts should continue in the relatively shallow waters of emergent reefs, and to not expend resources searching for COTS outbreaks in deeper waters significantly below the zone of highest coral cover.		Beaman, 2018
3.1.1 Implementation of the crown of thorns starfish research strategy: regional strategies	A Review of Biologically Based Control Technologies for Crown-of-Thorns Starfish	Review biology-based technology for integration into IPM strategy since technology has advanced in recent years; considering the transfer of technologies applied in terrestrial, aquatic and marine environments and COTS specific traits for COTS control; biocontrol with predators, microbes, semiochemicals or genetic approaches	Biocontrol with predators (fish and giant triton), epifauna, including coral macro-symbionts as grazers of early COTS life stages and coral host defenders, microbiome like the 'sea star wasting disease' (SSWD) as pathogens	Low to medium risk for fish predator application; fish protection by fishery management and triton husbandry in aquaculture plus deployment on priority reefs; 'sea star wasting disease' (SSWD) as pathogen with high environmental risk, but investment could be useful for genetic biocontrol in future; financial risk, but low environmental risk of semiochemicals on local scales, increasing culling efficiencies and reducing	Investment in virulent processes and COTS immune response could be useful for genetic biocontrol in future; Significant research on semiochemicals is needed to develop efficienct and large-scale compounds, particularly in open water systems; establish multi-disciplinary expert panels to discuss and evaluate specific	Høj et al., 2020

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3.1.1 Implementation of the crown of thorns starfish research strategy: regional strategies	A Review of Biologically Based Control Technologies for Crown-of-Thorns Starfish		Semiochemicals as repellents or attractants and genetic modification, which generally causes a reduction in pest fitness and is selected against by natural selection	revisitation rates by the application of attracting semiochemicals in conjunction with manual control to pull out cryptic COTS, increasing time for culling by the application of repellent semiochemicals disrupting COTS aggregations for spawning events and repellent also to protect priority sites; genetic modification has a high risk and needs to be thoroughly investigated before application; support with modelling will be essential for all approaches	risk assessments, evaluation of relative cost-effectiveness, social acceptability and regulatory hurdles to choose best strategy	
4.1 Crown-of thorns starfish: surveillance and life history	Final Report: Tracking GBR water clarity over time and demonstrating the effects of river discharge events	11 years' of data used to investigate water clarity between Fitzroy, Whitsundays, Wet tropics and Cape York; photic depth was negatively correlated to freshwater discharge with 150-260 days recovery; strongest correlation found in COTS origin area from Cairns to Lizard Island		Reductions in river load can improve water clarify in the GBR		Logan et al., 2014

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4.1 Crown-of thorns starfish: surveillance and life history	Technical Report: How Effective Are Management Responses In Controlling Crown-of-Thorns Starfish and their Impacts On The Great Barrier Reef?	Assessment of the effectiveness of management responses to COTS outbreaks revealed that water quality improvement cannot be solely relied upon for managing COTS, while protected reef sites had fewer COTS and manual control proved effective		Scaling-up manual control to achieve ecologically meaningful outcomes for hard coral cover at regional scales on the GBR		Westcott and Fletcher 2018
4.1 Crown-of thorns starfish: surveillance and life history	Inter-reef variation in the demography of Pacific crown-of-thorns starfish (*Acanthaster cf. solaris*) relative to marine reserves	comparing growth and survivorship of early-stage juvenile *A. cf. solaris* among reefs with contrasting management zones shows high inter-reef and annual variability in recruitment rates, but no difference of higher rates of sub-lethal injuries between management zones; possible to detect recently settled COTS within shallow reef habitats; insights into the	new technologies provide much improved opportunities to identify potential predators (Kroon et al. 2020), while increased potential to tag and track benthic species within reef environments (Pratchett et al. 2020; Schlaff et al. 2020)	no-take marine reserves and fisheries regulation as a "no regrets" strategy	quantify spatiotemporal variation in demographic rates of COTS and across all life-stages; quantify rates of predation and mortality of crown-of-thorns starfish to better understand the specific role of reef predators on the population regulation of *Acanthaster spp*; establish the relative importance of different predatory species and at different life-stages, based on their capacity to regulate larval supply, settlement, and post-settlement	Pratchett et al., 2020

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4.1 Crown-of thorns starfish: surveillance and life history	Environmental Factors Influencing the Distribution of Crown of Thorns Starfish on the Great Barrier Reef	Statistical modelling (GLMM and random forest) to identify environmental factors that influence the distribution of COTS on the GBR as well as the response of COTS to bleaching and the preference of COTS in regard to bleached or unbleached hard coral sites; relatively weak associations with benthos variables, habitat, and bleaching; hard coral cover was consistently a primary indicator of higher observed COTS counts (confounding of bleaching with hard coral cover)		Environmental and habitat types are not informative; to prevent coral loss focus on the location of the outbreak, regardless of bleaching at a reef or site; even during bleaching events, managers should continue to target efforts at reefs near the outbreak front with high coral cover, rather than changing priorities to target reefs that have experienced significant bleaching, because reefs that suffered significant coral losses due to bleaching were likely to exhibit both lower hard coral cover and lower COTS numbers, making control there both less effective at protecting coral cover, and less efficient at removing COTS		Gladish et al., 2020
4.1 Crown-of thorns starfish: surveillance and life history	Monitoring and Surveillance for the Expanded Crown-of-Thorns Starfish Management Program	Existing monitoring programs require more reliable data on COTS abundance, hard coral cover and coral health in each phase of a COTS outbreak cycle	Towed Underwater Vehicles (TUVs) to replace Manta Tows	Three tools to be included in monitoring operations (culling, Towed Underwater Vehicles (TUVs) and eDNA) that should take place throughout the outbreak cycle and supported by statistical designs		Westcott, et al., 2021

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5.1 Matching the COTS IPM to the scale of the new control program	Technical Report: Social and Economic Outcomes of the COTS Control Youth Training Program	Social and economic outcomes, i.e. describing the non-COTS benefits derived from investment in COTS management; employed shortly after completing the training (43% move from unemployed or part-time to full-time positions); significant and positive impact on both the life satisfaction (59% up to 86% on average) and the employment prospects of the trainees (26.5 times more likely to be in full time employment); direct economic benefits to those individuals and their households	50% Indigenous participation on a six-month training on AMPTO run COTS control vessels acquisition of qualifications and certificates, such as diving certificates, first aid provider and operation of marine vessels	Address youth unemployment is to focus on the capabilities (personal identity, aspirations, literacy and numeracy, employability skills and career management) and experiences a young person needs to develop to gain and retain meaningful employment		Jarvis et al., 2020 Fletcher et al., 2021 Fletcher and Westcott 2021
5.1 Matching the COTS IPM to the scale of the new control program	The COTS Control Centre Supporting ecologically-informed decision making when and where decisions need to be made	CSIRO developed software and hardware to collect and share data to assist on-water decision making	COTS Control Centre Decision Support Tool (CCC-DST) entails three data collection apps on tablets that allow data sharing between networks	Technology advances can facilitate data collection and sharing	second app for data exploration	Fletcher and Westcott 2021

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5.1 Matching the COTS IPM to the scale of the new control program	Regional-scale modelling capability for assessing crown-of-thorns starfish control strategies on the Great Barrier Reef	Regional scale modelling can identify the effectiveness of COTS management assessing COTS and coral populations across years	Extensions of CoCoNet and ReefMod-GBR can detect best strategy able to reduce the number of reefs with COTS outbreaks	Current regional strategies already reduce the number of reefs with COTS outbreaks, including at Priority Reefs; a greater number of vessels significantly improves outcomes, similar to the ongoing control at the end of outbreak cycle		Fletcher et al., 2021
5.1 Matching the COTS IPM to the scale of the new control program	Integrated Pest Management Crown-of-Thorns Starfish Control Program on the Great Barrier Reef: Current Performance and Future Potential	The IPM COTS Control Program was successful despite small erroneous culling when non required and twice as efficient compared to previous programs; the region between 13S and 18S has highest chance of suppressing COTS outbreak; If the IPM COTS Control program takes place in this region, the likelihood of a spreading outbreak is very low		Control fleet should be always present to respond to COTS outbreaks at any given time; this fleet should conduct a COTS control specific monitoring program with new technologies and integrate the IPM strategy; improvements and refinement is to be made in regard to this strategy and the selection of targeted reefs; this represents a long-term investment	alternative and improved control technologies	Westcott. et al., 2021

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