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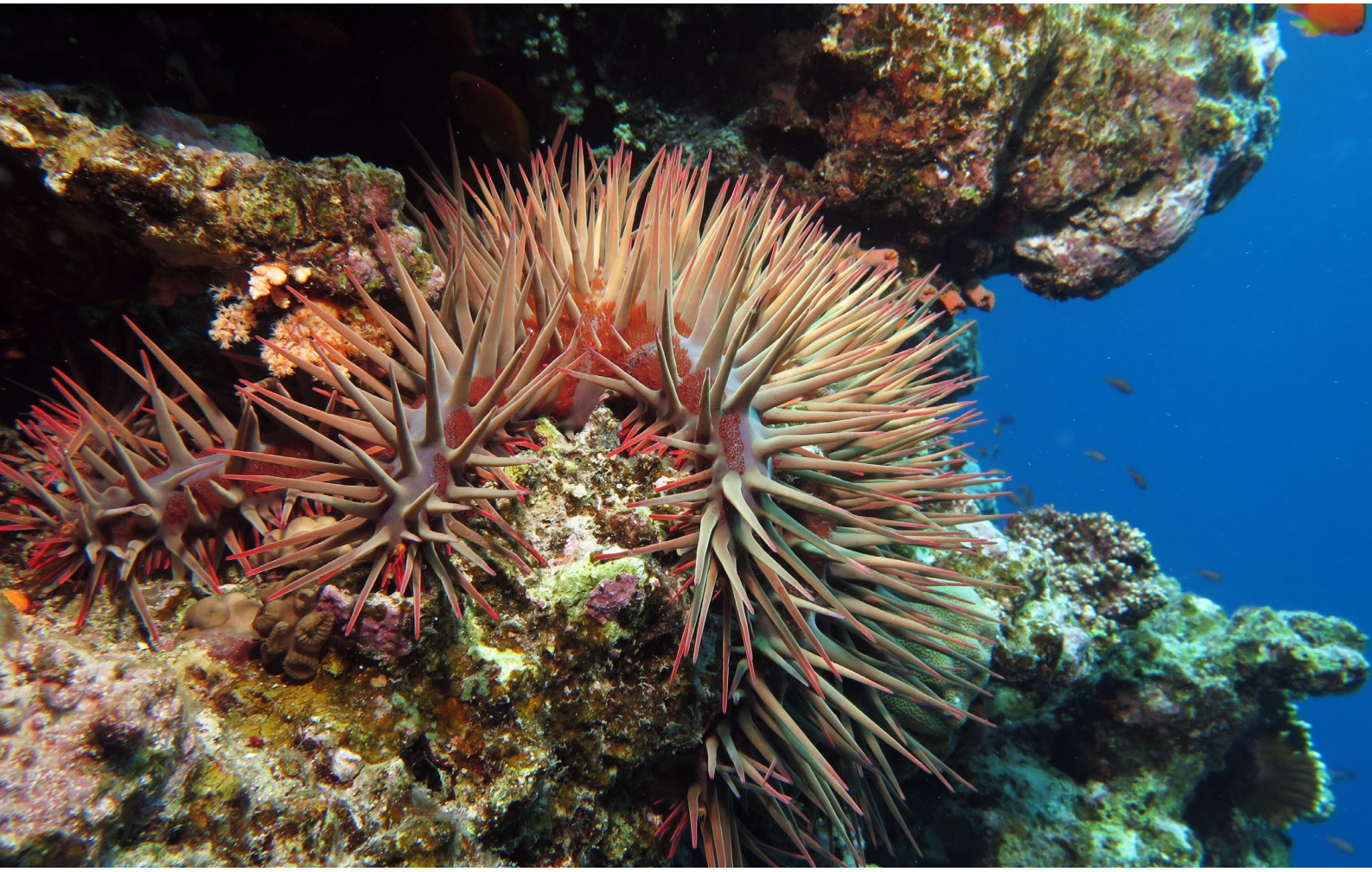

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Design of the COTS Control Innovation Program: a technical report and recommendations

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COTS Control Innovation Program | A research and development partnership to better predict, detect and respond to crown-of-thorns starfish outbreaks

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Traditional Owner Acknowledgement

The COTS Control Innovation Program extends its deepest respect and recognition to all Traditional Owners of the Great Barrier Reef and its Catchments, as First Nations Peoples holding the hopes, dreams, traditions and cultures of the Reef.

Disclaimer

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Acroynms and Abreviations

AIMS	Australian Institute of Marine Science
AUV	Autonomous Underwater Vehicle
BE	COTS Biology and Ecology (Program Area)
C	Population Control (Program Area)
CCIP	COTS Control Innovation Program
COTS	Pacific crown-of-thorns starfish (*Acanthaster* cf. *solaris*)
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DSM	Decision Support and Modelling (Program Area)
GBR	Great Barrier Reef
GBRF	Great Barrier Reef Foundation
IPM	Integrated Pest Management
JCU	James Cook University
MS	Monitoring and Surveillance (Program Area)
NESP	National Environmental Science Program
PA	Program Area
PC	Proximal Causes of Outbreaks (Program Area)
QUT	Queensland University of Technology
RO	Research Opportunity
RIMReP	Reef 2050 Integrated Monitoring and Reporting Program
RRAP	Reef Restoration and Adaptation Program
RRRC	Reef and Rainforest Research Centre
RTP	Reef Trust Partnership
SCU	Southern Cross University
SDM	Structured Decision-Making
SS	Social Science (Program Area)
SV	Surface Vehicle
Synbio FSP	Synthetic Biology Future Science Platform
TO	Traditional Owner
TUV	Towed Underwater Vehicle
UQ	University of Queensland
USC	University of Sunshine Coast
USYD	University of Sydney

EXECUTIVE SUMMARY

Outbreaks of crown-of-thorns starfish (COTS) cause significant damage and are a major threat to the long-term health of the Great Barrier Reef (GBR). Controlling these outbreaks is considered one of the most scalable and feasible direct management interventions available today to enhance the Reef's resilience in the face of climate change. Indeed, recent modelling has identified COTS control as one of the most effective interventions for reducing decline in coral cover across the GBR over the next 50 years under climate change. With a current outbreak still spreading across the Reef, and the next outbreak already potentially developing, there is an urgent need to invest in research that improves our ability to manage COTS outbreaks at scale.

To manage COTS outbreaks at scale, the Reef Trust Partnership (RTP) has invested $9.8m to establish the COTS Control Innovation Program (CCIP) to create a step change in the development and uptake of innovative methods of COTS surveillance and control, building on the Integrated Pest Management strategy developed under the National Environmental Science Program (NESP). The CCIP is being delivered as a scientific consortium of core research partners from the Australian Institute of Marine Science, Commonwealth Scientific and Industrial Research Organisation, James Cook University, and The University of Queensland, with input from additional technical experts from other institutions, and coordinated by the Great Barrier Reef Foundation. The CCIP is being delivered across a Feasibility and Design Phase (2020 – 2021), focused on prioritising and designing a research program, which will then be undertaken as part of the Research and Development Phase (2021-2024).

This report summarises the processes followed, and outcomes generated, through the Feasibility and Design Phase within six Program Areas: population control; monitoring and surveillance; decision support and modelling; proximal causes of outbreaks; biology and ecology; and social acceptability, regulatory and institutional arrangements. Within each Program Area, a flexible workflow was followed to identify key knowledge gaps, identify and scope Research Opportunities that could address those gaps, and then assess, prioritise and refine those Research Opportunities following feedback from research peers, culminating in a series of recommendations provided by each Program Area to the CCIP Program Director and Steering Committee about priority areas of research. This information then fed into several further steps (not covered in this report), including a Portfolio-level Design and Assessment process facilitated by a consultant, and the development of an Investment Plan by the CCIP Program Director and Steering Committee.

Across the various Program Areas, knowledge gaps were identified using a range of criteria, feeding into the development of Research Opportunities for assessment and prioritisation:

- The Population Control Program Area built its gap analysis on two recent reports, identifying 85 knowledge gaps across six control types, and leading to the generation of four Early Investment Opportunities and seven Research Opportunities.
- The Monitoring and Surveillance Program Area built off a recent report summarising monitoring and surveillance needs, identifying 24 knowledge gaps across different phases of the outbreak and monitoring needs, which led to the identification of 14 Research Opportunities, which were then further refined so that 10 Opportunities went through the assessment process.

- The Decision Support and Modelling Program Area identified 86 knowledge gaps across nine broad areas, which were further refined to 52 sub-classes, leading to the identification of 17 Research Opportunities, some of which were merged, leaving 10 for assessment.
- The Proximal Causes Program Area identified 52 knowledge gaps across four major potential drivers of primary and/or secondary outbreaks, leading to the proposal of 14 Research Opportunities, which were further refined to provide 12 Opportunities for assessment.
- The Biology and Ecology Program Area built on several recent reviews on the state of biological understanding of crown-of-thorns starfish, identifying 71 key traits across 10 distinct life stages and processes, leading to the proposal of eight Research Opportunities.
- There was little existing information on public perceptions of COTS or control methods, so the Social Acceptability, Regulatory and Institutional Arrangements Program Area conducted a thorough review of related literature, identifying six areas potentially important to implementing further COTS control research, leading to five Research Opportunity proposals for assessment.

Within each Program Area, the Research Opportunities identified through this process were then assessed against a range of Evaluation Criteria designed to characterise their potential to deliver outcomes aligned with the CCIP values and objectives. These Evaluation Criteria included the 1) Path to impact, 2) Ability to supress outbreaks, 3) other Ecosystem co-benefits, 4) Socioeconomic co-benefits, 5) Time to viability, 6) Risk of the project, 7) synergies with other projects, and 8) innovation. The assessment followed a three-stage process: anonymous scoring by individual experts against established Evaluation Criteria using an online survey tool, followed by a detailed workshop discussing the outcomes of this assessment process, finalised in a narrative summary of recommended research priorities provided to the CCIP Program Director and Steering Committee.

This report describes the details of this process and provides a summary of the recommendations provided. In general, the careful process of gap identification, followed by research opportunity scoping and refinement in relation to those gaps, led most, but not all Program Areas to assign a similar level of priority to most Opportunities. As a result, most Program Areas did not rule out or strongly prioritise entire Opportunities. Rather, these programs presented the CCIP Program Director and Steering Committee with recommendations about how each Research Opportunity contributed to the overall research understanding important to COTS control, and, where possible, identifying where Opportunities could be scaled while still addressing the most important knowledge gaps.

Through this process, 43 technical experts across the six Program Areas identified and scoped a total of 52 Research Opportunities relevant for advancing COTS surveillance and control, using an expert elicitation and assessment process to generate data on their relative benefits, costs, and risks that was used in designing the innovation program.

1 INTRODUCTION

1.1 The Crown-of-thorns starfish Control Innovation Program

The Pacific crown-of-thorns starfish (COTS; *Acanthaster* cf. *solaris*) is a coral-eating starfish that is native to the Great Barrier Reef (GBR). Outbreaks of this starfish cause significant damage to coral reefs across large spatial scales and are a major threat to the long-term health of the GBR. Controlling these outbreaks is considered one of the most scalable and feasible direct management interventions available today to enhance the Reef's resilience in the face of climate change (GBRMPA 2017, GBRMPA 2020). Indeed, recent modelling has identified COTS control as one of the most effective interventions for reducing decline in coral cover across the GBR over the next 50 years under climate change (Condie et. al 2021). With a current outbreak still spreading across the central and southern regions of the Reef, and the next outbreak already potentially developing in the northern region, there is an urgent need to invest in research that improves our ability to manage COTS outbreaks at scale.

To manage COTS outbreaks at scale, the Reef Trust Partnership (RTP) has invested a total of $9.8m to establish the COTS Control Innovation Program (CCIP). The overarching goal of this program is to create a step change and accelerate the development and uptake of innovative methods that improve the efficacy and efficiency of COTS surveillance and control. This program builds upon the Integrated Pest Management (IPM) strategy developed under the National Environmental Science Program (NESP) and intends to deliver innovations that can be integrated into the on-water COTS Control Program. The CCIP is being delivered across two phases:

- Phase 1 - Feasibility and Design (2020-2021, $1.5m), focused on assessing the feasibility (technical, social and regulatory) and benefit (impact) at scale of a broad range of possible improvements and interventions in order to recommend an integrated program of research;
- Phase 2 - R&D Program (2021-2024, $8.3m), which will focus on implementing the recommendations of the Feasibility and Design Phase and identifying pathways for trialling and integration of research outcomes into the COTS Control Program.

1.2 Delivery model and governance

The CCIP is being delivered as scientific consortium of core research partners from the Australian Institute of Marine Science (AIMS), Commonwealth Scientific and Industrial Research Organisation (CSIRO), James Cook University (JCU), and The University of Queensland (UQ), and coordinated by the Great Barrier Reef Foundation (GBRF). These five partners have entered into a CCIP Collaboration Agreement, fostering a cooperative and outcome-focused approach where multidisciplinary teams work across institutional boundaries to maximise impact and ensure the program's findings are widely supported.

An open Expression of Interest process was also run from May to June 2020 to identify additional technical experts from beyond the core research partner institutions. This resulted in additional expertise from a range of institutions and organisations joining to design and/or

deliver the research program as third-parties (e.g., University of Sydney, Southern Cross University, University of the Sunshine Coast, Queensland University of Technology, Babel-sbf, Marenray).

The CCIP is governed by a Steering Committee chaired by GBRF and consisting of members from core partner research institutions, a Traditional Owner member, an independent member appointed by the Reef and Rainforest Research Centre (RRRC), and Observers from the Department of Agriculture, Water and the Environment (DAWE), the Great Barrier Reef Marine Park Authority (GBRMPA), and the tourism industry (***Figure 1.1***).

The CCIP Steering Committee oversees the design, progress and delivery of both phases of the research and innovation program, including endorsing strategic and operational plans, budget allocations, and reports. The Committee also provides strategic advice on risks and opportunities related to the program and ensures program funds are spent in accordance with the CCIP Collaboration Agreement. A Program Director reports to and acts under the direction of the Steering Committee, providing day-to-day oversight of program delivery by the technical teams.

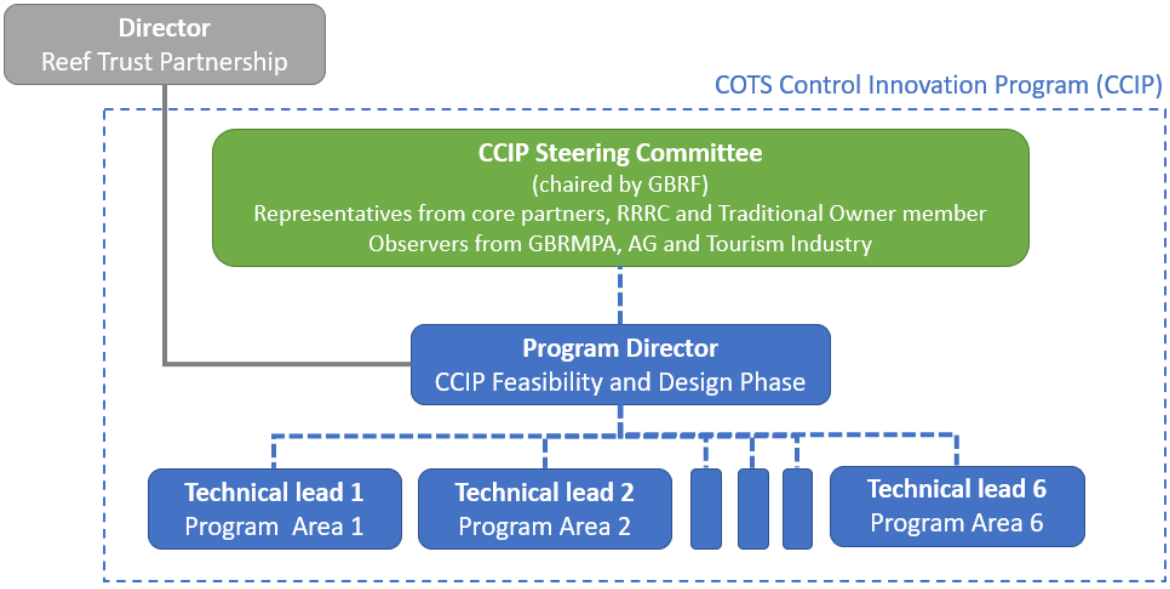

Figure 1.1 Governance structure for the COTS Control Innovation Program (CCIP)

2 THE FEASIBILITY AND DESIGN PHASE

2.1 Structured decision-making

Achieving the CCIP's overarching goal of delivering innovation in COTS surveillance and control requires targeted research that drives progress while also managing cost and risk. The problem at hand is that there are a wide range of Research Opportunities that could potentially achieve this goal, with no singular clear pathway for research investment. Moreover, the feasibility and benefit of many (most) Research Opportunities in delivering innovative COTS management outcomes is not well understood. Consequently, decision-makers are faced with a complex problem in determining which Research Opportunities warrant investment through the CCIP.

In the Feasibility and Design Phase a structured decision-making (SDM) process has been used to prioritise research investment in the three-year R&D program (Phase 2). The intention of this process has been to deliver insight to decision-makers about how well the objectives and vision of the CCIP will be met through a systematic assessment of the various investment options.

Structured decision-making is an organised, inclusive and transparent approach to understanding complex problems and evaluating alternative options to address them (Keeney 1982, Gregory et al. 2012). It is based on the concept that quality decisions are those which are based on values (i.e., understanding what's important) and consequences (i.e., understanding what's likely to happen). It is particularly useful when different disciplines need to work together to develop solutions to complex problems that are rigours, inclusive, defensible and transparent.

2.2 Program Areas

Prior to undertaking the Feasibility and Design Phase, six Program Areas were identified that represent key research themes for achieving CCIP goals:

- population control,
- monitoring and surveillance,
- decision support and modelling,
- proximal causes of outbreaks,
- COTS biology and ecology, and
- social acceptability, regulatory and institutional arrangements.

Teams of multidisciplinary technical experts were then assembled from across partner institutions and third-parties for each Program Area. An overview of each Program Area (PA) and its expert team is provided below.

2.2.1 Population Control

The technical team assembled under the Population Control (C) Program Area included 8 experts in molecular biology, COTS biology and pest management, including one expert from a third-party institution (***Table 2.1***). This team was led by Dr. Frederieke Kroon of AIMS. This Program Area was focussed on conducting a comprehensive review of innovation in the control of COTS population outbreaks, as part of an IPM strategy to protect live hard coral on the Reef. Specifically, this Program Area considered and prioritised potential innovations in the current (i) COTS Control Program and (ii) water quality improvement programs, as well as the broad range of possible biologically based control technologies for COTS reviewed in Høj et al. (2020), namely (iii) Predators and coral-symbiotic fauna, (iv) Microbial agents, (v) Semio-chemicals, and (v) Genetic biocontrol. The review included an in-depth assessment of the mode of action, level of maturity, technical feasibility and risk, deployment strategies and cost of biocontrol options, irrespective of their level of readiness.

Table 2.1 Population Control Program Area team.

Technical Expert	Institution
Frederieke Kroon	**AIMS**
Lone Høj	AIMS
Cherie Motti	AIMS
David Westcott	CSIRO
Owain Edwards	CSIRO
Sharon Hook	CSIRO
Bernie Degnan	UQ
Scott Cummins	USC
Maria Gomez Cabrera	AIMS

2.2.2 Monitoring and Surveillance

The technical team assembled under the Monitoring and Surveillance (MS) Program Area included 12 experts in COTS monitoring, technological engineering, eDNA techniques, and modelling, including two experts from third-party organisations (***Table 2.2***). This team was led by Dr. David Westcott of CSIRO. This Program Area was focused on conducting a systematic assessment of COTS monitoring and surveillance needs through a comprehensive review of existing and upcoming technologies/systems that could address these needs. This included an in-depth assessment of the level of maturity, technical feasibility and risk, deployment strategies and cost of these technologies/systems in order to prioritise investment as part of an integrated R&D program.

Table 2.2 Monitoring and Surveillance Program Area team.

Technical Expert	Institution
David Westcott	**CSIRO**
Cameron Fletcher	CSIRO

Emma Lawrence	CSIRO
Brano Kusy	CSIRO
Scott Foster	CSIRO
Sven Uthicke	AIMS
Jason Doyle	AIMS
Geoff Page	AIMS
Juan Carlos Ortiz	AIMS
Morgan Pratchett	JCU
Brett Kettle	Babel-sbf
Richard Stump	Marenray

2.2.3 Decision Support and Modelling

The technical team assembled under the Decision Support and Modelling (DSM) Program Area included 10 experts in decision science, cost-benefit analysis, and modelling (e.g., ecological, hydrodynamic, and systems models), including one expert from a third-party institution (***Table 2.3***). This team was led by Dr. Cameron Fletcher of CSIRO. The Decision Support and Modelling (DSM) Program Area had two roles in the CCIP Feasibility and Design Phase. One role involved assessing the modelling and decision support needs to enable the prediction, detection, and control of COTS outbreaks and to mitigate their impact. To achieve this, the Program Area comprehensively reviewed the current state of decision support and modelling as relevant to COTS surveillance and control in order to provide recommendations on investment as part of an integrated R&D program. In addition, this Program Area was also responsible for developing the framework for assessment of Research Opportunities identified across all Program Areas.

Table 2.3 Decision Support and Modelling Program Area team.

Technical Expert	Institution
Cameron Fletcher	**CSIRO**
Eva Plaganyi-Lloyd	CSIRO
Gabriela Scheufele	CSIRO
Scott Condie	CSIRO
Karlo Hock	UQ
Pete Mumby	UQ
Sam Matthews	JCU
Carla Ewels	JCU
Severine Choukroun	JCU
Michael Bode	QUT

2.2.4 Proximal Causes of Outbreaks

The technical team assembled under the Proximal Causes (PC) Program Area included 8 experts in COTS outbreak development and spread, including one expert from a third-party institution (***Table 2.4***). This team was led by Dr. Sven Uthicke of AIMS. This Program Area was focused on conducting an in-depth analysis of the conditions, processes and mechanisms that directly influence the likelihood and timing of a COTS outbreak as well as its scale and subsequent propagation. This Program Area identified knowledge gaps and developed recommendations on an R&D program to address such gaps, and guide the prioritisation, design and implementation of innovations identified under the population control and monitoring and surveillance Program Areas. For clarity, this Program Area did not consider the ultimate causes of COTS outbreaks which, while they can be informed by this program, are not considered within scope.

Table 2.4 Proximal Causes Program Area team.

Technical Expert	Institution
Sven Uthicke	**AIMS**
Morgan Pratchett	JCU
Ciemon Caballes	JCU
Laura Crous	CSIRO
Cynthia Riginos	UQ
Karlo Hock	UQ
Peter Mumby	UQ
Maria Byrne	USYD
Maria Gomez Cabrera	AIMS

2.2.5 COTS Biology and Ecology

The technical team assembled under the COTS Biology and Ecology (BE) Program Area included 10 experts in COTS biology and ecology, including two experts from third party institutions (***Table 2.5***). This team was led by Prof. Morgan Pratchett of JCU. This cross-cutting Program Area was focussed on conducting a systematic identification of gaps in our knowledge of COTS biology and ecology which affect our ability to understand, predict, detect, control and mitigate the impact of COTS outbreaks. This Program Area aimed to develop recommendations on research priorities that need to be addressed as part of an integrated R&D program to enable the design, implementation or ongoing improvement of long-term COTS management strategies.

Table 2.5 Biology and Ecology Program Area team.

Technical Expert	Institution
Morgan Pratchett	**JCU**
Ciemon Caballes	JCU
Bethan Lang	JCU

Technical Expert	Institution
Cherrie Motti	AIMS
Sven Uthicke	AIMS
Laura Crous	CSIRO
Kenny Wolfe	UQ
Amy Desbiens	UQ
Symon Dworjanyn	SCU
Maria Byrne	USYD
Dione Deaker	USYD

2.2.6 Social Acceptability, Regulatory and Institutional Arrangements

The technical team assembled under the Social Science (SS) Program Area included 6 inter-disciplinary experts in environmental social sciences, including policy, economics and behaviour change (***Table 2.6***). This team was led by Dr. Aditi Mankad of CSIRO. This cross-cutting Program Area was focussed on conducting preliminary desktop and qualitative enquiries to identify and prioritise research areas for social acceptability and implementation of COTS control methods with key stakeholders, with exploration of economic institutional and regulatory matters. This included identifying gaps in stakeholder and community understandings of COTS control and the potential direct and indirect costs and benefits of proposed innovations in the wider economy. This Program Area was also focussed on scoping the policy and regulatory implications of proposed COTS control methods and describing the related social, institutional and regulatory environment surrounding their implementation.

Table 2.6 Social Science Program Area team.

Technical Expert	Institution
Aditi Mankad	**CSIRO**
Lucy Carter	CSIRO
Matt Curnock	CSIRO
Gabriela Scheufele	CSIRO
Pedro Fidelman	UQ
Stewart Lockie	JCU

2.3 Overview of the design phase process

A total of 43 multidisciplinary experts were engaged across the six Program Areas in designing the research program. These teams worked together to identify, assess and recommend Research Opportunities for consideration as part of the R&D Phase (***Figure 2.1***), with strong emphasis on ensuring the synergies across Program Areas were identified. Additional input into program design was also provided by the Program Director, CCIP Steering Committee and four external assessors at later steps in the process.

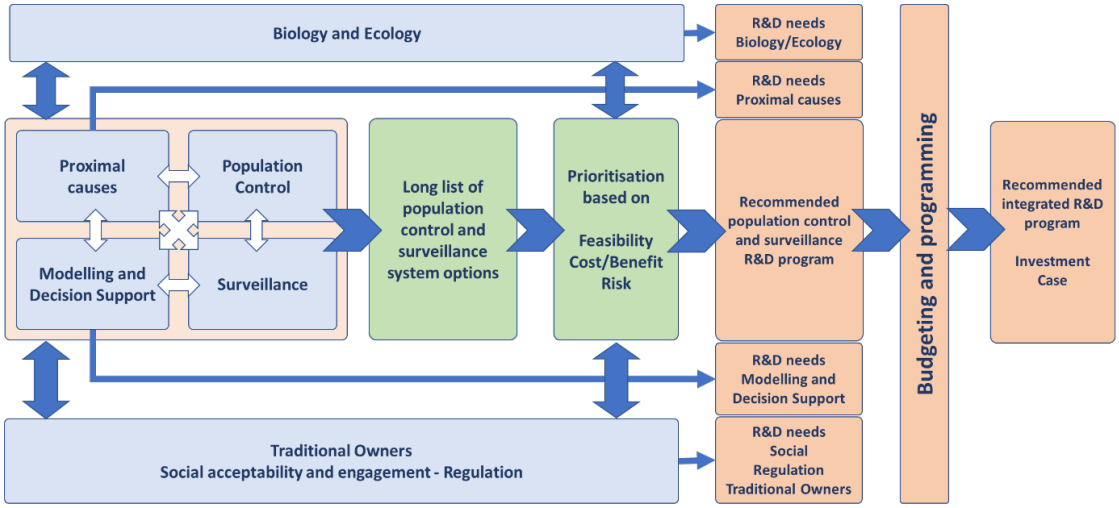

Figure 2.1 Overview of Program Areas and program design framework.

The broad steps involved in the CCIP Feasibility and Design Phase were as follows:

1. Gap analysis or literature review within each Program Area in order to systematically identify gaps in knowledge and capability within each research theme.

2. Identification and Scoping of Research Opportunities that fill the most critical knowledge and capability gaps within each Program Area, with experts collecting information on the benefits, costs, and risks of those opportunities.

3. Assessment of Research Opportunities through evaluation of their relative benefits, costs and risks by the experts within each Program Area using standard criteria.

4. Development and Assessment of alternative strategic R&D portfolio options using the Research Opportunities generated across Program Areas, in order to gain a directional view on the preferred R&D strategy and prioritised Opportunities to be included in final program design.

5. Final Program Design and Budgeting, including scope and cost rationalisation of prioritised Opportunities as part of an integrated R&D program.

This Technical Report focusses on detailing the process and outcomes of the first three steps listed above, which were delivered by the technical experts. Several companion reports detail the process and outcomes of the remaining steps. The CCIP Feasibility & Design Phase Investment Prioritisation report (Sivapalan 2021) reports on step four in the process. In the final step of the process: 1) guidance was provided by the CCIP Program Director and Steering Committee on which Opportunities would be targeted for investment, along with approximate target budgets, 2) Program Area Teams prepared formal project proposals and budgets aligned with this guidance; and 3) the final research program design was outlined in the CCIP Investment Plan (Bonin et al. 2022).

3 METHODS

The method used to achieve the generation, prioritisation and scoping of innovation opportunities was designed to provide a simple logical workflow, from the identification of key knowledge gaps, to Research Opportunities that could address those gaps, to prioritisation and refinement of those Research Opportunities following feedback from research peers (***Figure 3.1***). However, because CCIP covered a range of research areas from social to biological research, it was designed to provide this type of workflow flexibly, rather than as a rigid decision tree process, allowing: 1) modification of the process to suit different Program Area disciplines; 2) incorporation of new ideas that emerged throughout the process.

In practice, this approach meant that the information collected in each Program Area varied slightly at each step of the process. This was vital so that the most appropriate information could be collected and assessed based on disciplinary need. However, it did mean that slightly different information and characteristics were emphasised by different Program Areas as Opportunities were identified and refined. It also meant that although Opportunities were, in general, developed to address knowledge gaps identified during the Gap Analysis for each Program Area, by the end of the generation and refinement process there was not always a simple relationship between a single knowledge gap and a single Opportunity or project proposal (e.g. a single Opportunity could address multiple gaps). The work covered in this report encompassed the first three key stages identified in ***Section 2.3:*** a Gap Analysis, the identification of Research Opportunities that could address important gaps, and an Assessment process, culminating in recommendations from each Program Area to the CCIP Program Director and Steering Committee about priority areas of research. The methods followed for each of these components is outlined in detail below.

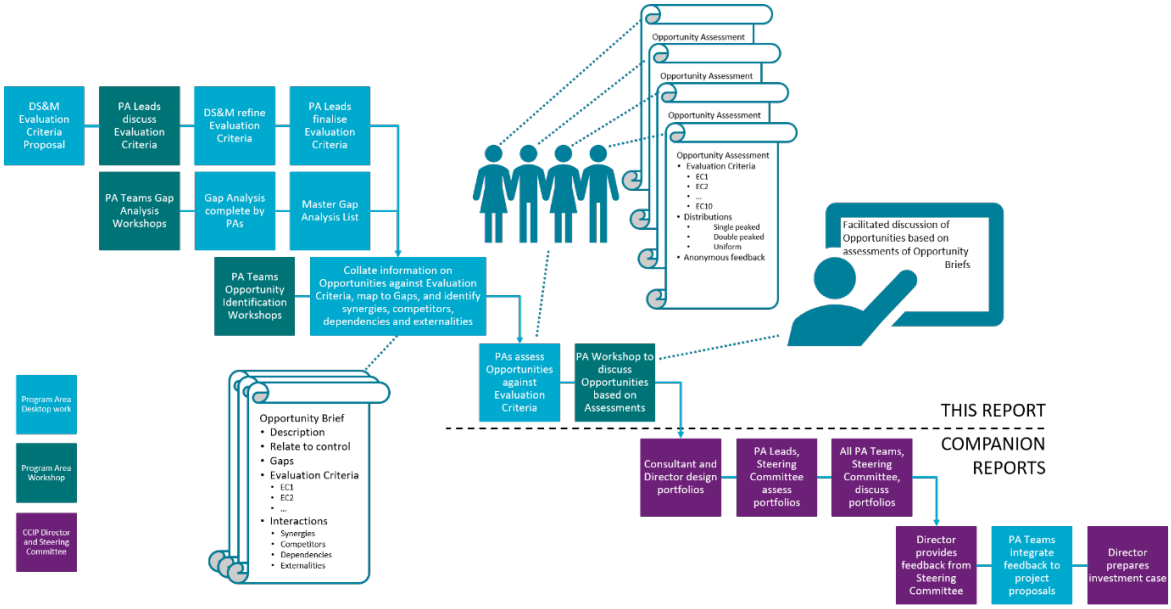

Figure 3.1 Workflow indicating stages of the CCIP Feasibility and Design Phase process; which components were desktop or workshop work within the Program Areas and which were the responsibility of other groups; and which components are described by this report and other companion report

3.1 Gap analysis

Between 03 October 2021 and 02 December 2021, each Program Area completed an analysis of the knowledge gaps within their Area. Each Program Area was able to design a gap analysis process that suited their area of domain expertise. However, broadly speaking, the gap analyses across all Program Areas aimed to identify:

- Specific knowledge gaps or needs,
- Why each gap was important,
- What existing knowledge was available to address each gap,
- The residual gap that remained in each case, given existing knowledge,
- What research would be needed to fill those gaps,
- Links to other Program Areas.

Different Program Areas collated this information in slightly different ways – some added additional information fields to those listed to help clarify the boundaries or linkages between gaps, for instance. Program Areas collected the information in a variety of ways, but generally involved:

- at least one workshop to brainstorm or assess gaps,
- desktop studies of existing material and articulation of the details of each gap,
- review of the accumulated gaps within the Program Area,
- followed, in some cases, by further synthesis and structuring.

The broad outcomes of these Gap Analyses within each Program Area are described in the following sections of this report.

3.2 Research Opportunity scoping and assessment

Technical experts from each Program Area then identified Research Opportunities to address the most critical knowledge gaps, based on the extensive knowledge of experts in the team. Subsequently, these opportunities were scoped, assessed and refined through an assessment process based on Structured Decision Making (SDM) principles (***Section 2.1***). This involved six steps, outlined in more detail below:

1. Definition of CCIP Values
2. Design of Evaluation Criteria aligned with those Values
3. Compilation of Opportunity details on a Template form designed to elicit information around those Evaluation Criteria
4. Anonymous assessment of each Opportunity within its respective Program Area team
5. Program Area Team workshop to discuss assessments
6. Compilation of a PA narrative and recommendations for the CCIP Director and Steering Committee

The methods for these six steps are outlined in detail below.

3.2.1 CCIP Values

On 02 November 2020, the CCIP Program Director and Program Area Leads participated in a kick-off workshop to establish a decision frame and define a set of values that underpin the process of identifying, developing and scoping Research Opportunities as part of the CCIP Feasibility and Design Phase

The decision frame was established by discussing the context for decision-making around Research Opportunity scoping for potential investment, and considering whether there would be any boundaries on the scope of Research Opportunities that were developed.

The discussion was linked back to both the CCIP goals – *to create a step change and accelerate the development of innovative control and surveillance methods while continuing to improve the efficacy and efficiency of current methods* – and the RTP COTS Component long-term goals – *coral cover is improved across the GBR and primary outbreaks are suppressed*. It was also linked to RTP COTS Component outcomes, including reduced coral mortality from COTS outbreaks at key reefs, the identification of new methods and innovative technologies, the development of early warning systems, and the ability to detect and predict primary outbreaks.

With that context in mind, the group agreed on the importance of taking a broad horizon scan of potential Research Opportunities and the need to keep an open mind. Consequently, no initial constraints or boundaries were placed on the scope of Research Opportunities that would be considered, with the exception that research should focus on controlling COTS outbreaks in the Great Barrier Reef ecosystem.

The group then brainstormed the values that would underpin scoping and assessment of Research Opportunities, initially generating a long list that was refined to seven value statements that described the ideal characteristics of a CCIP research portfolio:

1. maximises the benefit to coral (i.e., minimises loss and/or enhances resilience);
2. maximises the potential for future prevention of COTS outbreaks on the Great Barrier Reef;
3. maximises the capacity for early warning and effective suppression of the next outbreak;
4. able to be safely deployed in the Marine Park with risks minimised and/or manageable;
5. provides socio-economic benefits to communities and/or Reef-based industries;
6. maximises complementarity across Research Opportunities, capitalising on synergies, and;
7. delivers value for money when considering the costs of research, development and deployment.

3.2.2 Design of Evaluation Criteria

In developing the Evaluation Criteria for the CCIP process, the goal was to make them sufficiently high-level to apply to Opportunities across different Program Areas, while keeping them tangible enough to maintain their connection to on-ground implementation and impact (see **Appendix A**). It is important to note that the Evaluation Criteria Assessment process designed for CCIP was not intended to create quantitative assessments that could be used directly for prioritisation, but instead to provide a structure for expert assessment and discussion around the relative benefits, costs, and risks associated with proposed Research Opportunities and their ability to achieve the CCIP Values.

The Evaluation Criteria were developed with the input of the Decision Support and Modelling Team, the CCIP Program Director and an independent external consultant experienced in elicitation for SDM, then refined following feedback from the Program Area Leads.

The Evaluation Criteria were designed to be general enough to apply to all Program Areas, objective enough that two people provided the same information could score it similarly, orthogonal enough that they didn't cover the same ground, and of value, in that they referred to characteristics that required expert interpretation.

This process led to the identification of ten Evaluation Criteria:

1. Path to impact
2. Ability to suppress or prevent COTS outbreaks
3. Co-benefits: Ecosystem and coral health impacts
4. Co-benefits: Socio-economic impacts
5. Time to viability
6. Research cost
7. Implementation cost
8. Risks (Research, Economic, Environmental, Social, Regulatory)
9. Synergies, overlaps and dependencies with other Opportunities
10. Innovation potential

How these Evaluation Criteria relate to the CCIP Values identified in ***Section 3.2.1*** above is shown in ***Table 3.1***. For each Evaluation Criteria that was assessed (all Criteria except 6 and 7), an example scale was defined. These scales can be found in ***Appendix B***.

Opportunities within each Program Area were assessed against the Evaluation Criteria by members of that Program Area. Assessment values from each Program Area were then used by the Program Director and an external consultant to build portfolios of Research Opportunities to be prioritised and discussed at the whole-of-CCIP workshop that occurred in Cairns on 31 March 2021.

3.2.3 Opportunity templates

To provide the information Program Area Teams would require to systematically assess each Opportunity, proponents were asked to collate information aligned with the Evaluation Criteria for each Opportunity. To ensure that information of consistent distribution and level of detail was collated for each Opportunity, background information on the feasibility and design

phase (***Appendix C***) and an Opportunity Template (***Appendix D***) were provided, with thirteen fields based on the Evaluation Criteria identified in the previous section of this report:

1. Opportunity Title
2. Opportunity Proponents
3. CCIP Program Area
4. Opportunity Outline
5. Path to impact
6. Ability to suppress of prevent COTS outbreaks
7. Co-benefits: Ecosystem and coral health impacts (if applicable)
8. Co-benefits: Socio-economic impacts (if applicable)
9. Time to viability
10. Research cost
11. Implementation cost
12. Risks (Research, Economic, Environmental, Social, Regulatory)
13. Synergies, overlaps and dependencies with other Opportunities

Between 02 December 2020 and 11 February 2021, these Templates were completed by the lead proponents for each Opportunity within each Program Area. They were not designed to represent a full project proposal, but instead a brief collation of evidence of how each research Opportunity could drive impact, suppress or prevent COTS outbreaks and deliver co-benefits, over what timeframes and at what cost, and with what risks and synergies, sufficient to allow assessment and discussion during the Program Area Assessment Workshops.

Table 3.1 Evaluation Criteria and how they link to CCIP values.

#	Evaluation Criteria	CCIP Value	EC Question	EC Objective
1	Path to impact	Maximises the potential for future prevention of COTS outbreaks on the Great Barrier Reef	Does this Research Opportunity provide a pathway to deliver innovative COTS control outcomes, in alignment with CCIP vision and values, and how direct is the pathway to impact?	Ensure that research funded under CCIP has a path to impact
2	Ability to suppress or prevent COTS outbreaks	Maximises the potential for future prevention of COTS outbreaks on the Great Barrier Reef Maximises the capacity for early warning and effective suppression of the next outbreak	How significantly would realising this Opportunity improve our ability to prevent or suppress COTS outbreaks?	To assess the extent to which the research could contribute to suppression or prevention of future outbreaks, meaning that it could lead to less severe and / or less frequent outbreaks.
3	Co-benefits: Ecosystem and coral health impacts	Maximises the benefit to coral (i.e., minimises loss and/or enhances resilience)	Would this research deliver positive coral health impacts on the Great Barrier Reef above and beyond those provided by more effective reduction of COTS impact, and how significant would those benefits be?	To assess the extent to which the research would benefit coral health, meaning that it could lead to protection or improvement in coral cover, and/or enhanced resilience of coral communities
4	Co-benefits: Socio-economic impacts	Provides socio-economic benefits to communities and/or Reef-based industries	Would this research provide positive socio-economic outcomes for Traditional Owners, communities, and/or Reef-based industries beyond that generated by suppressing or preventing COTS outbreaks, and how significant would it be?	To assess the potential for the research to deliver socio-economic benefits, meaning that it creates economic opportunities for Traditional Owners and/or community, and is co-beneficial to the tourism and/or fishing industries.
5	Time to viability	Maximises the capacity for early warning and	What is an approximate time estimate for this research to	To assess the timeframe required for a research opportunity to achieve an applied outcome,

		effective suppression of the next outbreak;	generate on-water impact reducing the impacts of COTS on the GBR?	meaning that it delivers knowledge, tools or technologies that can be trialled and implemented in COTS management (assuming no regulatory barriers).
6	Research cost	Delivers value for money when considering the costs of research, development and deployment.	What are the approximate (± 25%) quantitative dollar estimates of all costs involved in conducting the research (e.g., personnel, facilities, fieldwork, consumables, travel)?	To assess the cost effectiveness of the research investment, in terms of research development.
7	Implementation cost	Delivers value for money when considering the costs of research, development and deployment.	What are the approximate (± 50%) quantitative dollar estimates of all costs involved in implementing the outcome of this research to generate the real-world impact outlined in section 1, at the scale most relevant to the Opportunity (e.g., per reef, over the entire GBR, per year)?	To assess the cost effectiveness of the research investment, in terms of implementation (if applicable).
8	Risks • Research • Economic • Environmental • Social • Regulatory	Able to be safely deployed in the Marine Park with risks minimised and/or manageable	How significant are the research risks associated with this Opportunity, including economic, environmental, social and regulatory risks?	To clarify whether there are additional risks of the innovation that could affect its success or acceptability not captured elsewhere
9	Synergies, overlaps and dependencies with other Opportunities	Maximises complementarity across Research Opportunities, capitalising on synergies	How does the proposed Opportunity interact with other potential research in CCIP? Is it primarily dependent on other research, does it overlap with other research, or does it enable other research?	To clarify whether the knowledge gap to be filled by the opportunity could be filled by other opportunities, or whether two opportunities together could generate more benefit than either on their own
10	Innovation potential	Overall	Overall, what is the potential for this Research Opportunity to deliver innovation in COTS surveillance and/or control on the Great Barrier Reef?	To assess the potential for research funded under CCIP to transform COTS surveillance and/or control on the GBR

3.2.4 Opportunity Assessment

Each Opportunity was scored against the assessable Evaluation Criteria by the entire Program Area Team of the Program Area in which it was submitted. This group was selected as the most appropriate for assessment because the context of each Opportunity was vital to its assessment, and the Program Area Team contained people with the technical expertise to understand this context. Additionally, proponents were able to assess their own Opportunities. This was considered appropriate because the quantitative assessment values were not being used to generate a priority ranking, only identify the relative characteristics of each Opportunity for further discussion.

The Assessment process was implemented using SurveyMonkey online survey tool. Individual recipients received personalised invitations to complete the survey, allowing participants to complete the survey over several sessions, or revisit the survey and revise responses until the survey closed. Surveys ran from 15 February 2021 to approximately 22 February 2021. Filling in the survey took approximately 15 minutes to complete if the respondent had already reviewed all Opportunities and considered what values they were going to assign. In addition, each recipient received an Assessment Instructions document and a pack containing all Opportunity Templates for their Program Area. The CCIP Assessment Instructions document is provided as ***Appendix E***.

The individual online Assessment was considered the first step of a two-part Assessment process, in combination with the Program Area Assessment Workshop during which factors

not well captured by the assessment could be discussed. Additionally, respondents were asked to assess a range encompassing their best estimate with uncertainty of each Evaluation Criteria for each Opportunity, reducing the sensitivity of the process to uncertain assessments. Respondents were advised to focus on providing assessments that were reasonable in both an absolute and a relative sense. Respondents were asked to assess all Evaluation Criteria other than the research and implementation cost of the Opportunities, because for these two categories, numerical estimates were provided in each Opportunity Template and could be used directly without requiring further interpretation.

To help respondents provide consistent absolute assessment values, scales were provided for each Evaluation Criteria. These scales are shown in ***Appendix B***. Respondents were asked to reference these scales each time they made an assessment, and to provide their assessment as a range of values based on their certainty. For instance, if they believed an Opportunity had a moderate ability to suppress or prevent COTS outbreaks and they were relatively certain of it, they might have selected assessment values of 4 and 5. On the other hand, if they felt another Opportunity also had a moderate ability to supress or prevents COTS outbreaks at best, but were much less certain, they might have selected assessment values of 2, 3, 4, 5, and 6. If respondents felt that a Criteria did not apply to a given Opportunity, they were able to select a "Not Applicable" response, and if they felt unable to assess a given Criteria, they were able to select a response of "No Idea".

3.2.5 Program Area Opportunity assessment workshops

The outputs from the individual online Assessment process were used to structure team discussions around the Opportunities during a series of Program Area Assessment Workshops. With the exception of the DSM Program Area, all other Program Area Assessment Workshops were facilitated by the DSM Program Area Lead, Cameron Fletcher, based on analysis of the results of the individual online Assessments. The DSM Program Area Assessment Workshop was facilitated by the CCIP Program Director to allow the DSM PA Lead to participate in the discussion and represent the Opportunities in which he was personally involved. Program Area Assessment Workshops took place between 05 March 2021 and 22 March 2021.

The Program Area Assessment Workshops were structured in two halves. The first half consisted of a facilitated discussion around:

- Relative assessments between Opportunities
- Consensus between assessments for each Opportunity
- Discussion of questions and feedback raised in anonymous comments

This information provided insights for refinement of the Opportunities as final proposals were developed. In some Program Areas, the Assessment values between Opportunities provided a clear explanation of Opportunity characteristics and a basis for discussion of relative priority. However, in several Program Areas, the relative assessments between Opportunities provided little discriminatory power because all Program Area Opportunities shared common characteristics, leading to similar Assessments. In addition, for some Program Areas, most notably Social Science, the limited applicability of the Evaluation Criteria limited the benefit of the quantitative data collated.

With that exception, however, most Program Areas achieved a range of levels of consensus across Assessments between Opportunities. This was reflected in the distribution of Assessment values. Some were approximately normally distributed with a clear single peak, reflecting a relatively high level of consensus. Others exhibited bimodal or occasionally trimodal distributions, suggesting two or three clusters of opinion. Finally, some exhibited essentially no consensus across the experts.

Finally, the SurveyMonkey form provided space for anonymous freeform questions or feedback on each Opportunity. As part of the Workshop, the most common feedback was reworded by the workshop facilitator to maintain anonymity, and shared back with the Program Area Team for discussion. The Opportunity proponent had first right-of-reply to these questions or feedback, after which discussion was opened to the floor.

The second half of each Assessment Workshop sought to identify research priorities within each Program Area. This process was facilitated by the relevant Program Area Lead, with some preparatory material provided by the DSM Program Area. As a result, both the prioritisation process and the amount of prioritisation completed during the Assessment Workshop varied slightly between Program Areas. During this process, the discussion around each Opportunity during the first half of the Workshop was reviewed and the goal was to assign each Opportunity to a “must have”, “should have”, or “nice to have” category.

This prioritisation process continued within the Program Area following the Assessment Workshops. The key output of this process was a Program Area Narrative reflecting the refined understanding of the Opportunities across the Program Area, how they fit together, how they could be rescoped, scaled, combined or split in response to the discussion during the Assessment workshop, and their relative priority. These narratives were provided to the CCIP Program Director and Steering Committee on 12 March 2021, and they form the basis of the “Recommendation of priority Opportunities” in ***Sections 4.4***, ***5.4***, ***6.4***, ***7.4***, ***8.4***, and ***9.4*** below.

4 RESULTS – POPULATION CONTROL

The objective of the Population Control Program Area was to 'conduct a comprehensive review for innovation in the control of COTS population outbreaks, as part of an integrated pest management strategy to protect live hard coral on the GBR'. This objective was considered throughout the Feasibility and Design Phase (year 1) when (i) reviewing the current state of the art, (ii) identifying gaps and opportunities, and (iii) ultimately recommending priority Research Opportunities. Specifically, the Population Control Program Area focussed on innovation in the control of COTS population outbreaks, i.e., the potential COTS management approaches that would create a step change in protecting live hard coal on the GBR. As such, this Program Area did not focus on improved understanding of the biology and ecology of COTS, or proximate causes of COTS outbreaks per se, unless such understanding would assist in accelerating the development of innovative COTS control methods.

4.1 Gap analysis

This Program Area considered and prioritised potential innovations in the current (i) COTS Control Program and (ii) water quality improvement programs, as well as the broad range of possible biologically based control technologies for COTS namely (iii) Predators and coral-symbiotic fauna, (iv) Microbial agents, (v) Semio-chemicals, and (vi) Genetic biocontrol (***Table 4.1***). Unlike most other Program Areas, the Population Control Program Area was able to build on two recent reviews pertaining to this Program Area, namely (i) a review of biologically based control technologies for COTS, conducted as part of the NESP TWQ COTS integrated pest management program (Høj et al. 2020), and (ii) an independent review of the COTS Control Program, commissioned by the Great Barrier Reef Foundation (Hewitt and Campbell 2020).

Table 4.1 The six different control types considered in the gap analysis for the Population Control Program Area. A brief summary is presented on current activities for each control type, as well as main relevant references.

Control type	What is currently being done?	Main references
COTS Control Program	Manual control of COTS to protect hard coral cover. Dedicated vessels with professionally-trained crews apply an integrated pest management decision support framework to guide effective control using single-shot lethal injections.	Hewitt & Campbell 2020; Westcott et al. 2016, 2020, 2021a; Westcott et al 2016; Fletcher & Westcott 2016, 2021a; Fletcher et al. 2020, 2021. Also, GBRMPA COTS Control Program (https://www.gbrmpa.gov.au/our-work/our-programs-and-projects/crown-of-thorns-starfish-management/crown-of-thorns-starfish-control-program)
Water quality improvement programs	Catchment management programs to improve land-based run-off since 2003, starting with Reef Water Quality Protection Plan, up to current including Reef 2050 LTS Plan and Qld Reef Regulation and Qld Vegetation Management Act.	Reef 2050 LTS Plan; Report card 2017, 2018, 2019 (https://www.reefplan.qld.gov.au/tracking-progress/reef-report-card); Fischer 1969; Randall 1972; Brodie 1992; Brodie et al. 2005; Fabricius et al. 2010; Brodie et al. 2012; De'ath et al. 2012; Pratchett et al. 2014; Wooldridge et al. 2015; Babcock et al. 2016; Kroon et al 2016; Condie et al. 2018; MacNeil et al. 2019; Gruber et al. 2020; Westcott et al. 2020.
Predators and coral-symbiotic fauna	Zoning, protecting threatened species, fisheries management	McCook et al 2010; Cowan et al. 2017; Hall et al. 2017a; Høj et al. 2020; Kroon et al. 2020, In review.

Microbial agents	Not currently used in COTS control	Høj et al. 2020
Semio-chemicals	Not currently used in COTS control	Høj et al. 2020
Genetic biocontrol	Not currently used in COTS control	Høj et al. 2020

To identify knowledge gaps relating to population control of COTS, the first formal workshop of the Program Area was held on 06 November 2021 (via Zoom) and attended by all Program Area team members (see ***Table 2.1***), as well as technical leads for all other Program Areas. Prior to the workshop, the members of the Population Control Program Area reviewed the two recent reviews (Høj et al. 2020; Hewitt and Campbell 2020). The workshop provided an introduction to all participants to the CCIP by the Program Director, and an introduction to the Population Control Program Area by the Program Area lead. Next, each of the six control types were briefly introduced by relevant experts including an overview of recent research, status of COTS control activities and their efficacy in controlling COTS outbreaks and protecting life hard coral cover (Westcott et al. 2020). The workshop finished with an agreed way forward to conduct a gap analysis for each of the six control types, to be led by the relevant expert with contributions from interested team members. Specifically, each of the gap analysis was to be conducted in the context of this Program Area's objective and build on the reviews by Høj et al. (2020) and Hewitt and Campbell (2020). The results of this gap analysis are presented in ***Table 4.2***.

Table 4.2 Summary of knowledge needs identified for the six different control types considered in the Population Control Program Area, including the Early Investment Proposals (EIP) and Research Opportunities subsequently developed to address knowledge needs considered of highest importance by the Program Area team. Topic lead is given for each control type.

Control type	Knowledge Need	Linked to Opportunity
COTS control program (Westcott)	Can remotely operated vehicles be an effective means of controlling COTS in waters too deep for divers?	Not pursued
	If semio-chemicals are developed, can they be effectively deployed?	EIP-2 Semio-chemical Delivery
	Can we increase efficiency of manual control program by improved decision making?	Pursued by Decision Support and Modelling PA
	Can we minimise disruption to manual control program by having sufficient spare parts available?	Not pursued
Water quality improvement programs (Kroon)	Will improved understanding of link between water quality and COTS population outbreaks result in changed catchment management? (Note that improved understanding can result in strengthening or weakening the relationship between WQ and COTS).	Pursued by Proximal Causes PA
	Which (combination of) water quality constituent(s) are critical in influencing COTS outbreaks, and can these be influenced through catchment management?	Pursued by Proximal Causes PA
	Spatially, where should water quality improvements need to focus to influence COTS population outbreaks (e.g., focus on initiation zone)?	EIP-1 Water quality
	Temporally, how many years or decades until improvements in water quality resulting from catchment management are expected to influence COTS population outbreaks?	EIP-1 Water quality
	What is the predicted change in magnitude or frequency of COTS outbreaks following water quality improvement? How would this change under climate change scenarios?	Pursued by Decision Support and Modelling PA
	What is the role, if any, of pesticides in influencing COTS outbreaks?	Not pursued
Predators and coral-symbiotic fauna (Kroon)	Will improved understanding of link between predation and COTS population outbreaks result in changed predator management? (Note that improved understanding can result in strengthening or weakening the relationship between predation and COTS).	Pursued by Proximal Causes PA

	Which (combination of) predator(s) are critical in influencing COTS outbreaks, and can these be influenced through management?	C-8 Predator conservation; also pursued by Biology and Ecology, and Proximal Causes PAs
	Spatially, where should predator management need to focus to influence COTS population outbreaks (e.g., focus on initiation zone)?	C-8 Predator conservation; also pursued by Decision Support and Modelling PA
	How many years or decades until management of predator(s) is expected to further influence COTS population outbreaks?	C-8 Predator conservation; also pursued by Decision Support and Modelling PA
	What is the predicted change in magnitude or frequency of COTS outbreaks following additional management of COTS predators? How would this change under climate change scenarios?	C-8 Predator conservation; also pursued by Decision Support and Modelling PA
	Which predator species are critical in influencing COTS outbreaks, and can these be influenced through management?	C-8 Predator conservation; also pursued by Biology and Ecology, and Proximal Causes PAs
	Can predator populations play a role in preventing or delaying outbreaks by reducing the number of (i) successfully settled larvae, (ii) maturing juveniles, and/or (iii) adult COTS when present at low densities between outbreaks?	Pursued by Biology & Ecology, and Proximal Causes PAs
	Does predator presence play a role in reducing or preventing adult COTS aggregations (e.g., for feeding or spawning)?	C-6 Deterrents
	What is the potential role of the giant triton snail (*Charonia tritonis*) in mitigating COTS population outbreaks, either through direct predation or 'landscape of fear' (see also control type 'Semio-chemicals')?	C-4 Triton, C-6 Deterrents
	What are the spatial and/or temporal scales that Giant Triton influence COTS population outbreaks?	C-4 Triton
	What is the potential role of invertebrates in mitigating COTS population outbreaks, or the impacts of COTS outbreaks, including through direct predation?	Pursued by Biology and Ecology, and Proximal Causes PAs
	Has the individual or combined take of various GBR fisheries (commercial, recreational, indigenous) played a role in influencing COTS population outbreaks? Either directly (through release from predator pressure) or indirectly (though other cascading effects).	C-8 Predator conservation
Semio-chemicals (Motti)	**Attractants - General Considerations**	
	What is the chemical nature of COTS foraging attractants? Are they emitted by coral prey (including microbial biofilms) items (foraging kairomones) or feeding conspecifics (pheromones or released foraging kairomones)?	EIP-2 Semio-chemical Delivery, C-5 Attractants
	What is the chemical nature of COTS conspecific aggregation pheromone attractants? Are they seasonal, or sex specific (i.e., during spawning time) or are they kairomones?	EIP-2 Semio-chemical Delivery, C-5 Attractants
	Is it more effective to elucidate and use attractants for adults, juveniles or larvae?	C-5 Attractants; also pursued by Proximal Causes PA
	What is their mode of action? Does the attractant (pheromone or kairomone) have broad spectrum or selective bioactivity?	C-5 Attractants
	What is the level of attractant specificity for COTS?	C-5 Attractants
	What is the efficacy of adult COTS pheromone attractants in the field?	EIP-2 Semio-chemical Delivery, C-5 Attractants
	Does attractant efficacy change between seasons?	EIP-2 Semio-chemical Delivery, C-5 Attractants
	Can the pheromone or kairomone be modified for increased or prolonged bioactivity? Or species-specificity (if not already)	EIP-2 Semio-chemical Delivery, C-5 Attractants
	Is the attractant (pheromone or kairomone) effective over the full geographical range of COTS? i.e., is it effective across the entire GBR, Japan, etc?	C-5 Attractants
	Repellents - General Considerations	

	What is the chemical nature of COTS repellents/deterrents? What type of deterrent are they, conspecific alarm pheromone, conspecific injury pheromone, or predator kairomone, or other?	EIP-2 Semio-chemical Delivery, C-6 Repellents
	What predators produce COTS kairomone deterrents? Giant triton is confirmed, but what about corals not widely predated on? What about macroalgae? What about other carnivorous Mollusca?	C-6 Repellents
	Is it more effective to elucidate and use deterrents for adults, juveniles or larvae?	C-6 Repellents
	What is their mode of action? Does the repellent/deterrent (conspecific or predator-derived) have broad spectrum or selective bioactivity?	C-6 Repellents
	What biological response does the repellent/deterrent elicit in COTS? E.g., aversive movement, physiological suppression including growth or reproductive maturation, spawning	C-6 Repellents
	What is the level of deterrent specificity for COTS?	C-6 Repellents, , C2 - Genetic approaches to COTS control
	What is the efficacy of COTS deterrents (pheromone or kairomone) in the field? Does efficacy change between seasons i.e., as predator behaviours change, during COTS spawning?	EIP-2 Semio-chemical Delivery, C-6 Repellents
	Is the deterrent effective over the full geographical range of COTS? i.e., is it effective across the entire GBR, Japan, etc?	C-6 Repellents
	Target life-stage	
	Could semio-chemicals be effective in disrupting/inhibiting/inducing egg/sperm maturation? There is evidence of chemical activation (1-Methyladenine)	EIP-3 Asynchrony, C-6 Repellents
	Could semio-chemicals be effective in disrupting/inhibiting fertilization? There is evidence of sperm/egg attraction to chemical cues but these have not been identified - would need to be highly specific given spawning occurs at the same time as coral spawning.	EIP-3 Asynchrony, C-6 Repellents
	What semio-chemicals are effective in changing behaviours of COTS larvae i.e., attractants such as foraging kairomones (prey)?	C-5 Attractants, C-6 Repellents; also pursued by Proximal Causes Program Area
	What semio-chemicals are effective in changing behaviours of COTS larvae i.e., avoidance allomones (i.e., from adult COTS or recently settled juveniles - competition allomones) that induce avoidance of unsuitable settlement substrate? Or settlement kairomones that induce settlement/metamorphosis on suitable cues (substrate)? Or pheromone attractants emitted by conspecific adults?	C-5 Attractants, C-6 Repellents; also pursued by Proximal Causes Program Area
	Could semio-chemicals be effective in changing behaviours of CCA-feeding COTS juveniles? No definitive evidence - need to consider CCA derived foraging kairomones	C-5 Attractants, C-6 Repellents; also pursued by Proximal Causes Program Area
	Could a semio-chemical or semio-chemical mimic interrupt the dietary transition of COTS? i.e., to delay transition into coral feeding adults, would need to be deployed in a very specific time frame ~6-8 months after spawning	C-5 Attractants, C-6 Repellents; also pursued by Proximal Causes Program Area
	Could semio-chemicals be effective in changing behaviours of coral-feeding sub-adult and adult COTS? Evidence of foraging kairomones, conspecific pheromone attractants, spawning pheromone attractants, conspecific alarm pheromones and predator alarm kairomones	C-5 Attractants, C-6 Repellents
	Could a COTS semio-chemical (kairomone) with specificity to attract parasite species with a very narrow host range, possibly limited to COTS, be applied as a control method?	Not pursued
	What is the chemical nature of COTS exogenous spawning trigger? Synchronous spawning maximises fertilization rates.	C-5 Attractants
	Could semio-chemicals be effective in disrupting synchronous spawning or inducing out-of-season spawning?	EIP-3 Asynchrony, C-6 Repellents
	Is the spawning semio-chemical species-specific and over what distance?	C-5 Attractants
	Is the spawning semio-chemical sex-specific?	C-5 Attractants
	Semio-chemical Formulation	
	Can and should the semio-chemical be applied as a slow-release biocontrol agent (i.e., year-round), as a fast-release single dose (i.e., during spawning), or in pulses (intermittent to reduce impacts on other species)?	EIP-2 Semio-chemical delivery, C-5 Attractants, C-6 Repellents
	Would the deployment of different release modes (of one or several semio-chemicals) enable targeting of multiple life-stages and behaviours?	EIP-2 Semio-chemical delivery, C-5 Attractants, C-6 Repellents

	Could COTS be triggered to produce altered (i.e., higher or lower) levels of conspecific cues?	C-5 Attractants
	How best can the semio-chemical be applied to ensure efficacy?	EIP-2 Semio-chemical delivery
	On what scale can the semio-chemical formulation be applied i.e., a broad scale, or local or individual?	EIP-2 Semio-chemical delivery
	What methods of formulation are suitable?	EIP-2 Semio-chemical delivery
	Could engineered microbes/animals could be used to produce and release peptide semio-chemicals at the desired rate over the desired time period?	EIP-2 Semio-chemical delivery, C-1 Genomic resources
	Could semio-chemicals be used in combination to enhance effectiveness i.e., a foraging kairomone + conspecific aggregation pheromone?	C-5 Attractants, C-6 Repellents
	Chemoreceptors	
	Can we exploit the COTS genome and their behavioural responses to pheromones or kairomones to identify target chemoreceptors?	EIP-4 Genome pipeline, C-1 Genomic resources, C-5 Attractants
	Can COTS chemoreceptors be exploited? i.e., can we identify receptor-specific ligands from both interspecies and intraspecies sources. Could these chemoreceptors be used to identify signalling functions of metabolic intermediates?	EIP-4 Genome pipeline, C-1 Genomic resources, C-5 Attractants
	Using knowledge of COTS chemoreceptors, could target-specific molecular bioassays be developed for rapid screening of semio-chemicals (natural and synthetic mimics)? Given that many chemoreceptors remain functionally un-annotated this would require extensive research to identify and characterise chemoreceptors. Could we produce recombinant chemoreceptors to rapidly identify and characterize semio-chemical ligands?	EIP-4 Genome pipeline, C-1 Genomic resources, C-5 Attractants
	Is it more effective to elucidate chemoreceptors for adults, juveniles or larvae?	C-5 Attractants
	Will genetic mutations of target-specific chemoreceptors abolish activity?	EIP-4 Genome pipeline, C-1 Genomic resources, C-5 Attractants
	Reef Prioritisation	
	Can semio-chemicals help to identify which reefs should be the focus of culling efforts? i.e., a COTS-specific chemical biomarker such as that used to induce aggregations; possible candidates include: saponins, given the specificity of some; secreted proteins - these compounds are continually/regularly secreted (i.e., not under stress) - so looking for presence vs absence.	Not pursued
	Could presence/increases in concentrations of specific semio-chemicals be used to monitor COTS numbers in the longer term? i.e., automated, unmanned, remote sensing of key semio-chemicals as an early warning system for future outbreaks?	Not pursued
	Scale of application	
	Could semio-chemicals be broadly applied on priority reefs? i.e., would require a long half-life of the semio-chemical, would need to be COTS-specific.	EIP-2 Semio-chemical delivery
	Will environmental change (related to climate change) impact semio-chemical efficacy rendering them less effective as COTS control agents? Especially important to consider if activity of semio-chemical is seasonal	Not pursued
	Does pollution/sediment/nutrient loading affect efficacy of semio-chemicals? Particularly relevant to larval phase.	Not pursued
	Manage population thresholds	
	On those reefs where culling has returned COTS numbers below reproductive (3 COTS ha-1)/ecological (4-5 COTS ha-1) thresholds, could predator kairomones or alarm pheromones be used to ensure continued and sustained population suppression? i.e., mimic predator odours that alter behavioural/phenotypic/physiological traits leading to sub-optimal performance of the prey, i.e., slow growth and delayed maturity	EIP-2 Semio-chemical delivery
	What is the best time to deploy semio-chemical attractant biocontrols to ensure optimal results? i.e., attractants could be deployed as baits/lures during an outbreak to complement current culling efforts	EIP-2 Semio-chemical delivery

	What is the best time to deploy semio-chemical repellent/deterrent biocontrols to ensure optimal results? i.e., used during non-outbreak periods to i) discourage aggregation formation especially at key times such as COTS spawning, ii) to disrupt/disperse aggregations at the outbreak initiation phase or ii) during conditions considered stressful to corals i.e., coral bleaching.	EIP-2 Semio-chemical delivery
	Augmentation of current culling methods	
	On those reefs where culling is deemed necessary, could semio-chemicals be used to enhance culling success? i.e., pheromone or foraging kairomone attractant to lure COTS into an area away from the reef substrate for easy access. Note this may prove useful on reefs where the outbreak is in the later stages and many individuals are seeking prey.	EIP-2 Semio-chemical delivery
	Could a pheromone be used to deliver a lethal agent (either chemical toxicant or biological agent)? i.e., a lure and kill technology would replace the need for divers and single injections. Note this would have to be highly COTS-specific - or a level of acceptable collateral damage to other species be established.	Not pursued
	Could a COTS-specific pheromone (i.e., will not impact on other echinoderms) be modified to have both attractant and toxic properties and applied *in situ*? i.e., replace the need for divers and single injections. Note this would have to be highly COTS-specific - or a level of acceptable collateral damage to other species be established. The semio-chemical would need to be amenable to modification or synthesis.	Not pursued
	Could a structural analogue (mimic) of a confirmed pheromone be used to block the semio-chemical receptor and alter COTS behaviour? Need to ensure specificity of the mimic.	Not pursued
	On those reefs where culling is deemed necessary, could semio-chemicals be used to enhance culling success? i.e., predator kairomone to flush COTS from cryptic sites for easy access by SCUBA. Note this may only prove useful on reefs where the outbreak is in the initial stages and many individuals, including sub-adults are cryptic - or would animals just retreat further into the reef structure?	EIP-2 Semio-chemical delivery
	Could a more potent structural analogue (mimic) of a confirmed semio-chemical deterrent be developed and alter COTS behaviour?	Not pursued
	Chemical profile of COTS	
	Does the chemical profile of COTS change across the life-stages? Could mining of the COTS metabolome assist in the identification of functional semio-chemicals?	Not pursued
Microbial agents (Høj)	Would pathogens and parasites (e.g., *Vibrio* species, *Orchitophyra stellarum* (ciliate)) be suitable as a microbial biocontrol agent for COTS?	Not pursued
	Would viruses (e.g., Parvoviridae, Nudiviridae) be suitable as a microbial biocontrol agent for COTS?	Not pursued
	Would symbiotic bacteria (e.g., *Spiroplasma*) be suitable as a microbial biocontrol agent for COTS?	C-3 Symbiont
Genetic biocontrol (Edwards)	Would sterile/Incompatible release program be suitable as a genetic biocontrol tool for COTS?	C2 - Genetic approaches to COTS control
	Would a COTS gene drive be suitable as a genetic biocontrol tool for COTS?	EIP-4 Genome pipeline, C-1 Genomic resources
	Would gene silencing be suitable as a genetic biocontrol tool for COTS?	Not pursued

4.2 Research Opportunity scoping

To discuss the gap analysis and associated next steps for the development of Research Opportunities, an informal meeting of the Program Area was held on 22 December 2020 (via Zoom) and attended by the leaders of each control type (see ***Table 4.2***). This was followed by the second formal workshop of the Program Area held on 21 January 2021 (via Zoom) and attended by all Program Area team members (see ***Table 2.1***). During this workshop, the

leaders of each control type discussed the identified key knowledge needs within their respective gap analyses, and together with the team identified and developed specific Early Investment Proposal and Research Opportunities to meet these knowledge needs. This resulted in a total of four Early Investment Proposals (EIP) and seven Research Opportunities (RO), summarised below (***Table 4.3***).

Table 4.3 Summary of Early Investments Proposals (EIP) and Research Opportunities (RO) that address knowledge needs identified for the six different control types and considered of highest importance by the Program Area team.

Control type	EIP or RO	Title	Aim
COTS control program	EIP 2 (See Semio-chemicals)	n/a	n/a
Water quality improvement programs	EIP 1	Building the evidence base for land management improvement influencing COTS population outbreaks	To leverage existing eReefs model outputs and water quality guidelines to assess whether improvements in land management are likely to deliver water quality improvements in the initiation zone for outbreaks of Pacific Crown-of-Thorns Starfish (COTS, *Acanthaster cf. solaris*).
Predators and coral-symbiotic fauna	C 4	The Giant Triton: does it have what it takes to be a biocontrol agent of the Crown-of-Thorns starfish?	To investigate Giant triton as an indigenous conservation biocontrol agent against COTS.
	C 8	Controlling outbreaks of the Pacific Crown-of-Thorns Starfish (Acanthaster cf. solaris) through identifying highly connected reefs for spatial management plans	To examine the effects of alternative spatio-temporal zoning arrangements on COTS population outbreaks in the GBR Marine Park.
Semio-chemicals	EIP 2	Deployment of semio-chemical biocontrol agents to manage COTS populations	To develop hydrodynamic models to understand the spatial and temporal footprint of semio-chemical delivery around reefs, and, based on these, review delivery strategies and systems for semio-chemical biocontrol of COTS, building on applications developed for other aquatic organisms.
	EIP 3	Disrupting reproductive synchronicity in COTS	To confirm the recombinant COTS RGP has gamete-releasing bioactivity by testing on male and female COTS, prior to, and during the spawning season.
	C 5	The search for Crown-of-Thorns starfish pheromones: modifying conspecific behaviour to control outbreaks.	To identify COTS pheromones capable of attracting conspecifics.
	C 6	Revealing the nature of the Giant triton's 'landscape of fear'	To identify kairomone deterrents capable of disrupting normal COTS behaviours.
Microbial agents	C 3	*Spiroplasma*-related symbionts: potential agents for targeted delivery of genetic COTS control?	To develop culture methods and genetic information for a bacterial symbiont (*Spiroplasma*) present in gonads and the digestive system of COTS, which has potential use as a targeted genetic vector for COTS control.
Genetic biocontrol	EIP 4	COTS genome database and analysis pipeline	To provide the data storage and IT capability to integrate all available COTS genomic data into the database and pipeline.
	C 1	Further development and delivery of COTS genomics resources	To substantially improve existing COTS genomic resources by: (1) improving the genome assembly, (2) identifying the function of more genes, (3) understanding within-species genetic variation, and (4) understanding between-species genetic variation.
	C 2	Genetic approaches to COTS control	To develop components of an area-wide management strategy for COTS using: (1) sterile male technology, and (2) mating disruption.

4.3 Research Opportunity assessment

Research Opportunities were assessed independently by all members of the Population Control Program Area. Similar to other Program Areas, team members independently scored all the Opportunities across standard Evaluation Criteria (***Table 3.1***) using an online survey tool. The outcomes of these assessments were discussed on 26 February 2021 (via Zoom) at a workshop with members of the Population Control Program Area. At the workshop, the team 1) reviewed the Research Opportunity Assessments; and 2) started to build a narrative for the Program Area Research Opportunities.

By virtue of the objective of the Program Area, i.e., '[…] *innovation in the control of COTS population outbreaks* […]', most Research Opportunities scored high to very high in innovation (***Figure 4.1***). However, this did not necessarily translate into high scores for path to impacts, ability to supress outbreaks and additional ecosystem and socioeconomic co-benefits. These relatively lower scores would have been, at least in part, due to the very fact that most Research Opportunities were developed as innovations (see also high scores for innovation in ***Figure 4.2***), and by definition would not have had outcomes that could have been clearly defined and assessed. Synergies across most Research Opportunities were very high, a clear result from the team collaborating within and across Program Areas to develop these Opportunities. Note also that the variation in scores for each of the criterion and most Research Opportunity was large, likely reflecting a varying understanding of the assessment criteria and/or Research Opportunities among team members.

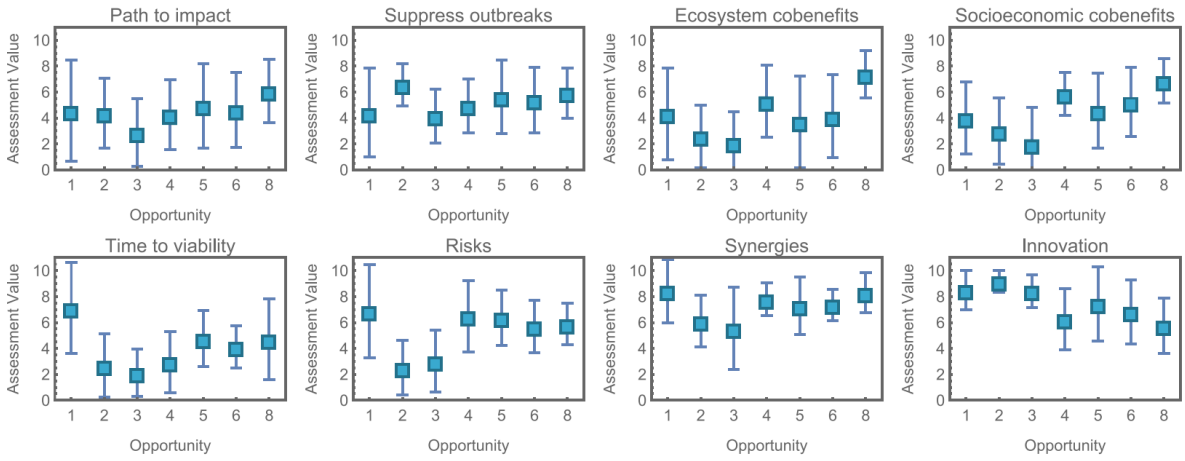

Figure 4.1 Assessments of the seven Population Control Research Opportunities across each Evaluation Criteria (all except research and implementation costs). Values are weighted means. Error bars represent standard deviation and are provided to give an indication of range of responses.

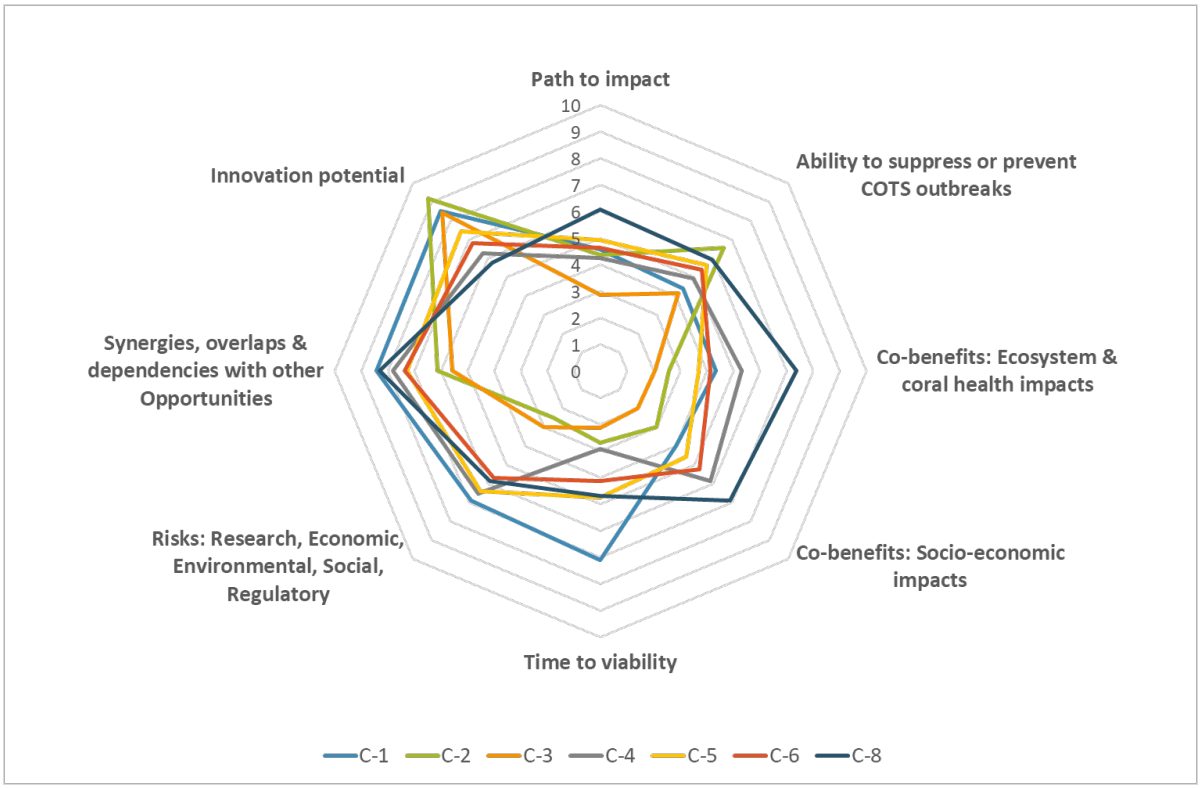

Figure 4.2 Spider chart highlighting differences in the weighted means of assessments against Evaluation Criteria across the seven Population Control Research Opportunities.

Following the discussion of the outcomes of the Research Opportunity assessments, the Population Control Program Area team continued to discuss each Research Opportunity in the context of the following categories, whether it was:

- 'Must have' – the future control of COTS outbreaks would not be achieved without it;
- 'Should Have' – the future control of COTS outbreaks would be diminished without it;
- 'Nice to Have' – it was not necessary but could be useful.

The outcomes of this discussion and overall workshop were summarised into a draft narrative for the Population Control Program Area. In this narrative, we also included the Early Investment Proposals as they formed critical components of the overall portfolio of Research Opportunities developed by this Program Area. For example, the Research Opportunities C 5 (Attractants) and C 6 (Deterrents) were reliant on the Early Investment Proposal EIP 2 (Delivery). This narrative was reviewed by all Program Area team members and finalised for submission to the CCIP Program Director and Steering Committee by the Program Area lead. This narrative is provided next.

4.4 Recommendations on priority Opportunities

The Population Control Program Area conducted 'a comprehensive review for innovation in the control of COTS population outbreaks, as part of an integrated pest management

strategy to protect live hard coral on the Great Barrier Reef'. The Program Area is a core component of the CCIP focussing on innovation (i.e., step-change) in the control of COTS population outbreaks. Building on recent comprehensive reviews (Hewitt and Campbell 2020; Høj et al. 2020), it developed Early Investment Proposals and Research Opportunities across three currently used control methods and three potential future biocontrol methods (**Table 4.3**; **Figure 4.3**).

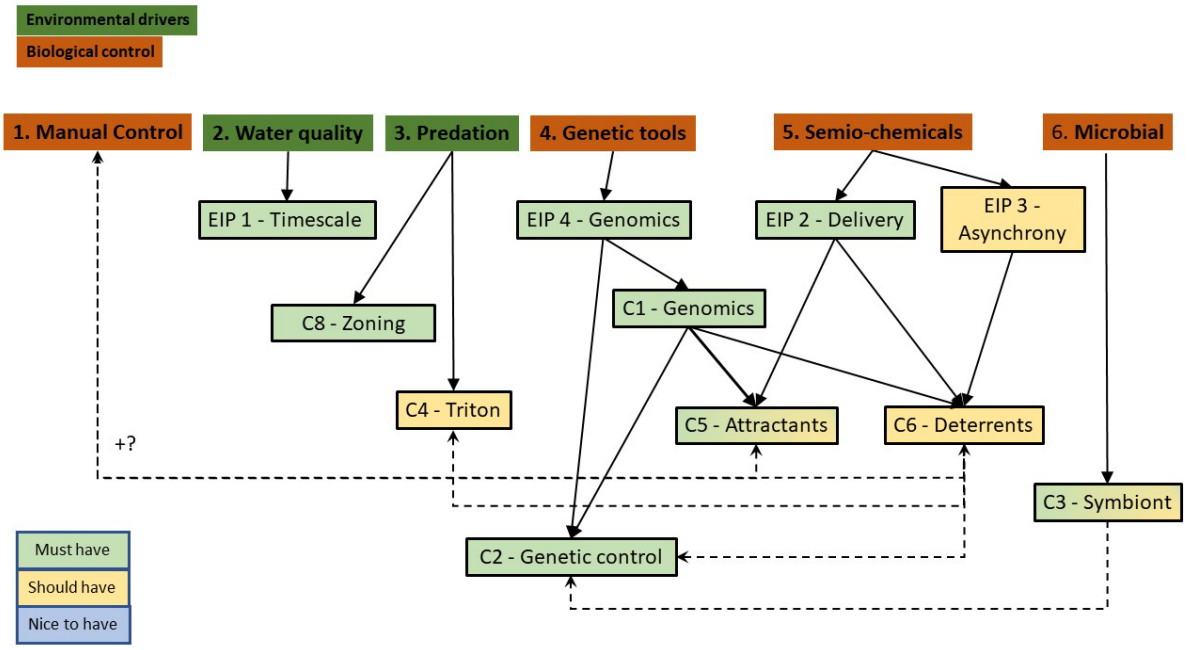

Figure 4.3 Linkages between the Early Investment Proposals (EIP), the Research Opportunities (C1 – C8), across the six COTS control types considered in the Population Control Program Area. Colours indicate 'must have', 'should have' or 'nice to have', or a combination of these if there was no agreement.

Current COTS control methods on the GBR comprise (1) manual COTS control, (2) water quality improvement, and (3) management of predators through zoning, threatened species and fisheries management. First, **manual COTS control** is based on ecologically and operationally based IPM approaches, with the current iteration of the program able to reduce COTS densities and reduce larger size classes of COTS at priority reefs (Hewitt and Campbell 2020). It is a relatively mature technology where the level of knowledge and documentation on the outcome of control efforts is currently much higher than for other current control methods (Fletcher et al. 2020; Westcott et al. 2020). No gaps or opportunities were identified for this control method within this Program Area, aside from refinement through integration with other control methods considered here (Høj et al. 2020).

Second, **water quality improvement programs** have been implemented since 2003 to protect the GBR from diffuse-source pollution from agricultural land uses (The State of Queensland and Commonwealth of Australia 2003). The purported link between elevated terrestrial runoff and COTS outbreaks has since become a central argument for policy and investment (Commonwealth of Australia 2018). While ongoing water quality monitoring demonstrates some positive results for inshore water quality in the Great Barrier Reef for the 2019–20 sampling period, sustained improvements in the marine water quality of the inshore reef have not yet been observed (Waterhouse et al. 2021). Hence, water quality

interventions, as they have been implemented thus far, cannot currently be solely relied upon for reducing COTS densities or population outbreaks (Westcott et al. 2020). Early investment in the low-cost (<$30K) desktop study (**EIP 1 – Water quality**) would inform COTS management, first by providing rapid evidence of the likely efficacy of existing ReefPlan targets and catchment regulations to influence water quality in the COTS outbreak initiation zone, and second by highlighting remaining questions regarding the link between land management and COTS outbreaks that may be addressed by other opportunities.

Third, **Marine Protected Area (MPA) zoning** has been a key component of GBR management since 1981. Although the 2004 zoning was not designed with management of COTS outbreaks in mind, unfished reefs have lower COTS abundance, density and frequency of outbreaks, as well as reduced impacts of COTS predation, compared to fished reefs (Sweatman 2008; Mellin et al. 2016; Vanhatalo et al. 2016; Westcott et al. 2020; Kroon et al. In review). The mechanistic basis for these zoning effects is still poorly understood but are likely to be related to more or less complex trophic cascades associated with fishing and affecting COTS predation (Kroon et al. in review). Close to 100 species of coral reef organisms consume planktonic and settled life stages of COTS (Cowan et al. 2017b), including 80 coral reef fish species from 17 families (Kroon et al. 2020). Both predator conservation and augmentation strategies could be brought to bear in COTS control (Høj et al. 2020), and two opportunities along these lines were developed:

- An evaluation of alternative spatial zoning arrangements, specifically for reefs integral in COTS connectivity networks, and whether this would contribute to maximising the potential for future prevention of COTS outbreaks by 2040 (**C8 – Zoning**). This was universally agreed as a ‘must have’. The social risks of exploring alternative zoning needs to be assessed in parallel; additional synergies with DSM Clusters 2 and 3, and potentially with PC 9 and 10 (quantifying and modelling predation).
- Further investigations on using Giant triton as an indigenous conservation biocontrol agent against COTS (Hall et al. 2017a) (**C4 – Giant Triton**). This was considered to have many uncertainties on the path from research (e.g., closing of life cycle) to application (e.g., benefits to COTS control). Arguments for ‘should have’ include natural biocontrol agent that could be deployed as part of a control toolbox. Proposed steps to scale and de-risk this 3 yrs., ~$500K opportunity include (i) modelling potential benefit of triton restocking (PC 10); (ii) monitoring triton abundance using eDNA (MS 14) and COTS predation rates (PC 9), and (iii) pilot study to observe COTS response to triton in the field.

The three potential biocontrol methods considered include (4) **genetic biocontrol**, (5) **semio-chemicals**, and (6) **microbial control**. Genetic biocontrol approaches have the potential to provide high degrees of COTS specificity and control of spread, depending on the construct. Formalised environmental risk assessments as well as legal, ethical and social considerations in the Australian context need careful evaluation at an early stage. While the COTS genome has been described (Hall et al. 2017b), only limited work has been done to identify candidate genetic mechanisms and processes that could be targeted for editing (Høj et al. 2020). The low-cost ($20K) project (**EIP 4 - Genomics**) to include COTS genomic data into the Australian Research Data Commons was considered a ‘must-have’. It will consolidate and make available genomic data resources generated by COTS research and help to expedite the full range of fundamental biological and ecological research that can benefit from genomic data. In addition, the laboratory project (**EIP 3 – Asynchrony**) provides

an early assessment of inducing asynchronistic or out-of-season broadcast spawning in COTS by turning on a starfish specific neuropeptide. Two additional opportunities were developed:

- Improving existing COTS genomic resources (**C1 – Genomics**) will provide the foundation for any genomic methods that may become part of COTS control. It will broadly enhance our understanding of COTS biology and ecology, and could identify opportunities for genetic, chemical, or biological interventions that assist in COTS management. Agreed that this was a 'must have' with low social and regulatory risk. The project needs support from the Biology and Ecology Program Area; and explore additional synergies with PC 1 (COTS larval connectivity).
- Developing genetic approaches to COTS control (**C2 – Genetic Control**) including (1) sterile male technology, and (2) mating disruption. The project is separate from C1 as both approaches have very different social and regulatory risks. For C2, an initial feasibility and risk analysis is a 'must have' if there is an interest and appetite for pursuing innovative genetic control in COTS, followed by a staged approach. This would include a modelling exercise to determine release and efficacy; potential synergies with DSM-10. Before progressing, the mating disruption approach needs to be evaluated as a delivery system as part of **EIP 2 – Delivery** (see below).

The use of semio-chemicals in terrestrial insect pest management has become increasingly common. In the context of COTS control, semio-chemicals could be used to either attract COTS to a specific location or trap to facilitate culling or to disperse COTS to protect specific sites or prevent spawning aggregations (Høj et al. 2020). While demonstrated in controlled laboratory settings (Hall et al. 2017b), uncertainty exists around how semio-chemical spread around reefs due to, e.g., currents and tides, would influence the propagation of the signal. The development of a strategy for implementation and operationalization is critical to evaluate the feasibility of semio-chemical delivery in tropical marine environments, and their efficacy in contributing to COTS control by 2040 (Høj et al. 2020). The desktop project (**EIP 2 - Delivery**) would inform the feasibility of deploying and integrating semio-chemicals into a COTS IPM and was agreed to be a 'must-have'. The project would provide improved understanding of spatio-temporal footprint of semio-chemical delivery around reefs and propose targeted delivery strategies and systems. Two additional opportunities were developed:

- Further investigations on COTS attractants (**C5 – Attractants**) to improve culling efficiency and reduce revisitation frequency, as well as for deployment in baited traps. This opportunity was considered to have the potential for a step-change in COTS control, albeit with many research uncertainties and a pathway to impact that is unclear for a $1.4M, 3-year project. Arguments for 'must have' include potential step-change in control assuming effective delivery strategies, while for 'should have' include impact on efficiency of manual control program may not be huge. Proposed steps to scale and de-risk this opportunity include (i) first conduct feasibility study on semio-chemical delivery and efficacy in COTS control (**EIP 2 - Delivery**); (ii) develop and apply clear stage-gates in the context of CCIP goal and vision; and (iii) merge with C6 for cost-savings. Also explore potential synergies with PC 3 (Peter Pan effect).
- Further investigations on COTS deterrents (**C6 – Deterrents**) to disrupt normal COTS behaviour including spawning aggregations. This was also considered to have the

potential for a step-change in COTS control, although with lack of consensus on path to impact. Arguments for 'should have' include that deterrent work is further from impact than proposed attractant work. Proposed steps to scale and de-risk this 3 year, $800K opportunity include (i) first conduct feasibility study on semio-chemical delivery and efficacy in COTS control **(EIP 2 - Delivery**); (ii) develop and apply clear stage-gates in the context of CCIP goal and vision; and (iii) merge with C5 for cost-savings.

Finally, the use of microbial pathogens for biological control most often involves culture and broadscale release of viral or bacterial pathogens, or parasites, to control COTS populations (Høj et al. 2020). However, no viral pathogen of COTS is known, and no echinoderm cell line is available for large-scale virus production. Likewise, no primary bacterial pathogen (i.e., causing disease in non-stressed individuals) or suitable species-specific parasite is known. These factors, combined with the associated risks of this strategy in a marine environment, mean that no proposal is put forward for developing a strategy based on a horizontally transmitted microbial pathogen for COTS control. Instead, the proposed opportunity (**C3 – Symbiont**) would develop culture methods and genetic information for a bacterial symbiont (*Spiroplasma*) present in gonads and the digestive system of COTS, which has potential use as a targeted genetic vector for COTS control. As a potential delivery system, it is a 'must have', however, given its specificity to COTS and transmission mode is currently unknown (but to be evaluated by the project) combined with significant social risks it could be considered a 'should have'. This project was developed in consultation with C2 and C3, with all three having very different risk profiles and methods for COTS control.

5 RESULTS – MONITORING AND SURVEILLANCE

The effectiveness and efficiency of the COTS Control Program will ultimately be dependent upon its capacity to use information collected through monitoring and surveillance (MS) in order to deploy its control resources at the locations where they will have the greatest impact in achieving Program objectives, and, to do so at the time that maximises the probability of success. Doing this requires up-to-date information on the distribution and density of COTS and of the distribution of the assets being protected, i.e., coral cover and reef condition, at the scales of individual sites and reefs, across reefs in a region, and across the Great Barrier Reef. The Research Opportunities in the MS Program Area seek to meet the Monitoring and Surveillance needs of the COTS Control Program. They draw on a recent review of the COTS Control Program's monitoring needs and provide the statistical, technological and analytical foundations for the implementation of the recommended strategies. Critically, they would revolutionise the scope, scale and quality of the data underpinning decision making in the COTS Control Program.

5.1 Gap analysis

At the outset of the work the Monitoring and Surveillance Program Area Team adopted the following as its mission:

- First, conduct a systematic assessment of the monitoring and surveillance needs of the COTS Control Program now and into the future. This included identifying the role of monitoring and surveillance in the program and the monitoring and surveillance strategies that could transform COTS control by providing timely and reliable data on relevant metrics (e.g., COTS abundance and distribution, coral assets, reef health), do so across the necessary scales (from the site to GBR scale), and in all phases of the outbreak cycle (from inter-outbreak baselines, to early warning of incipient outbreaks to monitoring outbreak progress and decline).
- Second, conduct a comprehensive review of existing and upcoming technologies/systems that could address these needs. This included a qualitative but in-depth assessment of the level of maturity, technical feasibility and risk, deployment strategies and cost of these technologies/systems.
- Third, assess the balance of costs, benefits and risks of these technologies and prioritised them for further investigation in the subsequent R&D program.

The work of the team was greatly simplified by research that was conducted under the NESP Tropical Water Quality Hub's COTS Integrated Pest Management Research Program. A report by Fletcher et al. (2020) provided a detailed description of the decision processes, and the information on which those decisions are based, in the COTS Control Program. In a separate report, Westcott et al. (2021a) reviewed the performance of the program to date and, based on this data, assessed the future potential of the program to operate at the scales required to stop, or effectively moderate at the GBR-scale, future outbreaks. In doing so this report identified critical data needs to achieve this necessary goal. In a third report, Høj et al. (2020) reviewed potential future control technologies. This report provided the team with guidance on what these technologies might look like and how they might be used, which allowed consideration of any relevant monitoring and surveillance implications. Finally, and most significant for the Monitoring and Surveillance Team, was Westcott et al. (2021b)'s

comprehensive review of the monitoring and surveillance needs of the COTS Control Program going forward. This report identified the needs, reviewed the current and future technologies, and based on these assessments developed monitoring and surveillance strategies that would enable comprehensive monitoring and surveillance at appropriate scales to meet the challenge of future outbreaks.

The members of the Monitoring and Surveillance Team reviewed these documents and any other material they felt was relevant. There was verbal agreement that combined these reports effectively contributed to the Team's review and analysis tasks and provided the strategic framework for the implementation of COTS monitoring and surveillance as part of the COTS Control Program. This meant that the Team started their work with a clear strategic context for what information was needed, at what spatial and temporal scales it was required, how it might be collected, and of the decision and operational context into which the activities would have to be integrated. This allowed the Team to identify any additional Research Opportunities and then to consider what research and development gaps had to be filled in order to implement the strategies outlined by Westcott et al. (2021b).

The process of identifying the key knowledge and technology gaps was conducted by considering the COTS Control Program's information needs in each phase of the outbreak cycle (Westcott et al. 2021b) and how this information would be used. This was used to then determine what specific question needed to be addressed and the type of data required for this, how the information would be used and by whom, the spatial and temporal scales at which it needed to be collected, and what this meant for the most appropriate technology for its collection given the operations of the Control Program. The results of this process are summarised in ***Table 5.1***.

Table 5.1 Monitoring and Surveillance Gap Analysis. Candidate technology "TUV/SV/AUV" refers to image-based monitoring technologies such as Towed Underwater Vehicles (TUV), Surface Vehicles (SV) or Autonomous Underwater Vehicles (AUV).

Monitoring Need	Outbreak Phase	Information or Technology Need	Candidate Technology
Trends in distribution COTS abundance	Inter-Outbreak	Baseline data on distribution, abundance and population size structure of COTS collected at site, reef, regional, GBR scales	TUV/SV/AUV Diver Based eDNA
	Initiation and Establishment	Detect changes in COTS density and abundance that outbreak signal initiation or need for management, delimit initiating outbreak	TUV/SV/AUV Diver Based eDNA
	Outbreak	Delimit outbreaks, describe age/size structure across the outbreak, describe distribution and abundance to inform management, tracking of these through outbreak	TUV/SV/AUV Diver Based eDNA
	Post-Outbreak	Document decline of outbreak, return to Inter-outbreak monitoring	TUV/SV/AUV Diver Based eDNA
Population reproductive condition	Inter-Outbreak	Baseline population reproductive parameters	TUV/SV/AUV Diver Based
	Initiation and Outbreak	Detection of deviations from inter-outbreak period that heralding spawning	TUV/SV/AUV Diver Based
	Outbreak	Monitor reproductive status of sites, trigger management	Semio-chemical detectors
	Post-Outbreak	detect changes leading to decline	TUV/SV/AUV Diver Based

			Semio-chemical detectors
Trends in larval distribution and abundance	Inter-outbreak	Larval distribution and dispersal, description of phylogeography and connectivity within the GBR	eDNA Genomic Analyses
	Initiation and Establishment	Detection of deviation from baselines	eDNA Genomic Analyses
	Outbreak	Link larval plumes and hydrodynamic models to predict i) fertilization success and ii) source/sink reefs to provide early warning of likely areas of management need	Modelling
Juvenile settlement	Inter-outbreak	Baselines for juvenile settlement and abundance	Fine-scale surveys eDNA samplers
	Initiation and Establishment	Early detection of recruitment events that presage an outbreak	Fine-scale surveys eDNA samplers
Distribution and condition of coral assets	Inter-outbreak	Baselines for coral assets (type, cover etc), distribution and condition	TUV/SV/AUV Diver Based eDNA (P/A only)
	Initiation and Establishment	Trends in coral assets (type, cover etc), distribution and condition	TUV/SV/AUV Diver Based eDNA (P/A only)
	outbreak	Trends in coral assets (type, cover etc), distribution and condition	TUV/SV/AUV Diver Based eDNA (P/A only)
	Post-outbreak	Trends in coral assets (type, cover etc), distribution and condition	TUV/SV/AUV Diver Based eDNA (P/A only)
Distribution and trend in reef condition and community structure	Inter-Outbreak	Baselines in general reef condition, and community structure – focus on fish and large invertebrates	TUV/SV/AUV Diver Based eDNA (P/A only)
	Initiation and Establishment	Trends in general reef condition, and community structure – focus on fish and large invertebrates	TUV/SV/AUV Diver Based eDNA (P/A only)
	Outbreak	Trends in general reef condition, and community structure – focus on fish and large invertebrates	TUV/SV/AUV Diver Based eDNA (P/A only)
Biophysical Pre-Conditions for outbreak initiation	Inter-outbreak	Monitor environment factors hypothesis to influence outbreak initiation: water quality including key nutrients, runoff, and other factors upwelling, water temperature etc.	Various RIMReP, remote sensing, water quality monitoring
Improved in-water data collection	All Phases	Ensure cull data collection provides high quality and reliability information (# culled, size, depth, location, date/time, etc) while reducing data collection overheads for divers	Data collection technology
Improved vessel reporting	All Phases	Integrated system for reporting vessel activities	Informatics tools
Data Management and Handling	All Phases	Data management systems for current and new technologies from point of collection through to upload, QC, analysis and interpretation	Informatics tools

5.2 Research Opportunity scoping

The Gap Analysis process made it possible to describe the structure of the research that would be carried out by the Monitoring and Surveillance Program Area, the linkages between different activities and how they fitted together to flow into the decision making of the COTS Control Program. Three key areas of activity were identified, Monitoring Design, Tool Development and Informatics and Data Use, and within these 1-3 key areas for research (***Figure 5.1***).

Team members then identified and developed specific Research Opportunities to meet these needs. Where there were clear opportunities to do so these Research Opportunities were merged into collaborative Research Opportunities. However, in two areas, Image-Based Monitoring and Cull Data Collection, the technologies proposed involved very different development pathways and had very different final capabilities. In these instances, separate Research Opportunities were developed in order to better judge the relative merits of the proposals.

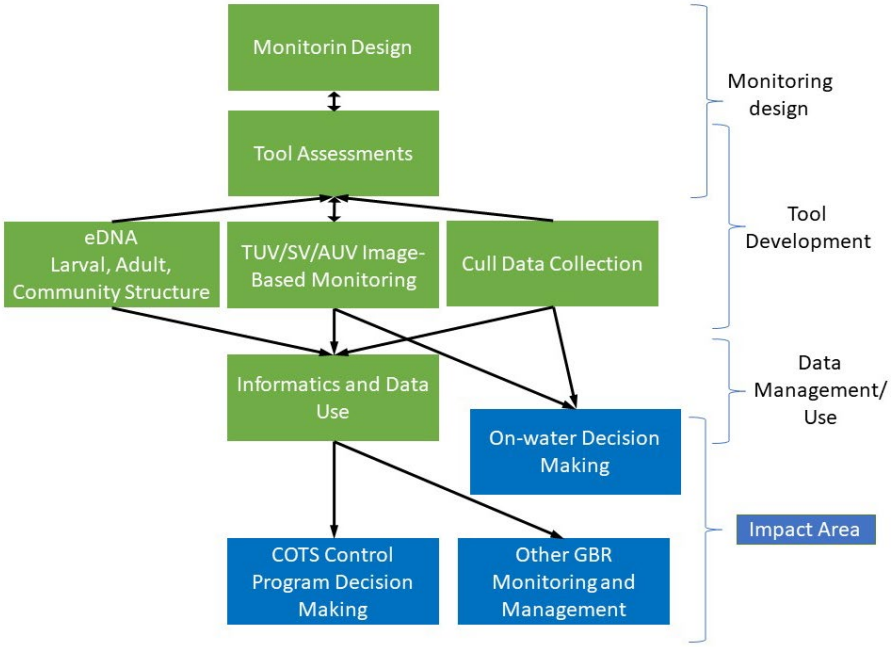

Figure 5.1 Schematic of the structure and linkages of the Monitoring and Surveillance Program's recommended research program. On the right the brackets represent the general research and development areas along with the impact area. The green boxes identify research needs or tools within those general areas.

In total 14 opportunities for research were identified, with these being refined down to 10 through merging of projects and rejection of projects (e.g., due to their being logistically too difficult to implement).

MS-1 COTS Monitoring Design: sample design for management decisions and science: This RO would develop and appropriate sampling design to underpin monitoring and surveillance for the COTS Control Program. This design would incorporate monitoring of COTS and the coral and other assets across all stages of the outbreak cycle to establish baselines, provide early warning of outbreaks, detect and monitor outbreaks and their progress, inform how Control is invested across the reef and through time, and assess Control performance. The program would be developed and implemented in collaboration with on-water operators and Control Program managers.

MS-2 Estimating and accounting for error in COTS monitoring for improved inference: This RO would assess the current and new monitoring tools, describing their errors and

performance under a variety of conditions. This information would allow a calibration of each tool enabling their integration into the monitoring activities of the Control Program.

MS–5 Operationalising and Implementing COTS eDNA monitoring on the GBR: This RO sought to initiate, operationalise and further refine an eDNA COTS monitoring strategy for early warning and detection of COTS larvae and post settled COTS.

MS-6 Operationalise Vertigo3 true-flight TUV for COTS use in GBR: This RO sought to develop an Image-based monitoring tool, Vertigo3 true-flight TUV, a sonar and vision-based robotic glider capable of rapid broadscale survey in high relief reef areas that performs tasks otherwise equivalent to manta tow, but more quickly, with better COTS detection rates, and with advanced skillsets such as COTS size estimates, geolocation of individual targets, simultaneous multi-target analyses (coral cover, habitat classification, feeding scars) and full archiving of imagery and metadata. This RO sought to complete a small amount of research and then to operationalise the glider for near-term deployment in COTS management in the GBR under CCIP. The Base Case project presented would have deployed advanced prototypes by the end of 2021 and fully ruggedised versions with the advanced skill sets by the end of 2022.

MS-7 Informatics systems for data management and real-time situational awareness for COTS monitoring program: This RO sought to develop the informatics systems that would manage and harness the large volumes of fine-grained video/image data produced by Image-Based monitoring tools (e.g., MS-6 and MS-8) to provide real-time analytics to inform management in the COTS Control Program. The RO would develop a hardware-agnostic underwater survey data management system able to ingest large imagery datasets, used machine learning (ML) models/workflows to understand marine ecosystems at reef to GBR scale (e.g., COTS population density and size structure, coral coverage, and reef/asset condition) and visualisation and analytics tools to allow non-expert and experienced teams to rapidly review analytics results.

MS-8 ReefScan-Transom – a visual survey system for COTS detection: This RO sought to develop an Image-based monitoring tool for COTS monitoring, 'ReefScan-Transom', part of AIMS' end-to-end monitoring system, called 'ReefScan'. 'ReefScan-Transom' would comprise i) a tender based, transom mounted, visual data collection system that used high-resolution optical cameras, ii) on-node Artificial Intelligence (AI) for the detection of COTS and other targets of interest, iii) an app based control system for viewing detections and entering metadata and other ancillary information, iv) more complex and off-node analysis conducted through the AIMS Research Data Platform, a cloud-based work-flow system for more complex image processing, AI based analysis and unified reporting.

MS-11. In-water data collection / wearable-tech: This RO sought to improve the quality and reliability of the critical cull data collected during culling dives. It sought to do this through the development of video-recording of each dive with Machine Learning used to identify and record data on each cull event. This would free divers of manual data entry and provide data on time, location (estimated from dive entry/exit points, cull times and a model of diver activity), depth and a tagged image corresponding to the moment of injection. Data would be automatically downloaded from devices (diver tech), transmitted ship-to-ship (comms hub in tenders, minus images), and ship-to-shore (back-to-base station on mother boat, minus images) for more detailed and automated analyses.

MS-12 Underwater human-machine interface for logging Crown-of-Thorns starfish cull events: This RO sought to improve the quality and reliability of the critical cull data collected during culling dives using a waterproof, depth rated handheld device for divers to manually, but simply, record COTS cull events. This device would have featured waterproof buttons for a diver to record events and a small waterproof display to give feedback. Bluetooth communications would be used to download recorded data to a database on the surface. The device would be fully enclosed and waterproof with wirelessly rechargeable batteries. The proposal built on an existing CSIRO NCMI underwater sensor system for low-power data collection and real-time communication.

MS-14 Environmental DNA survey of interspecies interactions to determine the drivers of COTS outbreaks: The RO was based on the hypothesis that predator removal was a potential driver of COTS outbreaks, and intended to use the eDNA detection of the presence and abundance of COTS predators on reefs as a means of surveillance for detecting incipient COTS outbreaks. To do this the RO would establish whether; i) predators can prevent COTS outbreaks by influencing spawning aggregations; limiting fertilisation success; and/or reducing the abundance of pelagic larvae and settled juveniles and adults, and, ii) plankton can drive COTS larval condition, survival and abundance, and ultimately successful recruitment into the settled population. This would be done using eDNA based methods.

MS-15 Operational modelling of COTS sources and risk from downstream recruitment, in-situ and in real-time, using the Vertigo3 glider's empirical data. This project sought to develop a probability mapping tool for locating COTS populations using Vertigo3 glider surveys integrated with scaled larval advection modelling that identifies settlement (forecast) and spawning (hindcast) locations to inform operations in the COTS Control Program on the GBR.

5.3 Research Opportunity assessment

The assessment of the Research Opportunities was based around a pre-workshop survey in which Monitoring and Surveillance Program Area team members independently scored their 10 Research Opportunities across standard Evaluation Criteria (***Table 3.1***). The outcomes of these assessments were discussed on 24 February 2021 (via Zoom) at a workshop with members of the Program Area. At the workshop, the team 1) reviewed the Research Opportunity Assessments; and 2) started to build a narrative for the Program Area Research Opportunities.

MS Research Opportunities scored, on average, >6 across most of the assessment criteria (***Figure 5.2*** and ***5.3***). The exception to this were scores for Socio-Economic Co-Benefits and Ecosystem Co-Benefits and to a lesser extent Synergies and Innovation, where scores were more variable. Across the different assessment criteria there was a general trend of Research Opportunities MS1 to 8 scoring similarly, and relatively highly, compared to ROs MS11-14, which tended to be more variable and to score lower. Not surprisingly, MS-11 to 14 were all Research Opportunities that were also considered "Nice to Have" and "Should Have". All ROs scored relatively highly for "Path to Impact", "Time to Viability" and "Risks" but there was greater variability, particularly amongst MS11 to 14, in the assessments for "Ecosystem Co-benefits", "Socio-Economic Benefits", "Synergies", and "Innovation".

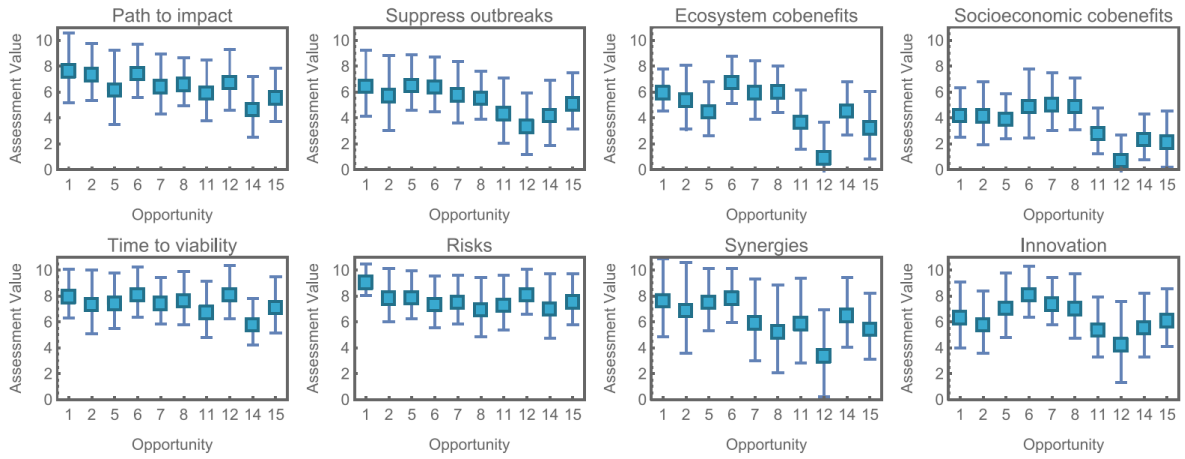

Figure 5.2 Assessments of the 10 Monitoring and Surveillance Research Opportunities across each Evaluation Criteria (all except research and implementation costs). Values are weighted means. Error bars represent standard deviation and are provided to give an indication of range of responses.

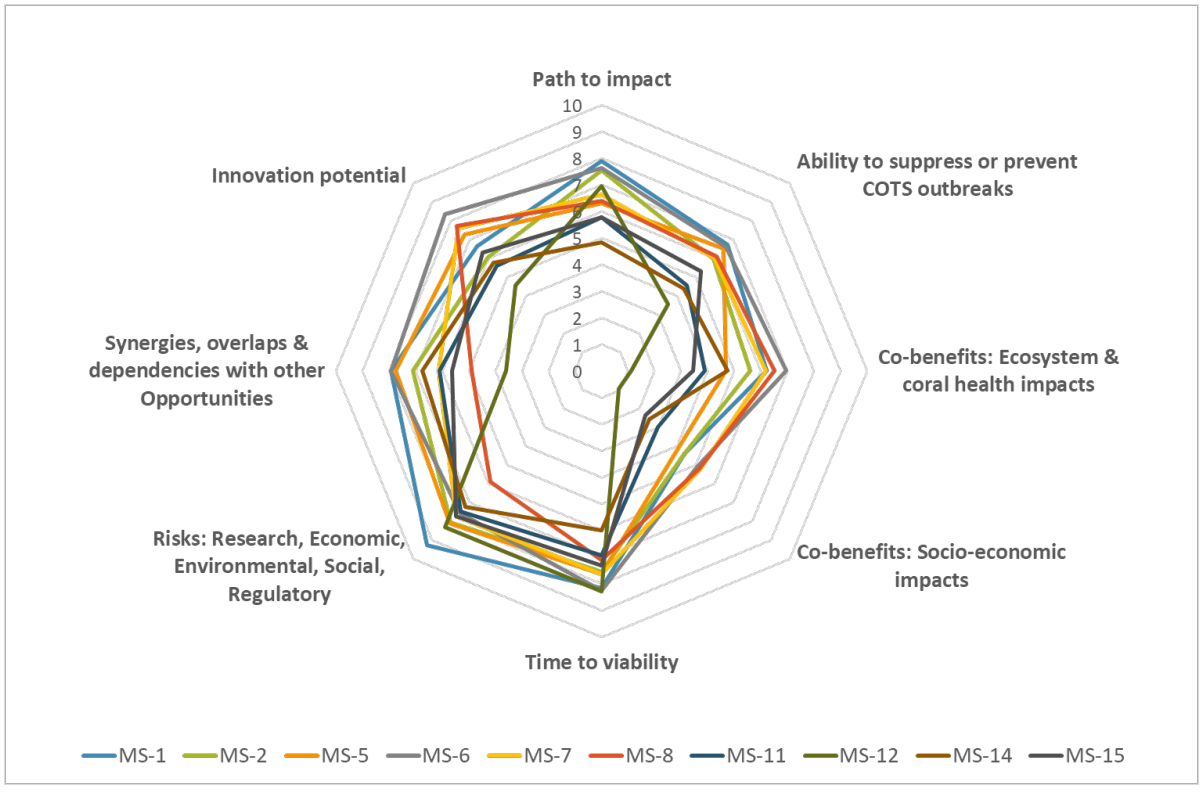

Figure 5.3 Spider chart highlighting differences in the weighted means of assessments against Evaluation Criteria across the 10 Monitoring and Surveillance Research Opportunities.

While the Team conducted the formal pre-assessment survey and the analysis of these results was presented and discussed in the first half of the workshop, they were not used explicitly as a basis for prioritising amongst opportunities in the second half of the workshop. There were a number of reasons for this. The most significant of these is that the ROs in the MS PA were explicitly conceived of as an integrated suite of projects designed to ensure that the COTS Control Program could implement Monitoring and Surveillance that would guide its decision making and do so at the scales that would enable success in meeting the challenge of future outbreaks. As such each project was designed to fill an identified data or capacity gap. This meant that there was no question of whether they fulfilled the objectives and values of the CCIP, contributed to improved COTS control, or fitted into the broader program – they were all explicitly designed to do these things. Instead, the relevant question was, how necessary were they to the successful implementation of the monitoring and surveillance program. As a consequence, the MS Team assessed the ROs on this basis.

While this was main reason for the pre-assessment not contributing to the discussions, there were also some additional factors. First the lack of time available to digest the results meant that it wasn't possible to give them full consideration. Second, across many measures there was very little variation between the ROs, reducing the discrimination possible with the scoring. Third, there was uncertainty about how consistently the questions had been interpreted and scored by team members. This is not a novel situation in expert elicitation processes and is sometimes addressed by conducting a second round of assessments, using the first to accustom participants to the process, the questions and to allow for discussion, with the second round being used to finalise their scoring (e.g., Hanea et al. 2018).

The assessment discussion of the team ultimately centred assessing each Research Opportunity on the basis of how necessary the resultant product would be to a successful Monitoring and Surveillance program. Each Research Opportunity was discussed in the context of the following categories, whether it was:

- 'Must have' – the future monitoring couldn't be implemented without it
- 'Should Have' – the future monitoring would be diminished without it
- 'Nice to Have' –it was not necessary for the future monitoring but could be useful

There was strong agreement that both Research Opportunities in the Monitoring Design area were 'Must Haves' as robust statistical design for data collection is an absolutely fundamental foundation underpinning the reliability of the data, its interpretation, and decision making in all outbreak phases, from early detection to outbreak decline (***Figure 5.4***). Robust sampling design (**MS-1 Monitoring Design**) would be foundational for any transformation in the COTS Control Program going forward and itself is founded on a good understanding of the performance of the tools being used to collect the data, their errors and performance under different conditions (**MS-2 Estimating and Accounting for Error**).

There was a consensus that some form of Image-Based monitoring was a 'Must Have'. Transformation of CCP will require monitoring not just of COTS but also of coral and reef condition at sites, reefs, across regions and across the GBR. Image-based monitoring tools will enable this by transforming the scale, scope, and quality of monitoring data collected and making this data collection cheap, rapid and almost comprehensive. Such tools will be fundamental to a performance step-change in the CCP and to GBR management more

generally. Two Research Opportunities were considered; one focused on a COTS Control purpose designed platform (**MS-6 Vertigo3**) and one focused on a more general monitoring platform (**MS-8 Reef-Transom**). The two platforms had very different use-cases and capabilities but could use the same data standards and protocols, and, could have robotic and data cross-compatibility. MS-6 was costed with implementation but could be scaled to a slightly higher cost than MS-8 if implementation was excluded. Decisions about investment (one or both) were considered to require formal assessments of their relative performance in meeting the COTS Control Program's monitoring needs and it was decided that this should include field trials. It was also decided that investment and funding should be staged based on meeting performance standards.

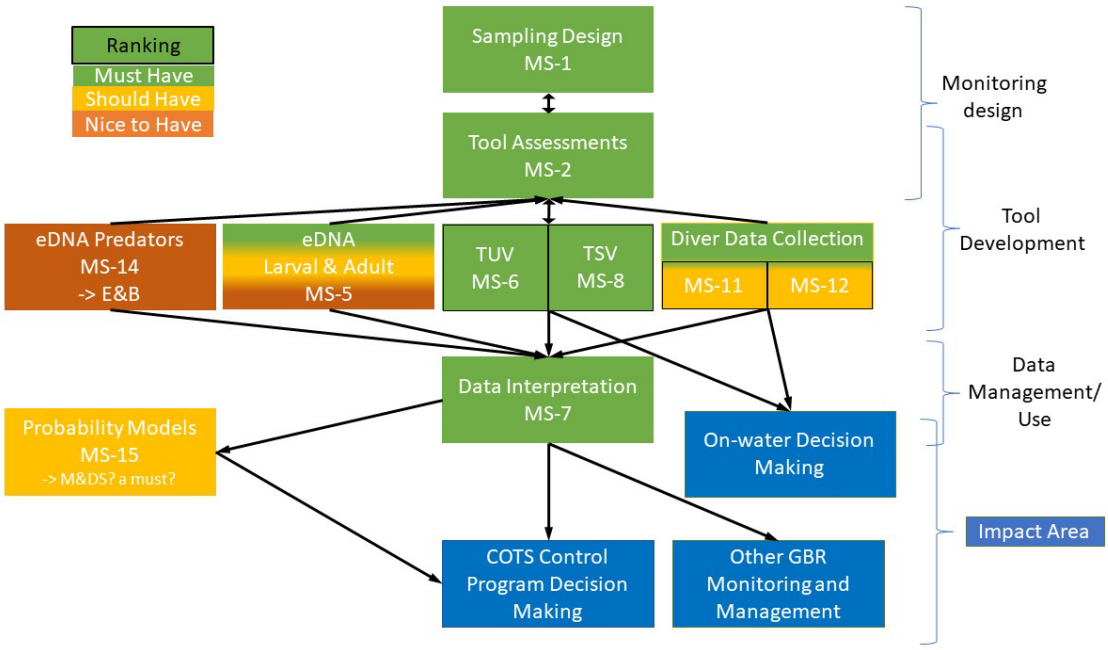

Figure 5.4 Research Opportunities mapped onto the Monitoring and Surveillance Program structure. Colour coding indicates the final assessment of each Research Opportunity. Multiple colours indicate Research Opportunities where there was disagreement over the final assessment.

There was not a consensus on **MS-5 Operationalising and Implementing eDNA**. The 'Must Have' case was based on the its potential for monitoring larval eDNA for early-warning and confirmation of the initiation box and of adult eDNA as a means of detecting low-density adult populations and monitoring threshold breaches. The case for 'Should/Nice to Have' was based on the assessment that not having eDNA tools would not prevent the MS program or the COTS Control Program from achieving a step change in performance, providing the early-warning service, or detecting low density populations. All these tasks could be effectively performed by an Image-Based Monitoring system (MS-6,7,8) making the eDNA method redundant in some instances. Furthermore, there was concern about the lack of confidence about i) larval detection site and settlement site (for off-reef sampling), and, ii) the relationship between larval/settler and adult densities (see also Biology and Ecology ROs). Similarly, there were concerns that; i) adult eDNA offered little if any advantage over existing and Image-Based tools and provides a narrower scope of data, ii) can be deployed with less confidence about sampling adequacy, iii) a lack of clarity about the management need for detecting very low-density adult populations, iv) the fact that it provides presence/absence data only and may have insufficient discrimination for quantification or

detecting threshold breaches, and, v) rapid DNA degradation appears to rule out any sentinel role. The recommendation was that any eDNA investment should be based on an assessment that it is providing management-relevant information not provided by other methods, can be readily implemented as part of the COTS Control Program, and that it's support should be staged. Ultimately opinion was divided equally between Must Have, Should Have and Nice to Have.

Irrespective of which Image-Based platform is ultimately used there will be a need for an underwater data management system that is designed to meet the COTS Control Program's specific needs and to do so on its specific timeframes. **MS-7 Informatics Systems** outlined a tool that managed data flows and storage, provided enhanced machine learning capabilities for image analysis, provided visualisation and analytics tools, and linked to other programs (e.g., RIMReP). This was considered a 'Must Have'.

The next two ROs, **MS-11 In-Water Data Collection** and **MS-12 Underwater Interface**, considered technology to automate and standardise data collection by divers in order to reduce errors during culling data collection. There was a lack of consensus about these Research Opportunities with opinions varying between 'Should Have' and 'Must Have'. The 'Must Have' case is based on the fact that data on numbers of COTS culled, their size, and their location on a reef is core information underpinning decision making in the CCP. This fundamental data is currently collected in a variety of ways, all of which are subject to error and mishap. These Research Opportunities sought to reduce the potential for these errors. The 'Should Have' case was based on a perception that reducing errors in cull data collection wouldn't have a significant impact on decision making. Of the two ROs presented MS-12 was the simpler and preferred option.

MS-14 eDNA Survey of Interspecies Interactions, focused on using eDNA to monitor COTS predator communities at reefs. This RO was considered to be relevant but more closely linked to BE than MS as its contribution was perceived to be most strongly linked to understanding rather than decision making. Consequently, this RO was ranked as 'Nice to Have' in the MS context.

MS-15 Probability Models, was judged as 'Should Have'. It seeks to use monitoring and connectivity data to predict where COTS risk will be highest in order to guide monitoring and control activities. This was judged to be a fundamentally important task for the CCP overall and one was strongly links to MS-1 or DSM. It was assessed as 'Should Have'.

5.4 Recommendations on priority Opportunities

The Monitoring and Surveillance Program Area Team recommends investment in the portfolio of research shown in ***Figure 5.5***. These projects should not be considered as independent pieces of work. Rather, they are designed to be the integrated solution to the problem of implementing an appropriately scaled monitoring program that will ensure the COTS Control Program can meet the challenge of the next COTS outbreak. This integrated package comprises a core program based on:

1. strong statistical underpinning for the monitoring design (MS-1), including assessment of the errors associated with the main monitoring tools employed by the

program (culling, Image-Based, eDNA) to guide their development and the design of the sampling approach (MS-2),

2. development of a key new monitoring technology (MS-6,7,8) that will supplement the monitoring data provided by cull divers, replace Manta Tows and transform the COTS Control Program by providing rapid, economical, simple, comprehensive and reliable monitoring of COTS and coral on reef perimeters,

3. development of supplementary validation and potentially early warning capacity in the form of eDNA methods (MS-5),

4. and provision of an informatics system (the MS-7 part of MS-6,7,8) to facilitate data management and inference for the COTS Control Program and to ensure data flows quickly and efficiently to other reef management databases and uses.

The successful completion of this integrated suite of projects would provide each of the necessary components identified by Westcott et al. (2021b) as required for the implementation of a Monitoring Program within the COTS Control Program. They would provide a suite of tools that could be readily incorporated into the Control Program's operations and conducted alongside culling or other activities as dictated by conditions. Because the monitoring would be primarily based on existing monitoring methods, i.e., culling, or methods that are analogous to currently used methods, Image-Based Monitoring, their incorporation into the program would require minimal investment or change to on-board activities or processes.

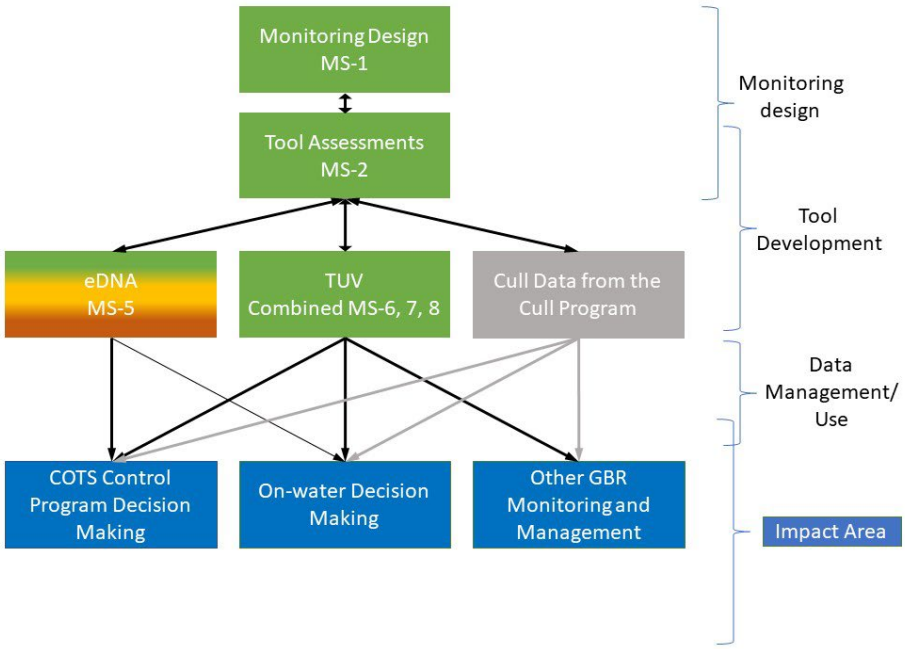

Figure 5.5 Final Monitoring and Surveillance Program Area Strategy. Green boxes indicate the core activities that would underpin the transformation required to meet the challenge of the next COTS outbreak. eDNA monitoring tools would provide a means of validation and contribute to early warning. Additional cull methods used in the COTS Control Program that would also be assessed as part of this work are shown in grey. Links between the tools and the impact areas would be direct (green and grey boxes) and indirect (all boxes), either through additional processing or through additional modelling.

6 RESULTS – DECISION SUPPORT AND MODELLING

6.1 Gap analysis

A total of 86 knowledge gaps were identified in the Decision Support and Modelling Program Area (DSM PA). These covered nine broad areas: 1) Informing on-water control; 2) Informing regional planning; 3) Prioritising research and investment; 4) Statistical analyses; 5) Fundamental model development; 6) Model interpretation; 7) Communications tools; an 8) Early Warning System; and 9) Links to other Program Areas. Within these clusters were 42 sub-classes, as shown in ***Table 6.1***.

For each Gap, the DSM PA Team collated ten key pieces of information: 1) Knowledge Need; 2) Description or Specific Hypothesis; 3) Whether the problem required a DST or a Model; 4) Importance; 5) Existing Research / Sources of Information; 6) Intersections with other Gaps / Program Areas; 7) Residual Knowledge Gap; 8) Research Required to fill Residual Knowledge Gap; 9) Comments; and 10) DSM PA Team Members responsible for further collation of information. Gaps could be related to Decision Support Tools (DST) or Models, both, or models that inform DSTs. The "Importance" category explicitly focused on what filling the gap would change and by how much. The "Residual Knowledge Gap" category focused on what knowledge gap would need to be filled, given the information currently available from other sources. There were overlaps between the categories and sub-classes of gaps identified; for instance, some fundamental model developments required information likely to come from other Program Areas, such as improved biological understanding. Similarly, some model developments would provide improvements that would inform regional planning or on-water control.

The bulk of gap sub-classes (52) fell into three core areas related to existing efforts in COTS decision support and modelling: 1) informing on-water control; 2) informing regional scale planning; and 3) fundamental model development. The first two of these are impact focused; namely, how best to take information produced by data analysis or modelling and interpret it to assist decision making. The third provides the scientific underpinning to enable this impact.

The next cluster of work, statistical analyses, focused on how to improve, validate and demonstrate the performance of models, decision-making processes, and the control program. This is both key enabling information of immediate relevance to the current control program, which is based on empirical analysis of control program data to inform on-water decisions, and important in the longer term for both demonstrating and ensuring the performance and impact of the control program.

Three core ideas not covered by existing COTS decision support and modelling efforts arose: 1) a unified approach to how models are implemented to continuously ingest live data, interoperate, and provide outputs to inform decision support systems; 2) tools to prioritise research and investment; and 3) an early warning system to help decision makers and control staff target emerging COTS outbreaks. The first of these identified the need for repeatable and interoperable data and modelling digital workflows to increase efficiency and drive further innovations. The second was focussed on how to make investment decisions over the long terms (years) in both research and control efforts. The third was a pragmatic

tool focussed on providing actionable insights before the next major COTS outbreaks projected to begin around 2025.

Finally, the last two clusters related to communications tools and links to other Program Areas. While these were important, they generally provided links to gaps noted in other clusters, rather than their own standalone gaps.

Table 6.1 Summary of clusters of gaps identified by DSM PA Team. Numbers in parentheses indicate the number of gaps within each class.

Broad Class	Narrow Class	Linked to Opportunity
Informing on-water control at the local scale (19)	Refining the Current Program (8)	DSM-3
	Revolutionising the Current Program (5)	DSM-3
	New types of Control Program (4)	Not pursued
	Understanding / optimising the decision-making process (2)	DSM-3
Inform regional planning (14)	Reef Prioritisation (2)	DSM-6, 12
	Regional Control Strategies (1)	DSM-6
	Adding Detail to Models (6)	DSM-5, 6
	Uncertainty (3)	DSM-9, 5, 6,12
	Logistics (2)	DSM-6
Prioritising research and investment (7)	Research and Investment DST (3)	DSM-16
	Sensitivity Analysis (1)	DSM-16, 12, 9, 5, 6
	Value of Information (1)	DSM-1, 9, 12, 5, 6
	Cost-Benefit Analysis (1)	DSM-16
	Compatibility with other GBR initiatives (1)	Not pursued
Statistical analyses (9)	Demonstrating Effectiveness (1)	DSM-4
	Parameterising Models (2)	DSM-12
	Combining Data Sources (1)	DSM-4
	Model Validation (1)	DSM-12
	Understanding Model Uncertainty (1)	DSM-9,12
	Hybrid Data-Model Synthesis (1)	DSM-1, 4, 5, 6
	Empirical decision-making data (1)	DSM-3
	Collecting additional data (1)	BE and PC PA ROs
Fundamental model development (19)	Model resolution (2)	DSM-12
	Climate Change (1)	DSM-6
	Hydrodynamics (1)	DSM-12, 6
	Connectivity (2)	DSM-12, 6
	Habitat (2)	DSM-5, 6,12
	COTS Population Dynamics (3)	DSM-5, 6,12
	COTS Biology (4)	DSM-5, 6,12
	Traditional Knowledge (1)	DSM-6
	Management (3)	DSM-6, 5,12
Model implementation (6)	Improved connection between models (3)	DSM-1
	Improved modelling workflows (3)	DSM-1
Communications tools (3)	Tools for communicating results to decision makers (1)	DSM-1, 3, 4
	Tools for communicating results to operators (1)	DSM-1, 3, 4
	Tools for communicating results to funders (1)	Not pursued
Early Warning System (2)	Tools for informing early warning of next outbreak (2)	DSM-4
Links to other PAs (7)	Modelling for ecological understanding (1)	DSM-5, 6,12
	Modelling for proximal causes (1)	DSM-6, 5
	Modelling for Monitoring and Surveillance (2)	DSM-6,12
	Population control (3)	DSM-6,12

6.2 Research Opportunity scoping

The core ideas from the Gap Analysis were used to shortlist seventeen individual Opportunities. After preliminary work, some of these were further combined to yield ten Opportunities. The Opportunities with a brief title are shown in ***Table 6.2***.

Table 6.2 List of Opportunities generated by DSM PA Team to provide coverage for most important gaps identified in Gap Analysis

Opportunity	Brief Opportunity Title
DSM-1	Information Infrastructure to Underpin and Accelerate Innovation in COTS Control
DSM-3	Increasing the efficiency and effectiveness of the COTS Control Program through improvements
DSM-4	Empirical analysis of control program and monitoring data for modelling and early warning
DSM-5	Dynamic models to inform COTS intervention strategies at the reef-scale
DSM-6	Design and optimisation of regional models and decision support strategies
DSM-9	Risk and uncertainty analysis of COTS control strategies and innovations
DSM-10	A unified COTS management modelling capability for application and exploration
DSM-12	Ensembles of biophysical larval dispersal models to improve robustness and uncertainty
DSM-16	Platform for understanding relative effectiveness, cost-effectiveness and economic efficiency
DSM-17	Multi-criteria decision-making framework for balancing management priorities

How these Opportunities were linked to the gaps identified in the Gap Analysis is shown in the third column of ***Table 6.1***. The Opportunities did not, generally, map directly onto the classes used to cluster the gaps, but balanced where the innovation needed to be made against clusters of similar gap-filling innovations. For instance, many of the innovations in "Informing regional planning" were combined with other ideas in "Fundamental model development" around Opportunity DSM-6 *Design and optimisation of regional models and decision support strategies*. By and large, innovations related to: (1) improvements to the current control program's on-water decision making process, which were implemented as part of DSM-3 and 4; (2) both model improvement and informing regional planning were implemented as part of DSM-6, 5, 12 and 9; (3) statistical analyses, as well as the development of an Early Warning System, were provided as part of DSM-4; (4) prioritising research and investment, especially using cost-effectiveness analysis, were implemented as part of DSM-16; and (5) improvements in model implementation facilitating connection between models and to other parts of CCIP and to decision makers were implemented as part of DSM-1.

The ten Opportunities were designed to fit together to provide coverage across the major gaps identified in the Gap Analysis, and to provide innovations to each of three key areas of decision-making around COTS control (***Figure 6.1***). These were: 1) Empirical Decision Making used to inform on-water control actions on timescales of weeks to months (DSM-3

and 4); 2) Biophysical Models to underpin our understanding of COTS population dynamics and our ability to dynamically target control actions over months to years (DSM-5, 6 and 12); and 3) Strategic Decision Making (DSM-9, 16 and 17) that allows us to make investment decisions in control and research priorities over timescales of years. In addition, DSM-1 was defined as a foundational Opportunity providing an information infrastructure designed to increase the connectivity between: 1) all other DSM Opportunities; 2) data flowing in from other parts of CCIP; and 3) model outputs and decision makers. In doing so, DSM-1 was designed to drive both improved efficiency of current research and innovation feedbacks to multiply the impact of CCIP. Finally, a compendium Opportunity, DSM-10 was defined to capture the potential of the modelling frameworks to provide additional innovations beyond those immediately focused on short-term decision support, including the interaction of COTS and climate change or other innovation programs on the GBR, and the incorporation of indigenous knowledge into models.

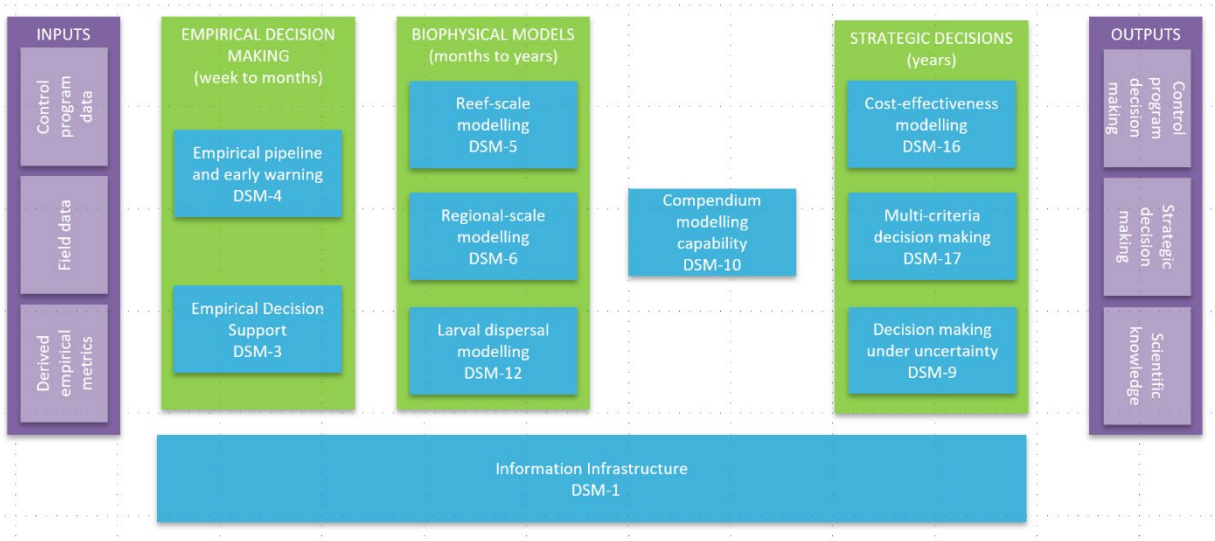

Figure 6.1 Outline of the Opportunities proposed within the DSM Program Area, and how they fit together to inform decision making.

A brief summary of the aims of each Opportunity as it was scoped at this phase of the process is provided below.

DSM-1: Information Infrastructure aimed to create an Information Infrastructure to underpin the sharing and distribution of field, derived and model data between the control program, researchers across CCIP, and on water operators, as well as a digital delivery mechanism to provide research recommendations back to decision makers quickly and efficiently.

DSM-3: Empirical Decision Support aimed to refine existing decision support tools, the COTS Control Centre and the GBRMPA Dashboards, to provide better and more efficient decisions and increase the impact of current COTS control efforts. Specific refinements and a sequence of innovations were identified, starting from those that could immediately (within

a few month) improve the performance of the current control program, to those that could improve performance and ecological understanding of COTS over longer timeframes.

DSM-4: Analysis and Early-warning system aimed to provide 1) better understanding of the short and long term trends in COTS populations in Australian's GBR through empirical analyses of data collated from multiple sources, and particularly, to deliver high quality data to other modelling enterprises in timely manner through digital infrastructure, reducing the likelihood of data handling error and noise; and 2) implement an early warning system for primary outbreaks using data from different aspects of the COTS management system.

DSM-5: Reef scale modelling aimed to: 1) evaluate relative performance of different intervention strategies (including surveillance) for management control of COTS populations at the scale of management sites; 2) characterise the conditions under which alternative and / or suites of management interventions are most efficacious in limiting COTS impacts at management sites; and 3) refine ecological thresholds for management control of COTS by incorporating local factors that impact COTS-coral dynamics.

DSM-6: Regional scale modelling aimed to: 1) refine and calibrate existing reef meta community models of coral and COTS against current and future field data; 2) design strategies for regional deployment of control resources, test the sensitivity of COTS outbreaks to proposed regional control strategies and distribution of effort (e.g. number of vessels, decisions of vessel crews), and identify strategies that engender optimal ecosystem outcomes; and 3) translate optimised control strategies into practical guidelines for use in on water operations (e.g. regional prioritisation and route planning)

DSM-9: Uncertainty analysis aimed to: 1) measure uncertainty in a) the empirical measurements that underpin our understanding of the current state and dynamics of COTS outbreaks; and b) the hydrodynamic, biological, and ecological models that are used to forecast COTS abundance and distribution; and 2) to develop a comprehensive risk analysis framework for choosing priority COTS control locations in the face of this uncertainty

DSM-10 aimed to provide access to and interpretation of the suite of COTS-related models developed under CCIP (reef-scale, regional-scale, larval dispersal, empirical analysis of data) to answer questions beyond the immediate management-relevant questions addressed in other DSM Opportunities. These will include questions around the proximal causes of outbreaks; the biological relationships that underpin COTS population dynamics at the reef scale; the identification of management research needs based on a value of information analysis of existing models; and the long-term outcomes of COTS control in terms of large-scale reef resilience, interaction with other GBR initiatives, and climate change. It will also include a component liaising with other researchers, managers, traditional owners and community and industry stakeholders to establish and begin to address their highest priorities for COTS modelling capability.

DSM-12: Larval dispersal modelling aimed to: 1) harmonise multiple diverse hydrodynamic models of the GBR lagoon and surroundings, to ensure that they make comparable predictions about currents, across the same spatiotemporal window, on the basis of input data of comparable quality (e.g., habitat maps and bathymetry, low frequency forcing, tides, wind); 2) contrast the predictions of this model ensemble with each other, and with spatiotemporal empirical validation data on observed COTS densities on sampled and

controlled reefs; and 3) support the integration of the modelling ensemble with decision making processes.

DSM-16: Cost-effectiveness modelling aimed to assess relative effectiveness, cost effectiveness, and economic efficiency of COTS control methods.

DSM-17: Multi-criteria decision-making aimed to, through a combination of surveys, workshops, and computational decision support tools: (1) elicit and understand the range of stakeholder values; (2) use the best available ecological science and multi criteria decision analysis methods to determine how a range of alternative COTS control strategies will affect these values; and (3) present these results in an interactive forum to examine the resultant trade-offs, and to allow stakeholders and Traditional Owners to express their judgements about the methods and control strategies.

6.3 Research Opportunity assessment

For each of these Opportunities, an Opportunity Template was prepared describing the characteristics of the Opportunity against the ten key areas of interest to CCIP, as described in sections 2.4 and 4.3.4 of this report. Between 15 February 2021 and 22 February 2021, each DSM Opportunity was then anonymously assessed by all twelve members of the DSM PA Team via a SurveyMonkey elicitation process, against the Evaluation Criteria described in section 4.3.3 of this report. On 01 March 2021, the outcomes of these assessments were discussed by the DSM PA Team during an Assessment Workshop. The full Assessment process consisted of the pre-Workshop Assessment, the Assessment Workshop, and the synthesis of recommendations coming out of the Assessment Workshop for the CCIP Program Director and Steering Committee. Care should be taken in interpreting the results from any of these steps in isolation. The first two steps are described below, and the recommendations are described in the following two sections of this report.

6.3.1 Pre-workshop assessments

The key outcomes of the pre-workshop assessment are shown in ***Figures 6.2*** and ***6.3*** below. ***Figure 6.2*** shows the mean (box) and standard deviation (bars) of the assessments provided by the DSM PA Team against the Evaluation Criteria (***Table 3.1***). Note that although the error bars reflect the standard deviation of the data collected, they should be interpreted as a rough indication of the range of responses rather than a quantitative estimate because the underlying distributions were often non-normal.

Figure 6.2 displays each Evaluation Criteria as a separate plot, with the ten Opportunities displayed beside each other within each plot. This highlights the relative assessments across Opportunities. Most DSM Opportunities exhibited good Path-to-impact and hence Ability to suppress or prevent COTS outbreaks, limited co-benefits, but rapid time to viability, low risks, and high synergies and innovation potential. This is unsurprising, given the nature of modelling and decision support research. Decision support is highly synergistic because it's the place that other COTS research is interpreted, and it drives direct real-world impact by providing those insights to decision makers. It's quick to generate impacts compared to other types of research. However, because it is focussed primarily on COTS control decisions, it has limited co-benefits.

Figure 6.3 shows an alternative visualisation highlighting the difference between means. The most notable result was that the mean for almost all Opportunities across most Evaluation Criteria lay within the approximate range of assessments across all Opportunities – that is, there wasn't a wide difference between Opportunities. There were some exceptions to this: DSM-16 and 17 had relatively lower Ecosystem co-benefits but higher Socioeconomic co-benefits that other Opportunities, because they focused more on incorporating socioeconomic factors into longer term strategic decision-making rather than using a detailed ecological understanding to inform short-term on-water decisions.

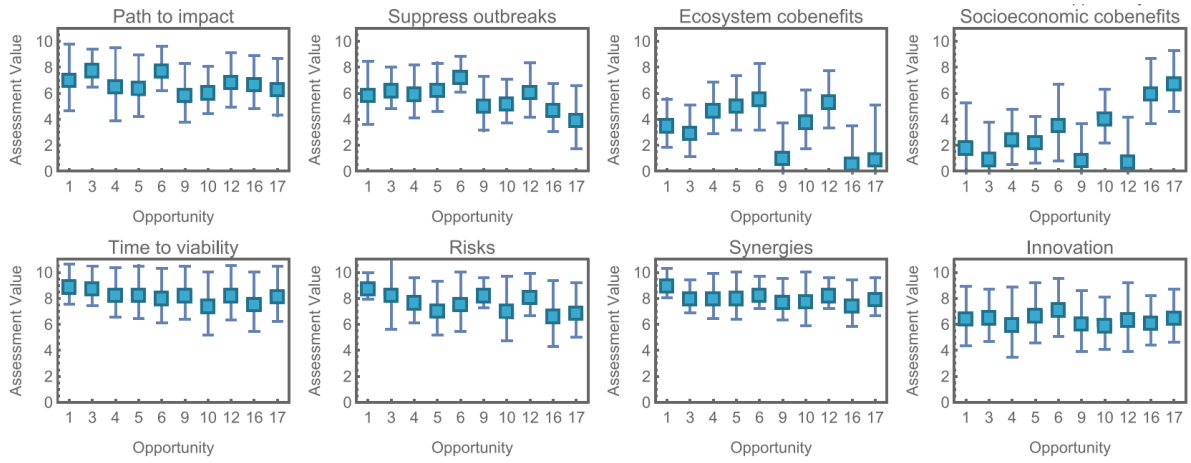

Figure 6.2 Assessments of the 10 Decision Support and Modelling Research Opportunities across each Evaluation Criteria (all except research and implementation costs). Values are weighted means. Error bars represent standard deviation and are provided to give an indication of range of responses.

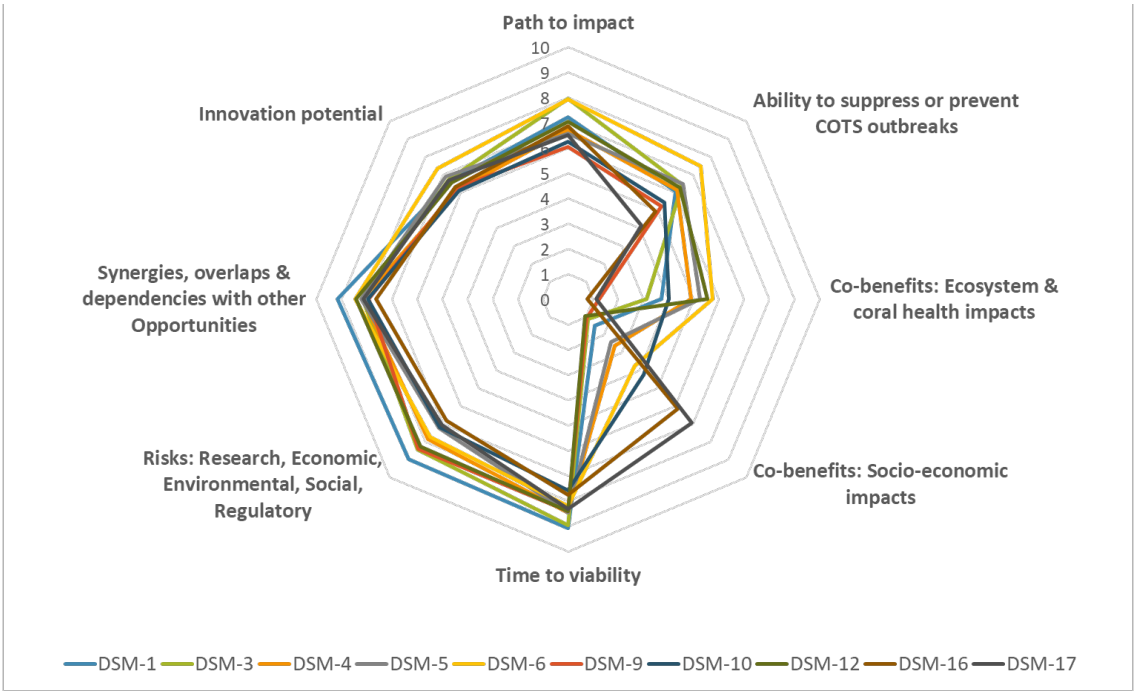

Figure 6.3 Spider chart highlighting differences in the weighted means of assessments against Evaluation Criteria across the 10 Decision Support and Modelling Research Opportunities.

The other two crucial pieces of information that were provided by the Pre-Workshop Assessment were the consensus around the assessments and the free-text anonymous feedback provided for each Opportunity via the SurveyMonkey platform. Discussion of both of these components formed a key part of the Assessment Workshops.

6.3.2 Assessment workshop

For other Program Areas, the DSM Program Area Lead, Cameron Fletcher, provided preliminary analysis of the Pre-Workshop Assessment data and then facilitated the Assessment Workshop around the results from that preliminary analysis. The DSM Program Area Assessment Workshops was facilitated by the CCIP Program Director to allow the DSM PA Lead to participate in the discussion and represent the Opportunities in which he was personally involved.

As with other PA Assessment Workshops, the DSM discussion during the workshop was facilitated to focus on:

1. Relative assessments between Opportunities
2. Consensus between assessments for each Opportunity
3. Discussion of questions and feedback raised in anonymous comments.

As noted above, in the DSM PA, the relative assessments between Opportunities provided little discriminatory power because DSM Opportunities tended to share common characteristics that led to similar Evaluation Criteria Assessments.

However, there were a range of levels of consensus achieved across those assessments. This was reflected in the distribution of assessment values. Some were approximately normally distributed with a clear single peak, reflecting a relatively high level of consensus. Others exhibited bimodal or occasionally trimodal distributions, suggesting two or three clusters of opinion. Finally, some exhibited essentially no consensus. Respondents were able to provide a distributed assessment for each Opportunity against each Evaluation Criteria – for instance they could assess “Path-to-impact” as a single value of 8 (weighted as 1 vote for an assessment of 8), or as a range from 6 – 10 (weighted as 0.2 votes for 6, 7, 8, 9 and 10). This richness provided additional structure to the distribution of assessments.

Relative to other Program Areas, assessments of DSM Opportunities provided generally clearly singly peaked distributions, indicating a relatively high level of consensus of opinion across the assessors. Some Evaluation Criteria did exhibit dual peaks, and the origin of these were discussed during the workshop. Respondents exhibited a range of certainties, some assessing small ranges for some Evaluation Criteria, but many assessing some Evaluation Criteria, such as Socioeconomic Benefit, quite broadly, suggesting either uncertainty in the potential benefit of this type from DSM Opportunities, or some uncertainty in how the Opportunities should be assessed against this Evaluation Criteria. There was a good level of response, with very few people indicating the “Not Applicable” or “No Idea” responses for any Evaluation Criteria, except for “Socioeconomic Benefit”.

Finally, the SurveyMonkey form provided space for anonymous freeform questions or feedback on each Opportunity. As part of the Workshop, the most common feedback was

reworded and shared back with the DSM PA Team. The Opportunity proponent had first right-of-reply to these questions or feedback, after which discussion was opened to the floor.

The key outcomes and discussion points for each Opportunity are provided below.

DSM-1 had generally single peaked responses, with some outlying responses for Path to Impact. Ability to suppress or prevent outbreaks, Socioeconomic benefits and Innovation Potential. The comments and discussion focussed on the fact that this Opportunity was an essential part of CCIP and fundamental to tying together other Opportunities, streamlining, driving and amplifying innovation. There was no suggestion that this Opportunity needed to be bundled or split, but it did need tight linkages to everything in the DSM PA, multiple Opportunities in the MS PA and field data collected by the BE and PC PAs.

DSM-3 had simple single peaks with relatively tight ranges, indicating a good degree of consensus, although it did have some outlying assessments for Socioeconomic benefits and Risks, and a fairly wide range of responses for innovation. The discussion suggested that these assessments reflected the clear short-term pragmatic focus of the Opportunity. The comments centred around the fact that it addressed currently identified needs so had a very direct path to impact, that it wasn't extremely innovative but was an important part of the CCIP impact pipeline, and that clarity was needed around how the estimates of efficiency improvements were generated. There was a comment that it either needed to be clearly delineated from DSM-4 or merged with it.

DSM-4 had wide ranges in the responses for many Evaluation Criteria. The discussion revealed that this was likely due to the two quite different components making up DSM-4: the first an empirical analysis pipeline, the second the development of an Early Warning System based on this empirical data. There was discussion about whether the two components should be separated, and also whether one or both parts should be combined with DSM-3. There was firm support from within the DSM Program Area for the urgent need for empirical analysis pipeline to streamline the incorporation of field data into models. Similarly, there was enthusiasm for the innovativeness and importance of the Early Warning System to address the new outbreak expected in 2025.

DSM-5 exhibited mostly single peaks in its assessments, reflecting a good degree of consensus across the DSM PA Team. The comments and discussion noted that it was an important foundational modelling capability for COTS Innovation on the GBR. The clearest immediate needs were around refining the ecological thresholds on which COTS control is currently based, and some discussion about how the model and empirical data approaches could work together to address these questions. There was some discussion on whether the reef-scale modelling efforts in DSM-5 were similar enough with the regional-scale modelling effort in DSM-6 that they should be merged, but the discussion supported keeping them separate.

DSM-6 also exhibited single peaks for most Evaluation Criteria, but they were quite wide ranging. Based on the Workshop discussion, this probably reflected the fact that the value of the regional-scale modelling provided by DSM-6 was clear, but that the way the Opportunity had been scoped was very broad. Again, it was noted as one of the three foundational modelling capabilities (along with reef-scale and larval dispersal modelling) required for COTS control, with both direct and longer-term paths to impact. It was noted as a

complicated and diverse Opportunity, with significant aspirations and a large resourcing requirement that was appropriate for the scope described, although there was some discussion about whether it was the right size in proportion to the overall investment pool in the DSM PA.

DSM-9 exhibited bimodal distributions under Path to impact and Synergies, with wide-ranging responses for several other Evaluation Criteria. The discussion showed that this probably reflected the fact that DSM-9 was designed to: 1) contribute to other modelling Opportunities, rather than delivering results directly; and 2) provide a better understanding of both model uncertainties and the way that they influenced decision recommendations. Although these were acknowledged as important, the comments and discussion centred around whether they should be a standalone Opportunity, or whether the uncertainty analyses for models should be integrated into the primary modelling Opportunities (DSM-5, 6 and 12) and the assessment of how uncertainty affected decision recommendations should be integrated into DSM-1.

DSM-10 was a compendium Opportunity containing all the additional innovations that could be provided by the modelling capability generated across other DSM Opportunities beyond those required to structure decision making in the current control program. Unsurprisingly, it had very wide-ranging assessments reflecting its breadth and the diverse components encompassed within it. The discussion centred around the fact that the Opportunity would require significant refinement and scope definition if it were to go forward, and that as part of that it would have to be clearly delineated from the contributions being delivered within DSM-4, 5, 6, 9 and 12. The need to link the work with TOs to efforts in SS-4 was also noted.

Like the other fundamental modelling Opportunities, **DSM-12** also exhibited single peaks for most Evaluation Criteria, but they were quite wide ranging for Ability to suppress outbreaks, ecological co-benefits and Time to viability. The discussion highlighted that this work was an important foundational modelling capability that had a direct path to impact through improved selection of priority reefs for COTS control. However, while acknowledging that larval dispersal models could be improved, and lead to improvements in regional scale models, there was also discussion around whether these improvements would be large enough to significantly change management decisions in the longer term. A potential overlap with MS-15 was noted for further exploration by the Opportunity proponents.

DSM-16 exhibited multiple peaks and quite large ranges in the assessments across multiple Evaluation Criteria, possibly due to the fact that it proposed an economic analysis quite different to the biophysical modelling used across the rest of the DSM PA. The discussion recognised the unique contribution provided by this Opportunity, in that it was the only one that could consider diverse economic costs and benefits. However, its dependence on DSM-6 scenarios required clarity around the boundary between the two Opportunities. The need for links into socioeconomics both within CCIP, in other GBR initiatives and in partner institutions was also noted. The observation was made that the Opportunity was quite tightly scoped and, if economic cost-benefit analysis was seen as a core component for CCIP, then the Opportunity scope and funding request may need to be increased to provide a more comprehensive analysis.

DSM-17 had wide-ranging assessments for most Evaluation Criteria, perhaps reflecting the fact that it contained two core components: a narrowly-defined multi-criteria assessment of

values for the reef prioritisation used in the current control program; and a longer-term and broader assessment of multiple criteria related to social and community values of reefs across the GBR. Like the economic analysis, the discussion noted that this capability was not captured anywhere else in CCIP, and if incorporating multiple values in decision making was important to CCIP it would need this Opportunity. It was acknowledged that this Opportunity was heavily dependent on other modelling Opportunities, for both providing input data to the assessment and presenting the results of the assessment to stakeholders. The discussion noted that a large proportion of the funds budgeted related to workshops, and that these may be aligned with efforts taking place in the Social Science Program Area.

6.3.3 Outcomes of Opportunity Assessment

Following the Opportunity Assessment process, the scope of the ten Opportunities were refined slightly, their contribution to innovation under CCIP clearly articulated, and the potential for them to be scaled or combined was summarised and provided to the CCIP Program Director and Steering Committee. A brief outline of this information for each Opportunity is provided below.

DSM-1 provides information infrastructure to: 1) standardise control program data, field data, and derived data, and to efficiently transfer this data to decision support tools and biophysical models; 2) couple biophysical models across scales and into ensembles; and 3) deliver results to decision makers via decision support platforms. It is designed to reduce the common overheads of handling data, and speed up the innovation cycle. **Innovation:** DSM-1 is not strongly innovative in and of itself, but it enables innovation in every other component of the DSM PA. **Scaling and thresholds:** DSM-1 is tightly scaled to deliver an engineering solution that can rapidly provide lightweight infrastructure to share data, connect models and deliver recommendations to decision makers, while connecting into larger and longer-term information innovations in the GBR space (e.g., RRAP). Any reduction in resourcing would require dropping one of these components. Overall, this version of DSM-1 is likely to provide efficiency gains that exceed its costs. However, discussion during and following the Assessment workshop identified that more substantial gains may be realised by incorporating a unified decision science approach across all empirical decision support and model analysis. This version of DSM-1 would leverage the existing decision support component of DSM-3 (additional 0.1 FTE resourcing to support generalisation and integration), the empirical analysis part of DSM-4 (no net change in resourcing) and parts of the uncertainty and risk analysis (DSM-9, no net change in resourcing) and multi-criteria analysis (DSM-17, no net change in resourcing), with an explicit decision science component designed to take raw model results, provide interpretation, and deliver robust recommendations to decision makers in the form of most use to them (additional resourcing of one decision scientist at 0.2 FTE per year for 3 years).

DSM-3 is focussed on extending and innovating the current on-water decision support tools and the GBRMPA dashboards using empirical data collected by the control program itself. It builds on existing tools to provide rapid refinements to the control program currently operating on-water. By providing significant efficiencies, it will allow outbreaks to be reduced at more reefs across the GBR within the current program. **Innovation:** This Opportunity contains innovative techniques (e.g., artificial intelligence), but is focused on rapidly refining, rather than revolutionising, the current control program. **Scale and thresholds:** This Opportunity addresses currently known needs within the control program, and because of

this is scaled accurately and could not be significantly reduced. It contains two components: refinements to on-water decision tools and GBRMPA dashboards. Both are important to better on-water control, but could be considered separately. As noted above, the need for a unified decision science approach has been identified which, if funded, would leverage the capability in DSM-3, with a slight increase in resourcing to facilitate this.

DSM-4 is focused on two innovations: 1) providing an empirical analysis pipeline for field and derived COTS data; and 2) leveraging this pipeline to create an early warning system for managers. The first shares many similarities with and delivers into DSM-1, and may be better viewed as part of DSM-1. The second has the potential to innovate the current COTS control program by providing tools that allow control effort to be targeted at reefs that are about to experience outbreaks, and could be considered in concert with DSM-3. **Innovation:** While not radically innovative, the first component creates efficiencies by reducing double handling of data. The second component is truly innovative and has the potential to improve the effectiveness of COTS control very significantly, by pre-emptively targeting locations that can prevent instead of supressing outbreaks **Scale and thresholds:** This Opportunity is already very tightly scoped for its aspiration, so no cuts are recommended. The two components of this Opportunity are weakly coupled and so could be split into two parts and considered separately. However, the Early Warning System is likely to benefit from empirical analysis pipeline inputs over the medium term. The empirical pipeline could be incorporated in DSM-1, but no resources would be saved.

DSM-5 builds on our existing capability in reef-scale modelling of COTS population ecology. In the short term it will better estimate threshold density targets for management. In the medium term it will provide adaptive refinements to these thresholds and design improved within-reef management strategies. In the long term it will help understand new innovations at the sub-reef scale, such as semio-chemicals. **Innovation:** This Opportunity both has a clear path to refining current COTS control methods, through refinement of management thresholds, and will be a core capability to understand major innovations, such as semio-chemicals and reef-scale biology and ecology. **Scale and thresholds:** This Opportunity is scaled appropriately for its aspiration, although overlaps with other parts of CCIP should be mapped to ensure efficient allocation of resources. The key threshold in resourcing is around the three-year full-time postdoc position, which could not be reduced without impacting employment contracts. This position is planned to deliver capability into multiple other Opportunities across the Decision Support and Modelling and other Program Areas, so the resourcing listed for this Opportunity is currently significantly overestimated, but unless those other Opportunities are funded and cover the postdoc's time, it could not be reduced without impacting delivery across all these Opportunities.

DSM-6 builds on our existing capability in GBR-scale modelling of COTS population ecology and management across two models, CoCoNet and ReefMod-GBR, both of which have key strengths for decision support. This will be vital to increasing the performance of the current control program through better regional distribution of management resources for manual control and reef prioritisation, as well as understanding new innovations and their implementation at the GBR-scale and estimating their cost effectiveness in relation to COTS removed and coral saved. **Innovation:** This Opportunity both has a clear path to refining current COTS control methods, through identification of higher performing and more efficient regional management strategies, and will be a core capability to understand major

innovations, such as new monitoring methods, genetic approaches, cost-effective regional manual control strategies, and leveraging the COTS control program to support a resilient GBR. **Scale and thresholds:** This Opportunity is scaled appropriately for its aspiration, although overlaps with other parts of CCIP and other GBR research programs should be mapped to ensure efficient allocation of resources. The key thresholds in resourcing are the maintenance of two regional-scale models (ReefMod-GBR and CoCoNet) and the staffing required to support that including a three-year full-time mid-career scientist position. The maintenance of two GBR-scale models is necessary to cover the breadth of questions being asked of these models from key stakeholders, and to underpin an ensemble approach capable of providing robust recommendations from stochastically-driven models exhibiting significant uncertainty and emergent dynamics. Scaling back to a single regional-scale model would significantly impact the robustness of the recommendations generated by this core CCIP capability. Both models currently receive some support for non-COTS components from other GBR research programs, and so it will be important to map these to make the most of synergies, some of which may provide efficiencies. However, these other research programs do not support development of the COTS components of these models, nor COTS management needs, so attempting to reduce resourcing of DSM-6 too far may compromise either or both models' ability to inform COTS management. The largest single allocation of staff time is related to the mid-career scientist position, which could not be reduced without impacting employment contracts. This is considered necessary due to the complexity of integrating multiple modelling approaches, outputs, and data streams within a complex modelling framework, and to support regular updates to integrate cutting-edge research and innovations from other parts of CCIP. It is important to note that this position is planned to deliver capability into multiple other Opportunities across the DSM and other Program Areas, so the overall resourcing listed for this Opportunity is currently an overestimate.

DSM-12 builds on our existing capability in hydrodynamic and biophysical modelling of larval dispersal by building an ensemble of biophysical models and developing the methods to analyse them to produce robust connectivity metrics. This has a direct route into current management decision making through the selection of priority reefs, as well as being a foundational input into GBR-scale models that will allow testing of proximal causes of COTS outbreaks and biology and ecology at GBR-scales. **Innovation:** This Opportunity will refine the selection of priority reefs for control using hydrodynamic models capable of resolving reef-scale processes much finer than those currently considered. It will also investigate hypotheses on COTS biology such as vertical migration, competency period and settlement habitat requirements. **Scale and thresholds:** The key threshold in resourcing is the development and maintenance of an ensemble of three hydrodynamic-larval dispersal models. This is necessary to robustly inform both decision making and other modelling efforts in DSM-5 and 6 from these complex and highly variable models. Multiple hydrodynamic models will resolve processes taking place at multiple spatial scales, from regional- to reef- to coral-scale, and at temporal scales unique to each model. Scaling this opportunity back to support fewer larval dispersal models is likely to significantly impact the robustness of the decisions recommended. This Opportunity overlaps strongly with MS-15, which proposes a near real-time larval dispersal estimation from monitoring data. Whether the two could be combined should be investigated.

DSM-10 is a compendium Opportunity to cover utilisation of the combined biophysical modelling capabilities of DSM-5, 6 and 12 in relation to questions of importance within DSM, from other Program Areas, and potentially from outside CCIP. The scope is currently unclear due to uncertainty about what will need to be included, however that should not be confused with unimportance. It is likely that this Opportunity will be the place where GBR-scale questions about the long-term performance of the COTS program and viability of GBR ecosystems under changing climates could be addressed, which will be vital to understanding COTS management in broader contexts and securing long-term funding for COTS control, as well as providing links into vital large-scale questions like the Proximal Causes of COTS outbreaks on the GBR. It is also the key Opportunity explicitly linking modelling to end-users through stakeholder and TO engagement. **Innovation:** Hard to say because of the current uncertainty, but the potential is significant. **Scale and thresholds:** This Opportunity is almost certainly under-scaled at the moment, but until it is defined more clearly this is hard to rectify. Because core modelling capability is covered in other Opportunities (DSM-5, 6 and 12), there are no inherent thresholds in DSM-10. However, it should not be scaled back to a point where its underlying goals cannot be achieved.

DSM-9 provides underlying capability around risk and uncertainty analysis likely to be important across all the biophysical models. It is possible this capability could be integrated into each individual Opportunity, but that introduces risks that a demonstrably unified approach is lost. Alternatively, it is possible that the core capability could be integrated into DSM-1 as a component interpreting model outputs to create management recommendations. **Innovation:** This Opportunity will likely have a less obvious impact on innovation of COTS control, but that doesn't mean it will be less important. COTS management systems are currently defined by their low levels of predictability and making decisions that are more robust to that could significantly improve the performance of the control program in the short, medium and long terms. **Scale and thresholds:** This Opportunity is tightly scaled for its aspirations, and so further reduction is unlikely to be viable. However, there may be some benefit to rolling it into other Opportunities, bearing in mind the risks listed above, both in terms of providing closer connection to either models or decision making, and reducing the overheads of contracting small allocations. This would not lead to reduced costs, however.

DSM-16 provides the only Opportunity in CCIP dedicated to looking at issues of cost-effectiveness and economic efficiency beyond COTS culled and coral saved. It would provide medium term (within-CCIP) assessment of alternative options under the current control program and would lay the foundation for long-term (after-CCIP) assessment of novel control options for COTS. **Innovation:** The techniques in this Opportunity are well established, but this is the only Opportunity that provides a generalised cost-effectiveness and economic efficiency assessment of novel control methods with the potential to completely innovate COTS control. This would be vital to understanding which step-change innovations could be viable under CCIP, while providing economic value of benefits associated with COTS control outcomes. It would also align CCIP efforts with research into other types of interventions currently underway as part of RRAP. **Scale and thresholds:** The necessary scale of this Opportunity will depend on which Opportunities are funded under other Program Areas of CCIP. If many novel methods are funded, the scale of this Opportunity may need to be increased (particularly to estimate cost) to encompass all of them. Alternatively, if few or no novel methods are funded, this Opportunity could be scaled

back to focus just on current control methods. In addition to these considerations of the current Opportunity, discussions during the Assessment workshops identified a potential missing Opportunity around the estimation of the economic value of benefits to assess economic efficiency. As currently proposed, DSM-16 would leverage existing benefit stream data from RRAP. This has the benefit of being freely available but comes with high uncertainty, which will limit the performance of economic efficiency analysis. The uncertainty in this data could be reduced with a dedicated Opportunity (currently not proposed within CCIP). Alternatively, under DSM-16 a first pass assessment using existing data could be used to inform where additional data collection should be targeted following CCIP, which would allow novel innovations proposed under CCIP to be developed to a point where cost and benefit data could be more accurately assessed.

DSM-17 provides frameworks for multi-criteria decision making. This is of immediate importance for the selection of priority reefs, and of future importance to many COTS management decisions. It will be vital for incorporating more nuanced perspectives if and as the scope and scale of COTS control increases, including socially acceptable management options and options that incorporate TO values. **Innovation:** This Opportunity will be vital to incorporating multiple stakeholders, community and TO perspectives in larger scale novel COTS control methods, such as zoning or genetic control methods, and so could be key to enabling step-change innovation in COTS control. **Scale and thresholds:** More than half the resources for this Opportunity are related to stakeholder workshops. These can possibly be scaled back by leveraging workshops already planned in the Social Science Program Area or combining fewer workshops with alternative cheaper elicitation techniques. There is little staff time allocated in this Opportunity, so it would be hard to scale that back further. There may be some benefit to rolling part of it into DSM-1 to provide closer connection to decision making, however there is also a clearly delineated standalone need for this capability around reef prioritisation, and there would not be any additional savings from doing so.

6.4 Recommendations on priority Opportunities

In the opinion of the DSM PA Team, CCIP “must have” some investment in all four areas of the Program: Information Infrastructure, Empirical Analysis and Decision Support, Core Biophysical Modelling, and Strategic Decision Making. Individual Opportunities can be classified as “must have”, “should have”, or “nice to have” depending on the overall investment priorities of CCIP Decision Makers (Program Director, Program Area Leads and Steering Committee)

Due to the overlap between DSM Opportunities and Opportunities listed in other Program Areas, especially with respect to staff time, it will be necessary to revise and finalise exact allocations and therefore costs before deciding whether or how to scale individual Opportunities while building CCIP portfolios. It will also be important to scope where Opportunities contribute to or can leverage from other GBR research programs to ensure efficient allocation of resources.

Within those bounds, the CCIP Decision Makers may be guided by the following considerations:

Integration vs federalisation: DSM-1 is a core enabling capability that is not strongly innovative in and of itself, but which will reduce overheads and speed up innovation feedbacks in every other component of the Decision Support and Modelling Program Area, as well as between other Program Areas and DSM. It is currently scoped to deliver a lightweight infrastructure to share data, connect models and deliver recommendations to decision makers, while connecting into larger and longer-term information innovations in the GBR space. However, if CCIP Decision Makers want to provide a consistent approach to data preparation, analysis of risk and uncertainty, and interpretation of model outputs and field results to provide multi-criteria recommendations for delivery to decision makers, they could recommend that DSM-1 is combined with several components of other Opportunities (DSM-3, DSM-4, DSM-9, DSM-17) and expanded to incorporate core decision science domain expertise. This could provide a more coordinated research portfolio, with a more consistent delivery of information to decision makers, and independent performance assessment, at the expense of some additional cost, reduced flexibility in component funding, and reduced specialisation of uncertainty analysis and validation within each biophysical model.

Near-term vs mid-term vs long-term focus: What split do CCIP Decision Makers want between research that can refine and improve the performance of what we have now, versus research that can drive step-change innovation over a longer timeframe? A stronger focus on the:

- Near-term: would move resources towards DSM-3, 4, and the components of DSM-5, 6, 12, 9 and 17 related to current efforts. DSM-1 would be focused on data distribution and recommendation delivery.
- Mid-term: would maintain resources in DSM-5, 6, 12 and invest more resources in DSM-9, 17 and the component of DSM-16 related to cost-effective strategies for the current control program. DSM-1 would focus on data distribution, recommendation delivery, and lightweight model connectivity.
- Long-term: would move more resources towards the component of DSM-16 focussed on novel COTS control methods, and the components of DSM-5, 6, 7, 10, 9 and 17 that are focused on considering how to make decisions about new methods of COTS control that can substantially innovate management. DSM-1 would focus on data distribution, recommendation delivery, and deep model connectivity.
- When making these assessments, however, it is important to note the hard thresholds in scaling DSM-5 and 6 related to postdoc and scientist positions.

Economic analysis: If CCIP Decision Makers are interested in cost-effective and efficient conservation decision making, then DSM-16 is a “must have”, because it is the only Opportunity delivering this capability across CCIP. The component of DSM-16 related to the manual control program could deliver guidance on cost-effective and efficient distributions of management effort within the timeline of CCIP. This would provide assessments of social costs and benefits associated with COTS control outcomes, beyond those provided by the analysis of regional scale strategies under DSM-6, such as COTS culled and coral saved. In contrast, the results from this analysis related to novel control methods, other than manual control, would depend strongly on the progress of work being conducted elsewhere in CCIP,

and due to this dependency would only be available to guide investment in the funding round that follows CCIP. Finally, if this area is high priority for CCIP Decision Makers, they could choose to invest additional funds in more accurately estimating benefits through a dedicated Opportunity.

Uncertainty, risk and validation: If CCIP Decision Makers place a high value on robust decision making despite uncertainty, and risk analysis that is both independent and seen to be independent, then either DSM-9 is a must-have in its current form, or this same capability must be rolled into either the individual Core Biophysical Modelling Opportunities (DSM-5, 6 and 12), or into the linking Opportunity DSM-1. As they are currently scoped, some validation has been included within each Core Biophysical Modelling Opportunity, but bringing this together with the uncertainty analysis in DSM-9 would achieve the most robust testing of model outputs and the decisions that are generated from them. Providing this Opportunity through the linking capability in DSM-1 could provide an increased perception of independence, but may decrease the tight integration of validation and uncertainty analysis from each model.

Multi-criteria analysis: If CCIP Decision Makers are interested in incorporating multiple values, including non-ecosystem values and TO values, into decision support tools for COTS control, then DSM-17 is also a “must have”, because it is the only Opportunity delivering this capability across CCIP. While some the underlying work will likely be driven out of the Social Science Program Area, this Opportunity is essential for this information to be quantitatively incorporated into decision making.

7 RESULTS – PROXIMAL CAUSES OF OUTBREAKS

7.1 Gap analysis

An in-depth analysis of the conditions, processes and mechanisms that directly influence the likelihood and timing of a COTS outbreak as well as its scale and subsequent propagation was conducted by a group of experts in the area to identify Knowledge Gaps and develop recommendations on an R&D program to address such gaps, and guide the prioritization, design and implementation of innovations identified under the population control and monitoring and surveillance program areas.

The analysis included a desktop exercise to review up to date literature, the creation of a preliminary table incorporating possible drivers of COTS outbreaks and Knowledge Gaps in these drivers. This table was used as the basis for the discussion during the first formal meeting of the PA on the 15 October 2020 (via Zoom). This table was further populated during and after this workshop and some Research Opportunities to address Knowledge Gaps also started to be added.

Four major drivers of primary and/or secondary outbreaks were identified during this analysis. The first two of these hypotheses represent the traditional dichotomy between bottom up (nutrient induced) or top down (predator induced) explanations for COTS outbreaks (and other ecological phenomena). The group recognises that a more modern view may be that both explanations can be part of a complex chain that explain outbreaks to varying extents. This is recognised by listing 'multiple causes' as a separate dot point below. The third hypothesis ('Natural causes') has also been brought forward for a long time, but never been systematically investigated. Climate change and other environmental change have substantial effects on marine ecosystems, and several recent publications have shown that COTS larval and adult ecology and performance is influenced e.g., by temperature changes or ocean acidification. Hence, 'environmental change' was recognised by the group as a nouvelle hypothesis. The entire Gap Analysis is listed in ***Table 7.1***, and the most pertinent gaps for the individual hypotheses are described in detail below.

Table 7.1 Knowledge Gaps relating to the Proximal Causes Program Area grouped by potential drivers of outbreaks (hypotheses) as identified by the PC team, including relevant source of information and potential Research Opportunities as discussed in the earlier stages of the program.

Drivers of outbreaks (primary and secondary)	Knowledge needs (not necessarily Gaps)	Importance	Key sources	Knowledge Gaps
Nutrient enrichment/ terrestrial runoff	Primary knowledge needs summarised in a schematic shown in Appendix F			
	Changes in land use and management increases sediment and nutrient runoff (Step 1 in schematic)	Without this assumption there is no merit in the nutrient hypothesis	Several reviews and modelling exercises clearly show that sediment and nutrient loads to the GBR lagoon have increased several times since European settlement (Kroon et al. 2016; Bartley et al. 2017)	Sufficient knowledge, not further considered here.

	Narrow down location of initiation box and understand if land-based runoff reaches this area (part of Step 2 in schematic)	Needed to understand nutrient availability in the water column and depth harbouring COTS larvae.	(Pratchett et al. 2014; Vanhatalo et al. 2017)	**Critical gap** Do (original or transformed) nutrients and/food sources reach initiation box.
	Nutrient transformation and transport (part of Step 2 in schematic)	Needed to understand if land-based runoff reaches outbreak area, either directly or through transformation	Most information on transport is derived from models (e.g., eReefs). Recent studies do suggest that remineralisation rates are high (Lønborg et al. 2017)	**Significant gap** · Which nutrients are enhanced and where? · Are alternative food sources enhanced? · Nutrient transformation and availability in coastal water.
	Relationship between nutrient supply and phytoplankton abundance/species composition (Step 3 in schematic)	· The assumption is that plankton (available as COTS larval food) or other food sources are limited by individual or combined nutrients. · Do COTS select for different phytoplankton food?	· Very limited information on phytoplankton species of GBR: (Revelante & Gilmartin 1982; Revelante et al. 1982; Devlin et al. 2013) · Growth and uptake response in general: (Furnas et al. 2005)	**Significant gap** · Species in mid-shelf reefs · Which species (or groups or size class) increase during increased nutrients? · Are there specific plankton groups/species enhanced in December/January? · Are these the species on which COTS thrive? · Does this plankton reach initiation box?
	· Spatiotemporal variability in larval abundance and condition. (Step 4 in schematic).	A fundamental and readily testable hypothesis of the larval starvation hypothesis is that survival and development of COTS larvae is often very constrained due to limited food source and poor condition of the larvae.	· Abundance: (Uthicke et al. 2015a; Doyle & Uthicke 2016; Suzuki et al. 2016; Doyle et al. 2017; Uthicke et al. 2019)	**Large gap**

	· Increase phytoplankton leads to higher survival rates of COTS larvae and increased recruitment (Step 4 in schematic).		· Conditions: no information	· Incidence and distribution of major flood events, adult distribution and abundance (stock-recruitment relationships) · What are 'threshold values for enhanced survival? Based on more realistic experiments (flow through, natural algae, low larvae density). · Redefine 'thresholds' from chlorophyll based to cell numbers, organic carbon or calories. · Do COTS larvae thrive on the actual phytoplankton potentially enhanced in the initiation zone · Does time and location of enhanced nutrients/ plankton blooms agree with spawning times and initiation box?
	High recruitment rates increase adult populations (Step 5) and high adult populations lead to secondary outbreaks (Step 6)	Required assumptions for the build-up and spread.	No COTS specific literature, but assumptions seem self-evident and logical.	Some knowledge gaps, mechanisms of secondary outbreaks considered elsewhere.
	Additional (outside the schematic in Appendix F, but contributing to individual steps) knowledge needs:			
	Energy requirement of larvae, importance of timing in food supply	Can larval survival be boosted through short bursts of energy? There are no data on natural mortality of larvae.	Nothing done specific on this question, see citations for food quantity	**Significant gap**
	Presence of larvae in time and space, in conjunction with WQ parameters	Understanding requirements of larvae in natural environments	(Suzuki et al. 2016)	**Significant gap** Hardly any info on WQ (beyond modelled or satellite chlorophyll) on mid-shelf reefs, on GBR

	Determinants Developmental speed/ Larval resilience to oligotrophic conditions	· Faster larvae less mortality (but less connectivity)? · Influence of spatio-temporal variation of plankton on larval development/growth · Determine if larvae can take up dissolved organic matter	· Food quantity: (Uthicke, Liddy et al. 2018) (Lucas 1982; Lucas 1984; Olson 1987; Okaji 1996; Brodie et al. 2005; Fabricius et al. 2010; Uthicke et al. 2015b; Wolfe et al. 2015a; Wolfe et al. 2015b; Pratchett et al. 2017b; Wolfe et al. 2017; Uthicke et al. 2018) · Quality: anecdotal, comments in above literature, some info on general sources and different algae (Ayukai & Hoegh-Guldberg 1992; Ayukai et al. 1993; Ayukai 1994; Okaji et al. 1997; Nakajima et al. 2016; Mellin et al. 2017) · Microbial: (Carrier & Reitzel 2018) (urchins); (Carrier et al. 2018)	**Significant gap** · Despite considerable work using nearly exclusively lab-based experiments · Natural development, growth and mortality rates · Natural supply and quality of food · How do changes in microbial communities affect larval survival? · Links to water quality?
	How does depth stratification of food and WQ stressors influence COTS larvae (e.g., growth, development, swimming ability)?	· Can they exploit organic matter and algae often accumulated in deeper layers?	No information	**Important gap**
	Location of larvae in the water column	· How do the larvae position themselves in the water column with regard to food, depth, time of day, thermal/salinity stratification, hydrodynamics etc.	Chan et al. conducted a pilot study	
	Importance of natural (e.g., upwelling, N-fixing) nutrient injections vs land runoff	need to understand 'anthropogenic' component of outbreaks	Detailed information on inputs and processes missing: (Furnas et al. 2011) Some info for GBR upwelling in (Andrews & Gentien 1982; Furnas & Mitchell 1996)	**Important gap**
	Significance and cause of the Swains outbreaks How does the WQ issue translate to other regions where outbreaks are observed without impacts from river runoff? E.g., the Swains (upwelling?)	If it is nutrient caused, it would confirm limitation hypothesis	(Miller et al. 2015) Comments on the "Capricorn Eddy" in (Weeks et al. 2010)	Some gaps

	Promotion of secondary, tertiary, etc outbreaks and connectivity	Are causes the same as primary? Are secondary outbreaks inevitable after primary outbreaks established, driven be shear number of larvae?	(Wolanski & Kingsford 2014; Condie & Condie 2016; Brodie et al. 2017) (Harrison et al. 2017) suggest high connections among locations but lacked power to test for recency of locational connections and strength of population expansions	**Important gap**
	Are there larval trade-offs between the benefits of enhanced food / phytoplankton supply and tolerating pervasive water quality stressors (e.g., sediments, salinity)?	Why no COTS inshore?	Some data on salinity exist (Allen et al. 2017) Early culture studies suggested lowering salinity to 30-32 increases culture success/decreases mortality (Lucas 1973; Keesing et al. 1997) but this is not supported by the results of Allen et al. (2017).	Gap.
Predator removal	Spatiotemporal variability in the abundance of key predators of gametes, larvae, juveniles, and adults	· Assess whether the spatiotemporal distribution of planktivores coincide with COTS recruitment rates · Can patterns of predator abundance explain areas of outbreaks?	Eggs: (Lucas et al. 1979; Cowan et al. 2016b; Cowan et al. 2017b) Juveniles: (Sweatman 1995; Rivera-Posada et al. 2014) Adults: (Cowan et al. 2017b) Life stage not specified: (Kroon et al. 2020) Predator abundances: (Dulvy et al. 2004; Sweatman 2008)	· Identify key predators · Abundance, distribution and exploitation level of these putative predators · What structures predator populations?
	What are key (functionally important) predators of COTS?	It is not enough to simply document which predators are seen feeding on COTS, but actually distinguish those capable of having meaningful impacts on population dynamics, and quantify their potential influence	Kroon et al. (2020) use eDNA to add to the list of putative predators, based on both direct observations and gut content analysis (e.g., Cowan et al. (2017b))	Need to explicitly quantify feeding rates of predators and predation rates for each relevant life-stage of the COTS (see below)
	Spatiotemporal variability in lethal predation rates for gametes, larvae, at settlement, juveniles and adults	· Gamete concentrations · Time of day of gamete release · Spawning synchrony · Juvenile/adult exposure and behaviour	(Ormond et al. 1990; McCallum 1992; Morello et al. 2014)	Measure predation rates in the field

	Role of Giant Triton	The genesis of the predator removal hypothesis relates to overfishing of giant Triton, but subsequent analysis challenge if these animals would have ever been capable of effective regulation of COTS populations	Endean (1969); Ormond et al. (1990) questioned the capacity of Giant Triton to effectively regulate densities of COTS and prevent population explosions (Hall et al. 2017a)	Do outbreaks occur regardless of "high" or natural densities of Giant Triton, either in past or on reefs (if they exist) that were spared from overfishing? What are the feeding rates (and preferences) of Giant Triton in the wild?
	Functional responses of putative predators (prey-switching)	Accurately model the role of predation in suppressing outbreaks	(Ormond et al. 1990; McCallum 1992; Morello et al. 2014; Cowan et al. 2020)	Field predation rates and how these changes based on variability in the abundance of prey (i.e., COTS)
	Effects of sub-lethal predation on energy allocation and reproductive capacity	Quantify the indirect effects of predation on COTS population replenishment	(McCallum et al. 1989; Budden et al. 2019)	Measure key reproductive traits in intact vs. injured starfish (e.g., fecundity, egg size, GSI)
	Behavioural and demographic consequences of changing predation risk	Show whether the presence/abundance of putative predators affect the behaviour (i.e., exposure, activity) and demography (i.e., size/age-class distribution) of COTS		· Reef-level survey of presence/abundance of putative predators · Associated changes in behaviour · Demography of populations within specific reefs
	Effects of zoning on the incidence of outbreaks and sub-lethal predation	Show whether the level of fishery protection is correlated with the incidence of outbreaks or incidence/severity of sublethal injuries	(Sweatman 2008; Rivera-Posada et al. 2014; Sweatman et al. 2016; Messmer et al. 2017; Vanhatalo et al. 2017; Wilmes et al. 2019; Pratchett et al. 2020)	Aside from zoning, correlate incidence of outbreaks and injuries with actual predator abundances (i.e., fish) within reefs
	Predation in different habitats	· Invertebrates may prey on juveniles in rubble vs. fish preying on young adults when they switch to corallivory. · The juveniles are also vulnerable to mortality caused by corals.	(Keesing & Halford 1992; Keesing & Lucas 1992; Sweatman 1995; Keesing et al. 1996; Keesing et al. 2018; Wilmes et al. 2019; Deaker et al. 2021)	· Distribution of putative predators among different habitats · Predation rates at different ontogenetic stages
Inherent life-history traits and dynamics	· Data on outbreak frequencies prior to 1960.	This would resolve if current outbreak frequencies are natural and if outbreaks do occur without anthropogenic impact.	(Cameron et al. 1991; Fabricius & Fabricius 1992; Henderson 1992; Henderson & Walbran 1992; Keesing et al. 1992; Pandolfi 1992; DeVantier & Done 2007)	· What is the natural periodicity?
	· Information on COTS outbreaks from regions with limited anthropogenic impacts e.g., more remote island nations?	Problem: Even small island nations often overfish, all coral reefs are impacted by humans, at least through CC and OA.		· What are the dynamics of outbreaks in other locations (especially with low human impacts)? · How does food (coral) availability feed-back on outbreak dynamics

	Spatiotemporal variability in reproductive output (fecundity, spawning, and fertilisation)	The level of synchronicity in time and proximity in space is an important variable determining reproductive outputs	(Babcock & Mundy 1992b; Caballes & Pratchett 2017b; Budden et al. 2019; Uthicke et al. 2019)	Some knowledge exists, but these are snapshots in time and space. Factors promoting or disrupting outbreaks are important to know (link to Control Options)
	Spatiotemporal variability in larval retention versus dispersal	· Are there conditions occurring naturally every 15-20 years which facilitate outbreaks (El Nino/La Nina, etc)? · Links to favourable connectivity patterns? Changes in current/water flow during El Nino years (e.g., as was potentially linked for lobsters further north)?	(Dight et al. 1988,1990; Hock et al. 2014; Wooldridge & Brodie 2015; Hock et al. 2017)	· Relative ratios of larval retention vs dispersal unknown · For dispersers, is dispersal predictable and does it match biophysical model predictions?
	Spatiotemporal variability in settlement rates	· Links to favourable connectivity patterns? · Links to habitat availability?	(Cowan et al. 2016a; Wilmes et al. 2020b)	Effects of larval supply on settlement unknown
	Larval adaptive traits for successful development in tropical waters	· Larval phenotypic plasticity in food capture system · Ability to clone in response to food levels – to balance larval population and resource availability · The potential for eternal larvae as appears the case in the Caribbean · Some independence of food due to augmentation from potentially phototrophic microbiome	(Wolfe et al. 2015b; Wolfe et al. 2015a,2017; Carrier & Reitzel 2018; Allen et al. 2019) · Allen et al. In prep – cloning in response to disturbance and presence of predators · On eternal larvae: We have a huge dataset of plankton samples, never detected COTS larvae outside summer (see Uthicke et al. 2019)	· What is the nature of the microbiome of larvae in nature? · If autotrophs are present, do they provide larvae with nutrients?
	· Juvenile density - herbivorous stage in non-outbreaks	· Availability of food items at key stages in the life cycle may constrain or promote population irruptions	(Deaker et al. 2020a; Deaker et al. 2020b; Wilmes et al. 2020b)	· To what extent does overall abundance (or availability of specific food types) limit the population dynamics of COTS?
	· Juveniles in waiting - phenotypic plasticity in biology and physiology	· Presence of algal feeding juveniles between outbreaks need to be established		· Need to determine age and food source of juveniles in the field during and between outbreaks
	· Effects of food-limitation on fitness and survival of benthic life stages (algae and coral)	· Ability to switch between coral and algal food sources - reverting to algae when coral is unavailable	Deaker et al. (2021)	

	Stock-recruitment relationships	High levels of larval retention and strong stock-recruitment relationships within initiation box are fundamental to demonstrating the initiation of outbreaks independent of any major anthropogenic disturbances	(Wilmes et al. 2018; Wilmes et al. 2020b)	· Influence of live coral/coral rubble cover on settlement success at small and large scale. · Is there a role of larval cloning in population build up?
	Timing of spawning events	Narrow down time window to understand hydrodynamics; multiple spawning events in a season?	(Pratchett et al. 2014; Uthicke et al. 2015b; Keesing et al. 2018; Uthicke et al. 2019)	Basics understood, but details on triggers still needed
	Cohort identification (both juveniles and adults)	· Evidence for natural build-up of larvae/juveniles over time? · How old are COTS? · Can the spine pigment bands ground-truthed with tagging provide an indication of age?	(Stump & Lucas 1990; Souter et al. 1997; Stump & Lucas 1999; MacNeil et al. 2017; Keesing et al. 2018; Deaker et al. 2020a)	**Large knowledge gap** See MacNeill et al. 2017
	Population build-up prior to/leading to aggregation	· Do adults change behaviour as population levels increase? · What is the relative influence of chemical, visual and other cues on aggregation behaviour? · How do the adults behave in low-density populations?	(Black et al. 1995; Sigl & Laforsch 2016; Sigl et al. 2016)	
	Thresholds that signal potential switch from background population levels to outbreak	Can we identify particular "tipping points" for this, by e.g., looking at larval influx, or juveniles or adults?	(Rogers et al. 2017)	
	Individual condition and fitness of high-density populations following declining prey availability	Need to understand what ends an outbreak?	(Rivera-Posada et al. 2012; Høj et al. 2018)	**Large knowledge gap**
	Juvenile-adult interaction (semio-chemicals)		No information	
	Juvenile biology and physiology		Deaker et al. (2021)	
Observed and projected environmental change	Effects of increasing temperature on larval development and survivorship	Projected changes in environmental conditions may accelerate larval development, but also probably depends on availability of prey resources to fuel development as well as the changes that might occur in the microbiome and algal species and nutrient quality with increased temperature	(Hoegh-Guldberg & Pearse 1995; Kamya et al. 2014; Lamare et al. 2014; Uthicke et al. 2015b)	Some gaps.

	Effects of increasing temperature on juvenile development and survivorship	The trade off in ability to undergo enhanced growth at increased temperature and food availability	Nothing available	
	Effects of increasing temperature on fitness and survival of adult crown-of-thorns	Apparent declines in the abundance of COTS in northern GBR during 2016 heatwave and bleaching has raised questions about how adult COTS respond to high temperatures. Can they withstand high temperatures? Is there a potential depth refuge?	Bethan Lang PhD research shows temperature sensitivity, based on metabolic rates and survival of adult COTS under different experimentally imposed temperatures	**Important gap** Need field-based information to elucidate behavioural responses of adult COTS during heatwaves and what temperatures lead to elevated adult mortality. Monitoring of deeper reefs possibly serving as refuges. Also, are adults even more susceptible during pre-spawning period, owing to energy invested in gonads?
	Effects of increasing temperature on settlement and recruit survivorship	· Does temperature increase promote outbreaks by improve settlement success and survivorship? · What are the transgenerational effects of heatwaves/increased temperature?	Nothing available, but TGP-temperature studies of other echinoderms are appearing in the literature.	**Important gap**, and clearly testable hypothesis
	Effects of coral bleaching in moderating reproductive capacity and/ or recruitment success (and predation?)	COTS are often attracted to injured corals and so may feed disproportionately on bleached corals, elevating rates of coral mortality during such events.	No literature (possibly part of Bethan's project?) (Keesing et al. 2019; Hue et al. 2020)	**Important gap** to understand wider ecosystem implications on COTS outbreaks. Tank-based feeding preferences for bleached versus unbleached corals will be easy to implement, but broader ramifications of such behavioural shifts require field sampling before vs during bleaching events. Field based studies important but requite high degree of operational flexibility (opportunistic field trips when corals have bleached on COTS infested reefs)
	Climate effects on water flow patterns, larval aggregation/ connectivity and cyclones	· Possibly links with row 4 above - are there cyclical events where water flow patterns change? · Do cyclones disrupt the boulder habitat of the juveniles and cause mortality.	Wooldridge & Brodie (2015) use long-term data on environmental conditions associated with initial onset of outbreaks for GBR to suggest that water retention is important	Need to better understand timing and mechanisms that promote build-up of starfish densities at key reefs within initiation box. Need to know if these outbreak promoting conditions are more likely in CC scenarios.

	· Will sustained declines in coral cover and corresponding shifts in the structure of coral habitats impede or promote population irruptions? · Do food sources for early juveniles (e.g., CCA) change with climate change.	Given the reliance of COTS on live corals it might be expected that low coral cover would constrain future outbreaks, but could also be some positive feedbacks associated with reef degradation (e.g., more coral rubble to promote settlement).	· Wilmes et al. (2020b) show importance of coral rubble as settlement habitat. · Wilmes et al. (2020a) model ontogenetic shifts in diet and constraints imposed by lack of coral prey; Deaker et al. (2020a) show that COTS in captivity may effectively delay diet shifts and development until coral prey is available.	What are the key limitations (population bottlenecks) that influence local abundance of COTS, and how might these change with shifts in reef structure?
	· Effects of Ocean acidification on fertilisation, larvae and juveniles and on settlement substrates of COTS. · Interactive effects of multiple stressors (warming, acidification, eutrophication, sediments, salinity) on fertilisation, larvae and juveniles and on settlement substrates of COTS.		(Uthicke et al. 2013; Uthicke et al. 2015a; Kamya et al. 2016; Kamya et al. 2017; Kamya et al. 2018; Hue et al. 2020)	
	Effects of environmental change on habitat availability/suitability	Reef degradation hypothesis		
Multiple Causes	Interactions among alternative drivers	Even if specific anthropogenic drivers only partly contribute (e.g., exacerbate) to outbreaks, thy might still represent important management levels	Nutrient and larval retention: (Wooldridge & Brodie 2015) Qualitative models suggest that there is a role for both predation and nutrients: (Babcock et al. 2016). See modelling papers (in press) by Sam Matthews.	**Significant gap** Potential modelling of new (or existing) data (to establish independent contribution of different drivers in a complex system, and to establish circumstances under which some drivers become more important.

Nutrient enrichment/terrestrial runoff. The notion that primary outbreaks of *Acanthaster* spp. may arise due to enhancement of larval survivorship through nutrient enrichment has been proposed several times (e.g., Pearson and Endean 1969; Lucas 1973; Nishihira and Yamazato 1974; Birkeland 1982; Brodie 1992; Brodie et al. 2005; Fabricius et al. 2010). Birkeland (1982) suggested that outbreaks of *Acanthaster* spp. at several locations in Micronesia and Polynesia tended to occur 3 years after extremely heavy rainfall events, often preceded by extended droughts. Birkeland (1982) argued that such events provide a pulse of nutrients that stimulate phytoplankton blooms, which supplement otherwise-limited food for COTS larvae. Lucas (1973) and Fabricius et al. (2010) suggested a similar mechanism for primary outbreaks on the GBR, and Brodie et al. (2017) suggested this is also relevant for the spread of secondary and further outbreaks.

To fully understand whether the nutrient hypothesis has merit, a number of significant knowledge gaps were identified and summarised in schematic shown in ***Appendix F***. The main gaps include:

- Do (original or transformed) nutrients and/food sources reach the initiation box of COTS outbreaks?
- Which nutrients are enhanced through runoff, and where do these get to?
- What is the relationship between nutrient supply and phytoplankton abundance/species composition? And are these the species on which COTS thrive?
- Where in the water column do larvae live? If these can exploit food readily available in deeper water column layers this would have significant impacts on interpreting nutrient limitation and connectivity.
- Is there a spatiotemporal variability in larval abundance and condition? And does increase phytoplankton leads to higher survival rates of COTS larvae and increased recruitment?
- Do high recruitment rates increase adult populations? And do high adult populations lead to secondary outbreaks?

Predator removal. The predator removal hypothesis was one of the first hypotheses proposed to account for COTS outbreaks (Endean 1969). Endean (1969) argued that initial outbreaks on the GBR (in the late 1950s and early 1960s) followed extensive over-fishing of giant triton. This removal of a purportedly “key” predator relaxed normally strong regulatory pressure on abundance of juvenile and sub-adult COTS, leading to increased abundance of large adult sea star that were capable of initiating outbreaks by virtue of their massive combined reproductive output. The predator removal hypothesis has evolved through time to place increasing emphasis on fish predators, and there is evidence that outbreaks are less prevalent in areas where there is limited fishing effort (Dulvy et al. 2004; Sweatman 2008), presumably due to higher abundance of key predators. The fundamental problem of the predator removal hypothesis is that it does not explain the dynamic nature of outbreaks, because widespread and sustained declines in the abundance of putative predators would in and on themselves, be expected to lead to sustained increases in abundance of COTS.

A number of knowledge gaps were identified within this driver including:

- Basic information such as the types of predators for individual live history stages is still scarce.
- Spatiotemporal variability in the abundance of key predators of gametes, larvae, juveniles, and adult COTS is unknown.
- What are the effects of zoning on the incidence of outbreaks and sub-lethal predation? The need to include investigation of food chain effects, because fished species may not be directly preying upon COTS, but their overfishing influences biomass on lower trophic levels. This can be particularly important to explain (mainly invertebrate?) feeding on juvenile COTS.

Inherent life-history traits and dynamics (Natural causes). There is widespread acknowledgement that COTS, like many other echinoderms with planktotrophic larval stages (Uthicke et al. 2009), are predisposed to major population fluctuations, owing to their inherent life-history characteristics, such as high fecundity and developmental plasticity. It seems

undisputed that outbreaks have happened prior to the 1960s, but there are suggestions these have become more frequent. The underlying question of this section is if outbreaks at the current frequency are natural, and what are the life-history dynamics facilitating this.

A number of knowledge gaps were identified within this driver including:

- Spatiotemporal variability in larval retention *vs* dispersal: What are the ratios of larval retention *vs* dispersal? For dispersers, is dispersal predictable and does it match biophysical model predictions?
- Effects of food-limitation on fitness and survival of benthic life stages (algae and coral): To what extent does overall abundance (or availability of specific food types) limit the population dynamics of COTS?
- Thresholds that signal potential switch from background population levels to outbreak: Can we identify particular "tipping points" for this, by e.g., looking at larval influx, or juveniles or adults?
- Is there a 'hidden army' of juveniles waiting by delaying development through remaining in pre-adult CCA feeding stage ("Peter Pan Hypothesis" - Deaker et al. 2020a)?

Observed and projected environmental change. Climate change and ocean acidification have profound effects on coral reefs (Fabricius et al. 2011; Hughes et al. 2018), but only a few experiments have thus far investigated individual or interactive effects (potentially outbreak-promoting or inhibiting) on COTS. In turn, the role or severity of impacts by COTS may also change due to climate change. COTS would feed on the remaining coral and indiscriminately also eat potential heat tolerant genotypes selected during heatwaves. Given lower food supply for adult COTS (i.e., corals) may exist in the future it is also conceivable that outbreaks become less frequent.

A number of knowledge gaps were identified within this driver including:

- What are the effects of increasing temperature on fitness and survival of adult COTS? Including behavioural responses of adult COTS during heatwaves and what temperatures lead to elevated adult mortality.
- What are the effects of increasing temperature on settlement and recruit survivorship? Does temperature increase promote outbreaks by improve settlement success and survivorship? What are the transgenerational effects of heatwaves/increased temperature?

Multiple causes. Although earlier ecological thinking leaned toward explaining ecological phenomena with individual drivers (often top-down *vs.* bottom up, e.g., predation pressure *vs.* nutrient stimulation), it seems more likely that drivers can interact, or that a combination of drivers leads to outbreaks. For instance, a qualitative model (Babcock et al. 2016) suggested that both overfishing of COTS predators and increased nutrient runoff is the most likely explanation for COTS primary outbreaks. It is easily conceivable that increased temperatures could also contribute to this, e.g., by altering current patterns and connectivity, altering settlement cues or promoting larval survivorship.

- The interactions among alternative drivers are unknown. Potential modelling of new (or existing) data to establish independent contribution of different drivers in a

complex system, and to establish circumstances under which some drivers become more important.

7.2 Research Opportunity scoping

The Proximal Causes of Outbreaks Program Area Gap Analysis generated a large and detailed list of important gaps in the knowledge of causes of COTS outbreaks. These Knowledge Gaps were discussed in a combined meeting with the Biology and Ecology Team on 15 January 2021 (via Zoom). After a thorough examination of the potential Research Opportunities the PC Team originally scoped 14 ROs. These opportunities were generated considering a balanced examination of the different drivers of COTS outbreaks (***Figure 7.1***), the pressing need to advance particular knowledge important for population control and monitoring and surveillance as well as incorporating the specific strengths of the group of experts in the Program Area. After the January discussion it became clear that RO PC-3 and PC-4 overlapped and that it was more appropriate to combine these in a single RO, keeping the number of the first (PC-3), also it became clear that PC-7 had a better fit within the Biology and Ecology Program Area and it was moved to this program ROs. To avoid confusion, since all ROs had already been assigned a number, these two numbers (PC-4 and PC-7) were taken away instead of reassigning them to other proposals. The final list of 12 Research Opportunities, including their titles, is given in ***Table 7.2***.

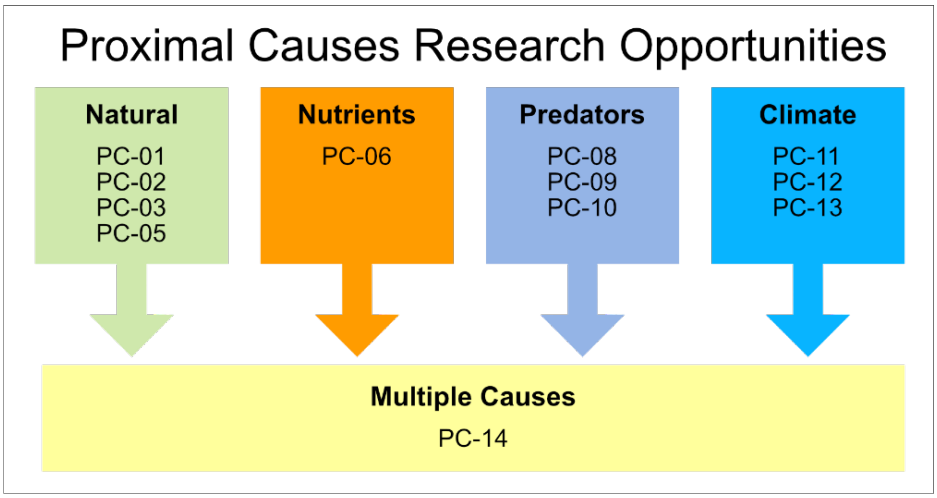

Figure 7.1 Diagram indicating how the Research Opportunities cluster into the five outbreak hypotheses.

Table 7.2 List of research opportunity titles put forward by the team. Note: research costs are indicative only, and are total costs including institute overheads and contributions.

RO #	Proximal Causes of COTS Outbreaks Research Opportunity Title	Estimated Cost ($)
PC-1	Using genomics to improve knowledge of larval connectivity	$276,837
PC-2	Effects of prey limitation on the boom and bust of COTS populations	$332,950

PC-3	Juvenile resilience hypothesis - the potential that reserve populations of herbivorous COTS may seed outbreaks and juvenile-coral and juvenile-adult interactions – assessing the potential for semio-chemical communication	$188,500
PC-5	COTS larvae in low salinity plumes – impacts of multiple water quality stressors on larval success	$111,500
PC-6	Understanding the nutrient hypothesis: Spatio-temporal abundance of COTS larvae in relation to water quality and nutrient sources, nutrient transformation and larval food demand	$985,898
PC-8	The other 90% - resolving the impact of benthic and cryptic predation on COTS	$571,960
PC-9	Quantifying predation rates on adult crown-of-thorns starfish relative to fisheries management zones and corresponding differences in abundance of putative predators	$432,850
PC-10	Models to test the efficacy of top-down predator control on COTS	$244,500
PC-11	Effect of elevated temperature and coral bleaching on distribution, feeding behaviour and physiological condition of crown-of-thorns starfish	$251,100
PC-12	Effects of ocean warming and marine heatwaves on settlement success and population replenishment of crown-of-thorns starfish	$95,350
PC-13	Modelling the potential effect of substate change and coral health on COTS dynamics and future COTS outbreaks	$202,500
PC-14	Data-driven dynamic models to interrogate multiple COTS outbreak hypotheses	$200,000
	Total Estimated Cost ($)	**$3,893,945**

Below we list the scope of these Research Opportunities in detail and also list linkages to other opportunities. It should be noted that there is a strong tie between the PC and BE research areas and the areas have closely collaborated in developing opportunities. Several important Research Opportunities listed under BE are also important for understanding the proposed hypothesis, and vice versa.

PC-01 uses **full genome sequencing of adults and larvae to improve knowledge of larval connectivity**. This work will investigate whether dispersal occurs from select source reefs or whether pulses of recruits originate from many simultaneous sources with the aim to understand whether dispersal is predictable and especially if it matches biophysical model predictions. It will help narrow down the location of the initiation box and help inform regional control efforts. This RO has strong synergies with several ROs, since it has the potential to contribute refined knowledge on dispersal to modelling and design of regional control strategies (DSM-6, DSM-12), investigations into COTS ageing (BE-2), larval detection (PC-6, MS-5), recruitment (BE-3), and monitoring (MS-14).

PC-02 focusses on the **effects of prey limitation on the boom and bust of COTS populations** and addresses important knowledge gaps (Spatiotemporal variability in reproductive output; Individual condition and fitness of high-density populations following declining prey availability; effects of prey-limitation on survival of benthic life stages) in the Natural Causes hypothesis. The consensus is that, although this RO has two independent components (Population Boom and Population Bust) that can be split and may assist in better sharing of resources (e.g., combine fieldwork with BE-3 and control vessels), it has a strong potential to contribute basic knowledge to better model and monitor COTS outbreaks.

PC-03 Juvenile resilience hypothesis - the potential that reserve populations of herbivorous COTS may seed outbreaks and juvenile-coral and juvenile-adult interactions – assessing the potential for semio-chemical communication, was considered a very innovative RO although with multiple components presenting overlaps/synergies with several other ROs (plasticity component with BE-4, BE-8, and PC-8; and semio-chemicals with C-5). One basic premise of the RO: Are we creating opportunities for population replenishment by juveniles by removing adults? Is an important gap in the Natural Causes/inherent; life history trait hypothesis) that is not addressed elsewhere.

PC-05 COTS larvae in low salinity plumes – impacts of multiple water quality stressors on larval success addresses a knowledge gap in the Nutrient/runoff hypothesis: Are there larval trade-offs between the benefits of enhanced food/ phytoplankton supply and tolerating pervasive water quality stressors (e.g., sediments, salinity)? Although not clear how this knowledge can be incorporated in present COTS management, it is important in disentangling different components of the effect of freshwater plumes on COTS outbreaks and the more general knowledge on the proximal causes of the outbreaks and links to water quality improvement. This data can also potentially be integrated into dispersal models (DSM-6; DSM-12).

PC-06 Understanding the nutrient hypothesis: Spatio-temporal abundance of COTS larvae in relation to water quality and nutrient sources, nutrient transformation and larval food demand is a comprehensive package clearly addressing all major knowledge gaps (ranging from nutrient transformation and transport to larval ecology) in the Nutrient hypothesis. This knowledge will improve modelling and monitoring and may contribute to argument for better land management. The cost may look large but relates to how comprehensive and multifaceted it is with complementary field, aquarium, and lab work, including a dedicated Postdoc (50% funded by AIMS).

PC-08 The other 90% - resolving the impact of benthic and cryptic predation on COTS addresses important knowledge gaps on early-stage predation of COTS after settlement in rubble, including the characterisation of benthic predators, their distribution and food webs involving COTS. The project has already merged initial proposals on eDNA to save costs and could combine fieldwork with BE-1, BE-5 and PC-9 to further reduce costs. The project may benefit from knowledge generated by RRAP on rubble substrate and incorporating a preliminary study at Heron on cryptic predators. Data collected from this RO would help inform models (e.g., PC-13; PC-14; DSM-5; DSM-6) thus enhancing path to impact.

PC-09 Quantifying predation rates on adult crown-of-thorns starfish relative to fisheries management zones and corresponding differences in abundance of putative predators. This opportunity will fill important gaps in the knowledge of predation of COTS and will explicitly compare zones within the GBR with different managements. Although it requires extensive fieldwork, it can be combined with PC-8 to reduce costs. It has strong synergies with PC-10 and data collected from this RO can be directly incorporated into models, enhancing path to impact.

PC-10 uses **ecological models (e.g., MICE) to test the efficacy of top-down predator control on COTS** to better understand whether predators may play a role in supressing COTS outbreaks (Predation hypothesis). This RO would incorporate data from various field-based studies (e.g., BE-08 and PC-09) and is able to cover larger spatial scales that are not possible with field work alone, and test various management and control scenarios based on

findings from the field. Thus, intersecting with several opportunities from BE and PC areas. It also has strong synergies with ROs from other areas including Population Control and Decision Making such as C-08, DSM-05 and DSM-11.

PC-11. This RO focusses on the **effect of elevated temperature and coral bleaching on distribution, feeding behaviour and physiological condition of COTS**. This is a timely research, since it is important to start considering how outbreaks will evolve under climate change. The fieldwork is dependent on comparing bleaching *vs* non-bleaching years/areas, so there is a suggestion to focus on the experimental work and replace fieldwork with existing datasets; alternatively, fieldwork can be opportunistically combined with fieldwork from other ROs. It will also help inform models of local and regional population dynamics (DSM-5; DSM-6).

PC-12 This RO explores the **effects of ocean warming and marine heatwaves on settlement success and population replenishment of COTS**. This research has clear synergies with PC-11 and it was suggested that these two ROs can be merged noting that this will possibly require changes to scope and scale of the RO. The findings of this opportunity could support coral recovery after bleaching.

PC-13 Modelling the potential effect of substate change and coral health on COTS dynamics and future COTS outbreaks will assess how changes to corals reefs due to climate change (such as coral bleaching, coral decline, rubble bed extent among others) may impact COTS population dynamics and future outbreaks. Although this model depends on data generated by other PC ROs, it can be developed in parallel and can also be scaled to target key interests. The usefulness of this model relies on the capacity of testing scenarios to prepare management to react appropriately to future outbreaks and thus would benefit from synergies with DSM-09 which explores model uncertainty and how best to account for this uncertainty.

PC-14 Data-driven dynamic models to interrogate multiple COTS outbreak hypotheses seeks to evaluate the evidence for causality of multiple outbreak hypotheses, both in isolation and combination, with the use of dedicated modelling tools in order to inform practical management action. This RO is highly synergistic with other PC ROs as it can be developed in parallel and receive data from these projects alongside existing data sources. This opportunity will add value to the PC Area by synthesising and evaluating the relative strength of evidence for different hypotheses across spatial scales and will lead to actionable management and control outcomes. As such, the opportunity is also highly synergistic with modelling effort that will guide control decisions and prioritisation efforts (e.g., DSM-5; DSM-6).

7.3 Research Opportunity assessment

Research Opportunities were assessed independently by all participants. Similar to all other Program Areas, participants scored Research Opportunities across standard Evaluation Criteria (**Table *3.1***) using an online survey form. The outcomes of these assessments were discussed on 05 March 2021 (via Zoom) at a joint workshop with the Biology and Ecology Program Area.

In general, there was little distinction in the scores between Research Opportunities (***Figure 7.2***). Most scores with intermediate values in the first 3 criteria and innovation potential, and low values for socioeconomic co-benefit. All projects scored relatively high in the time to viability and risk (i.e., they are associated with a low risk) criteria and were highly connected to other projects. The fact that all projects were highly similar in scores was emphasized when plotted as a spider diagram (***Figure 7. 3***). Most projects scored similar for each of the individual criteria.

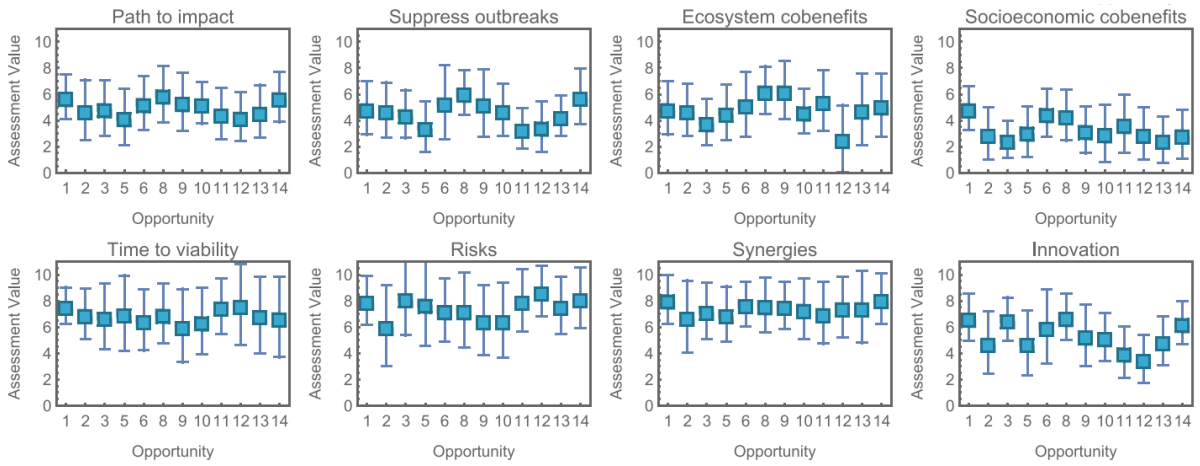

Figure 7.2 Assessments of the 12 Proximal Causes Research Opportunities across each Evaluation Criteria (all except research and implementation costs). Values are weighted means. Error bars represent standard deviation and are provided to give an indication of range of responses.

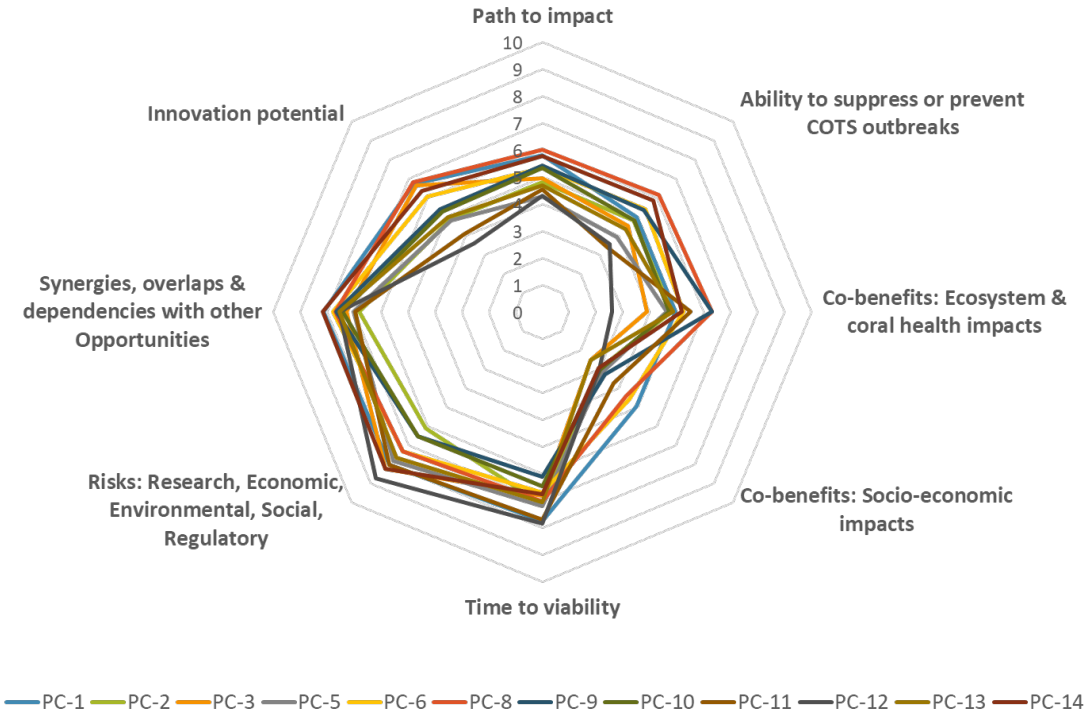

Figure 7.3 Spider chart highlighting differences in the weighted means of assessments against Evaluation Criteria across the 12 Proximal Causes Research Opportunities.

7.4 Recommendations on priority Opportunities

The brief for this area was to provide in-depth analysis of the conditions, processes and mechanisms that directly influence the likelihood and timing of a COTS outbreak as well as its scale and subsequent propagation. This program area has thus identified Knowledge Gaps and developed recommendations on an R&D program to address such gaps.

In all ROs in this program area there is an impact pathway towards maximising the potential to prevent COTS outbreaks. The main impact pathway is that work proposed here ***could improve the ecological underpinning for COTS management, i.e., improved biological understanding.*** Knowledge of drivers is needed to justify management actions, understand the factors impacting the efficacy of management actions and to decide which management actions or direct controls are more effective and the appropriate timing of these for maximum effectiveness. In case of work towards understanding the nutrient hypothesis, we can reveal the relevance of WQ targets and regulations for improved land management. In the case of work towards understanding predation a clear tool available for management action is changes in reef-zoning. Thus, the quickest path to impact for many of the ROs in this program area is for the field-based studies to generate data that (1) can be used to inform model structure and guide development, and (2) be incorporated directly into the models for model validation, with these models then ultimately used to test different COTS control measures and assess their performance.

The second main impact pathway is that research in this theme area ***could improve the performance of the current control measures, i.e., improved surveillance enabling more efficient targeting of control.*** For example, the eDNA based larval research will go hand-in-hand with the larval monitoring proposed in the MS program area. In addition, understanding the causes of outbreaks is required to design an early detection monitoring considering conditions (water quality, temperature, currents etc.) promoting outbreaks. It will also help parameterise models that will inform control decisions for the current COTS control program.

A detailed **gap analysis** has identified several important Research Gaps, grouped into major outbreak hypothesis (‘Natural Causes”, “Nutrients”, “Predation”, “Climate” and “Multiple Causes”). The team clearly identified research into each of those hypothetical causes as **‘must have’**. A total of 12 Research Opportunities were put forward from the team, including aquarium/laboratory studies, field research and modelling studies. Given that ROs are well interlinked and practically indistinguishable, according to the scoring system (see ***Figure 7.3***), and each address one to several important Knowledge Gaps, the team has also agreed to rank all Research Opportunities as **‘must have’**.

8 RESULTS – COTS BIOLOGY AND ECOLOGY

As a cross-cutting program (see section 2.2.5), the Biology and Ecology Program Area (BE PA) was tasked with identifying current gaps in knowledge relating to the biology and ecology of COTS that could potentially constrain the realization of the overarching goals for CCIP and all other Program Areas. The focus, therefore, was not so much on innovation, but in delivering a comprehensive and systematic assessment of knowledge gaps, and designing corresponding research activities (or Research Opportunities) aligned with apparent knowledge gaps. Crucially, it was highlighted from the outset, that all decisions about the relative importance or significance of knowledge gaps relating to the biology and ecology of COTS should be greatly influenced by the activities and requirements of other Program Areas. This is not to say that the information to be provided by the Biology and Ecology Program Area would not be important in its own right, but the application of this information would likely occur in other Program Areas, including Proximal Causes, Decision Support and Modelling, Monitoring and Surveillance, and Population Control.

8.1 Gap analysis

To identify knowledge gaps relating to the biology and ecology of COTS, the first formal meeting of BE PA was held on 27 October 2020 (via Zoom) and attended by all BE PA team members (see ***Table 2.5***), as well as technical leads for all other Program Areas. This meeting started with a provisional overview of recent research activities, including updates on relevant research that had been published since the last major reviews on COTS biology and ecology (e.g., Pratchett et al. 2017). More critically, however, discussion centred around the most relevant framework for assessing and compiling extensive prior information on the biology (e.g., demography) and ecology (e.g., behaviour, interactions and impacts) of COTS. Several alternative frameworks were considered, including (a) using lists of knowledge gaps or research questions posed in previous reviews, following Pratchett et al. (2017), and (b) established horizon scanning methodologies (*sensu* Sutherland and Woodroof 2009), following Pratchett et al. (In review). Ultimately, however, it was decided that an entirely novel approach was needed to ensure that comprehensive consideration was given to all key life-history stages and processes (***Table 8.1***).

The framework for assessing knowledge gaps relating to the biology and ecology of COTS was based on 10 distinct life stages and processes (e.g., from gametes to gametogenesis), which were then combined into a single schema (hereafter referred to as life-history stages), throughout the life-cycle of COTS (***Table 8.1***). For each of these life-history stages, a list of key biological and ecological traits was developed; many of the fundamental traits (e.g., growth, survival, and feeding preferences) were repeated for different life-stages, but this was considered appropriate given that knowledge of such traits needed to be specific to the particular life-stage and may vary enormously with ontogeny (e.g., Wilmes et al. 2018). At this stage, no consideration was given to what was or not known about the relevant combination of life-stages and traits, though the identification of a particular traits relevant each life-stages was inevitably informed by prior research and expert working knowledge of the BE PA team members. It is possible, therefore, that there are some critically important traits that have never before been considered for COTS or related organisms (i.e., unknown unknowns), which are not therefore included in this framework. Rather, the process was biased towards traits that are known to be important based on preliminary or ancillary

research (e.g., complementary biological studies on other echinoderms; Uthicke et al. 2009), but are yet to be studied for COTS (i.e., known unknowns).

The provisional framework for assessing knowledge gaps relating to the biology and ecology of COTS was sent to BE PA team members immediately after the meeting on 27 October 2020. The framework was modified (as required) as researchers worked independently to populate the required information, identifying relevant sources of information relating to each trait and life-stage. Additional traits (though no additional life-stages) were also added following discussions with other Program Areas, facilitated by participation of the technical leader (M. Pratchett) in all other PA workshops. The intention here was not to provide a comprehensive overview of what is known, but simply identify sources of information (mostly published research articles) containing relevant information and thereby help other researchers quickly identify key sources of information on the biology and ecology of COTS (e.g., during the development of population models). To maximise the utility of information compiled (without providing actual results) it was also decided to further sperate each trait into specific "dependencies", or key factors (e.g., environmental conditions such as temperature) that influence the reported rate or value of each trait (***Table 8.1***). This process was spearheaded (at least in the first instance) by C. Caballes and M. Pratchett, who recently reviewed the reproductive biology and early life-history of COTS (Caballes and Pratchett 2014), settlement rates and processes (Wilmes et al. 2018), as well as behaviour and biology of adult COTS (Pratchett et al. 2014). Other BE PA team members (especially those with specific expertise pertaining to specific life-stages or traits) then focused on populating remaining sections of the framework. In doing so, the collective efforts of all Program Area team members inevitably led to the identification of specific knowledge gaps, i.e., traits where there is no current information, or the available information is insufficient. This systematic approach to both cataloguing what is known and what is not known was considered fundamental in meeting the requirements of other CCIP Program Areas. The systematic identification of knowledge gaps was also expected to highlight broad range of fundamental research activities to guide the development of Research Opportunities.

Table 8.1 Knowledge gaps (and also relevant source of information) relating to the biology and ecology of COTS, as identified by the BE team, across 10 different life stages (distinguished by colour). Knowledge gaps are apparent based on lack of information available, or apparent limitations in the available information. Numbers in last column relate to the Research Opportunities (RO) relevant to addressing identified knowledge gaps.

Life-History Stage	Traits	Dependencies	Key Sources	Information Available / Knowledge Gaps	RO#
Gametes (Egg, Sperm)	Survival / Mortality rate	Planktivorous predators	Cowan et al. (2017b)	No information on *in-situ* survival of gametes (Wilmes et al. 2018);	
		Gamete concentrations	Cowan et al. (2017a)	Planktivorous fish rejected pellets with higher egg concentrations	
		Chemical defense (saponins)	Lucas et al. (1979); Cowan et al. (2017a)	Saponins in eggs make them unpalatable to planktivorous fish (Lucas 1979), but Cowan et al (2017) showed that some planktivorous fish species can tolerate saponins in COTS eggs based on aquarium experiments	
	Egg size	Maternal investment	Caballes et al. (2016); Caballes et al. (2017a)	Eggs from Acropora-fed females were larger compared to those from starved and Porites-fed COTS	
		Temperature	Hue et al. (2020)	Negative effect of temperature on egg size	
		pH / pCO2	Hue et al. (2020)	OA had no significant effect on egg size	

		Density of spawners			
		Sublethal predation		Unpublished data from Messmer, Caballes, Pratchett	
	Egg shape	Maternal provisioning	Caballes et al. (2016)	Eggs from fed females, regardless of diet, were more spherical compared to those from starved female COTS	
		Temperature	Hue et al. (2020)	Negative effect of temperature on egg sphericity	
		pH / pCO2	Hue et al. (2020)	OA had no significant effect on egg sphericity	
	Sperm motility	Temperature	Caballes et al. (2017b)	Higher proportion of motile sperm and faster sperm swimming speeds at ambient pH levels compared to OA levels (pH < 7.9)	
		pH / pCO2	Uthicke et al. (2013); Caballes et al. (2017b)		
		Presence of eggs	Caballes et al. (2017b)		
	Longevity	Timing of gamete release	Benzie & Dixon (1994)		
		Proximity of spawners	Benzie & Dixon (1994)		
	Rate of polyspermy	Gamete concentrations		Not yet explicitly tested for COTS	
		Spawning synchrony		Not yet explicitly tested for COTS	
	Egg maturation / ovulation	Chemical cues	Smith et al. (2019)	Ovulation can potentially be altered to disrupt synchronous spawning	
		Environmental cues			
	Fertilization rate	Sex ratio	Babcock et al. (1994)		
		Proximity of spawners	Babcock & Mundy (1992a); Babcock et al. (1994)		
		Spawning synchrony	Babcock et al. (1994)		
		Temperature	Rupp (1973); Kamya et al. (2014); Caballes et al. (2017b); Sparks et al. (2017)		
		Salinity	Caballes et al. (2017b)		
		pH / pCO2	Uthicke et al. 2013; Kamya et al. (2014); Caballes et al. (2017b);		
Zygote (Cleavage, Gastrulation)	Cleavage rate	Temperature	Rupp (1973); Johnson & Babcock (1994); Lamare et al. (2014); Caballes et al. (2017b); Sparks et al. (2017)		
		Salinity	Caballes et al. (2017b)		
		pH / pCO2	Caballes et al. (2017b); Sparks et al. (2017)		
	Gastrulation rate	Temperature	Kamya et al. (2014); Lamare et al. (2014); Caballes et al. (2017b); Sparks et al. (2017)		
		Salinity	Caballes et al. (2017b)		

		pH / pCO2	Kamya et al. (2014); Caballes et al. (2017b); Sparks et al. (2017)		
	Developmental abnormalities	Temperature	Lamare et al. (2014); Sparks et al. (2017)		
		pH / pCO2	Sparks et al. (2017)		
Larvae (Bipinnaria, Brachiolaria)	Survival / Mortality rate	Temperature	Kamya et al. (2014)	Absolute survivorship data not explicitly analysed	
		Salinity	Lucas (1973)	Lowered salinity (down to 30ppt) favours survival	
		pH / pCO2	Kamya et al. (2014)	Absolute survivorship data not explicitly analysed	
		Food quantity	Lucas (1982); Fabricius et al. (2010); Uthicke et al. (2015b); Wolfe et al. (2017); Pratchett et al. (2017b)	High food conc. Improves survival (Lucas 1982, Fabricius et al. 2010), but has an upper limit (Wolfe et al. 2017, Pratchett et al. 2017)	PC-6, BE-9
		Fluctuations in food supply	Fabricius et al. (2010)		PC-6, PC-14
		Phytoplankton species	Lucas (1982)	Successful development only achieved with *Dunaliella tertiolecta, D. primolecta, Phaeodactylum*	
		Maternal provisioning	Caballes et al. (2016); Caballes et al. (2017a)	No difference in absolute survival between maternal provisioning treatments	BE-9
		Microbiome	Carrier et al. (2018)		BE-9
		Predation	Cowan et al. (2016b); Cowan et al. (2020)	Some planktivorous fish species feed on COTS larvae, even in the presence of larvae from other starfish species	
	Body Size	Temperature	Kamya et al. (2014); Uthicke et al. (2015b)		PC-12
		Salinity		Caballes et al. (In prep.)	PC-5
		pH / pCO2	Uthicke et al. (2013); Kamya et al. (2014)		
		Food quantity	Fabricius et al. (2010); Wolfe et al. (2015a); Uthicke et al. (2015b); Uthicke et al. (2018); Wolfe et al. (2017); Caballes et al. (2017a)		BE-9
		Maternal provisioning	Caballes et al. (2016); Caballes et al. (2017a)		BE-9
		Larval density	Uthicke et al. (2018)		
	Gut size	Temperature	Uthicke et al. (2015b)		
		Salinity		Caballes et al. (In prep.)	PC-5
		pH / pCO2	Uthicke et al. (2013)		
		Food quantity	Uthicke et al. (2015b); Wolfe et al. (2015a); Caballes et al. (2017a)		BE-9
		Maternal provisioning	Caballes et al. (2016); Caballes et al. (2017a)		BE-9

	Ciliated band length	Food quantity	Wolfe et al. (2015a); Caballes et al. (2017a)		
		Maternal provisioning	Caballes et al. (2017a)		
	Development rate	Temperature	Uthicke et al. (2015b)		PC-12
		Salinity		Caballes et al. (In prep.)	PC-5
		pH / pCO2	Uthicke et al. (2013); Kamya et al. (2014)		
		Food quantity	Lucas (1982); Fabricius et al. (2010); Uthicke et al. (2015b); Uthicke et al. (2018)		BE-9
		Phytoplankton species	Lucas (1982)		
		Maternal provisioning	Caballes et al. (2016); Caballes et al. (2017a)		BE-9
		Larval density	Uthicke et al. (2018)		
	Cloning	Turbulence			
		Environmental stress			BE-9
		Density	Allen et al. 2019		
		Food availability	Allen et al. 2019		BE-9
	Developmental abnormalities	Temperature	Kamya et al. (2014)		
		Salinity		Caballes et al. (In prep.)	PC-5
		pH / pCO2	Uthicke et al. (2013); Kamya et al. (2014)		
		Food quantity	Wolfe et al. (2015a); Caballes et al. (2017a)		
		Maternal provisioning	Caballes et al. (2017a)		
	Abundance/ density	Timing	Uthicke et al. (2015a)	sampling ~7 days after spawning	
		Adult density (Stock-recruitment relationships)	McCallum (1992)	McCallum presents a theoretical model, which does little to actually advance understanding, and concludes that understanding the scale of stock-recruitment relationships is crucial	BE-3
		Adult reproduction (Stock-recruitment relationships)			BE-3
		Spatial scale	Uthicke et al. (2015a)	minimum of 2.6 x 10^{10} larvae in the outbreak area	
	Onset of feeding	Maternal provisioning	Caballes et al. (2017a)	Larvae under high maternal investment treatments can delay onset of feeding	
		Food availability	Lucas (1982)	Gut opens around Day 3	
	Feeding preferences	Food particle size	Okaji et al. (1997)		
		Phytoplankton species	Lucas (1982); Mellin et al. (2017)		
		Food quantity	Mellin et al. (2017)		
	Feeding rates	Food quantity	Lucas (1982); Mellin et al. (2017)	Ingestion rates increased with increasing food concentration (Lucas, 1982);	

		Larval stage	Lucas (1982)		
	Dispersal/ Connectivity	Hydrodynamics	Hock et al. (2016, 2017)		PC-1
		PLD	Caballes & Pratchett (2014); Pratchett et al. (2017b)	Actual PLD not accurately represented in existing models	
		Larval behaviour			BE-3
	Planktonic larval duration	Food quantity	Lucas (1982); Pratchett et al. (2017b)		PC-12
		Temperature	Henderson & Lucas (1971); Uthicke et al. (2015b)	PLD: 30-47 days	
		Availability of suitable settlement substrate	Yamaguchi (1973a)	COTS larvae can delay settlement in the absence of suitable substrate	
	Position in the water column	Thermocline		Unpublished data from Caballes, Pratchett	
		Halocline		Unpublished data from Dworjanyn	PC-5
		Phytoplankton gradients		Unpublished data from Dworjanyn	
		Larval stage		Unpublished data from Caballes, Pratchett	
Settlement	Settlement rates	Temperature			PC-12
		pH	Uthicke et al. (2013)	Settlement of COTS larvae was significantly reduced on CCA exposed to OA conditions for 85 d prior	
		Larval diet	Uthicke et al. (2018); Wolfe et al. (2017)		
		Larval age (post-fertilisation)	Pratchett et al. (2017b)		
		Larval size (pre-settlement)		Unpublished data from Caballes	
		Substrate type (microsite)		Dworjanyn et al. (In prep.); Caballes et al. (In prep.)	BE-5
		Larval density	Uthicke et al. (2018)	Caballes et al. (In prep.)	BE-3
		Water flow			BE-5
		Predator / conspecific cues	Cowan et al. (2016a)		PC-8
		Spatiotemporal variation		Doll et al. (In review)	BE-5
	Initiation of settlement searching behaviour	Presence of positive/negative cues		Dworjanyn et al. (In prep.); Peter Doll - PhD Research	BE-5
		Larval age / Competency			
		Time of day (light)			
	Substrate preferences	Physical microstructure		Peter Doll - PhD Research	BE-5
		Chemical cues		Dworjanyn et al. (In prep.); Peter Doll - PhD Research	BE-5
		CCA species	Johnson et al. (1991)	Does limited abundance of certain CCA constrain rates of settlement?	BE-5
		Presence of bacterial biofilm	Johnson et al. (1991)		
		Habitat type	Wilmes et al. (2020a)	Is settlement limited at certain reefs (e.g., inshore reefs) by lack of suitable settlement cues?	BE-5
	Survival / Mortality rate	Benthic predators	Cowan et al. (2016)		PC-8

		Habitat		Wilmes et al. (unpublished data) - This is very preliminary, but all that is available given the challenges associated with recurrent sampling of juvenile COTS	PC-8
		Exposure			PC-8
Metamorphosis	Metamorphic rates	Temperature	Henderson & Lucas (1971)		
		Salinity	Henderson & Lucas (1971)		
		Settlement substrate	Henderson & Lucas (1971)	Late brachiolaria kept for up to 14 days in clean, glass dishes without additional substrates failed to metamorphose; Peter Doll - PhD Research	
		Water movement			
	Metamorphosis cues	Substrate type	Henderson & Lucas (1971); Johnson et al. (1991)	No metamorphosis in the absence of CCA (but Dworjanyn et al. found high metamorphosis in the absence of CCA)	
		Chemical cues	Johnson et al. (1991); Johnson & Sutton (1994)	Induction of metamorphosis has been shown to be mediated by bacteria associated with the CCA; Peter Doll - PhD Research	
	Onset of metamorphosis	Larval size (pre-settlement)		Unpublished data from Caballes	
		Larval age (post-fertilisation)			
		Chemical cues		Peter Doll - PhD Research	
Settlers (Herbivorous juveniles)	Growth	Temperature	Kamya et al. (2016)	Temp had a significant effect on herbivorous juvenile growth rates	
		pH / pCO2	Kamya et al. (2016); Kamya et al. (2017)	pH levels had a significant effect on herbivorous juvenile growth rates	
		Post-settlement age	Wilmes et al. (2016)		
		Diet			
	Survival / Mortality rates	Predation	Keesing et al. (1996); Wilmes et al. (2019)		PC-3
		Sublethal injuries	Wilmes et al. (2019)		
		Habitat structure			BE-8
		Availability of CCA			BE-5
		Size at metamorphosis	Keesing et al. (1996)		
	Longevity	Ageing methods			BE-2
		Prey availability			PC-3
	Feeding rate	Temperature	Kamya et al. (2016)	Temperature had no effect on CCA consumption rates by juvenile COTS	
		pH / pCO2	Kamya et al. (2016); Kamya et al. (2017)	OA increases the success of early juvenile COTS; Higher consumption rates of CCA at OA conditions	
		CCA species		Dworjanyn et al. (unpublished data)	BE-5
	Feeding preferences	Availability of CCA			BE-5
	Locomotory capacity	Substrate type			
		Size	Yamaguchi (1973b)		
		Exposure			
		Growth rates			

Transitional stage	Survival / Mortality rate	Temperature			BE-8
		Coral health	Deaker et al. (2021)		BE-8
		Presence of predators		Does the presence of predators delay the transition from herbivory to corallivory?	BE-8
		Predator refuge			BE-8
	Competency / Initiation of corallivory	Coral type			
		Intraspecific competitive suppression			
		COTS density			
		COTS age/size	Wilmes et al (2020b)		BE-8
		Coral cover			BE-8
		Coral health		Is it easier for COTS to transition from herbivory to corallivory if the available coral prey are stressed?	PC-3
		Physiological enzyme systems			PC-3
Recruit (Coral-feeding juveniles)	Growth	Temperature			
		pH / pCO2			
		Post-settlement age	Wilmes et al. (2016)		
		Diet	Johansson et al. (2016)		PC-3
	Survival / Mortality rates	Predation	Keesing & Halford (1992); Keesing et al. (1996); Keesing et al. (2018)		PC-8, PC-9
		Sublethal injuries	Wilmes et al. (2019)		
		Density-dependence			
		Prey availability			
		Disease	Zann et al. (1987)		
	Density/ Abundance	Recruitment rates			BE-3
		Food limitation			PC-3
		Habitat	Wilmes et al. (2020a)		
	Feeding rate	Temperature	Kamya et al. (2018)		
		pH / pCO2	Kamya et al. (2018)		
		Presence of predators	Keesing & Halford (1992); Keesing et al. (1996, 2018)		
	Metabolic rate	Temperature	Yamaguchi (1974)	Bethan Lang - PhD research	
		Size		Bethan Lang - PhD research	
	Feeding preferences	Availability of coral species	Johansson et al. (2016)	Coral-feeding juveniles have a limited diet compared to adults	BE-1
		Size of juvenile			BE-1, PC-3
	Locomotory capacity	Substrate type	Pratchett et al. (2017a)		
		Temperature		Bethan Lang - PhD research	
		Size	Pratchett et al. (2017a)		
		Exposure			PC-3

Adults	Growth	Prey availability	Lucas (1984)	No field-based data on growth rates	
		Modelling size data	Ebert (1973)		
		Reproductive investment (Gonadosomatic index)	Pratchett et al. (2021)		PC-2
	Movement	Coral cover	Keesing & Lucas (1992); Pratchett et al. (2017a); Brauer et al. (1970); De'ath & Moran (1998a); Ling et al. 2020		BE-1
		Size	Pratchett et al. (2017a)		BE-1
		Substrate type	Pratchett et al. (2017a)		BE-1
		Reproductive condition			BE-1
		Season (summer vs. winter months)			BE-1
	Metabolic rate	Temperature		Lang et al. (In review)	PC-11
		Size	Kettle (1990)	Lang et al. (In review)	
	Exposure/ Detectability	Size	MacNeil et al. (2016); Burn et al. (2020)		
		Habitat structure			
		Density			
		Time of day	Burn et al. (2020); Ling et al. (2020)		
	Feeding incidence (proportion of day spent feeding)	Size	Burn et al. (2020)		BE-1
		Coral cover			BE-1
	Density/ Abundance	Recruitment rates (ontogenetic shifts)			BE-3
		Demographic shifts	Moran & De'ath (1992); Moran et al. (1992); Pratchett (2005)		BE-4
		Survivorship			BE-6
		Movement (aggregative behaviour)			BE-4
	Feeding rate (rate of coral removal)	Coral assemblage	Keesing & Lucas (1992); Pratchett 2010		BE-1
		Starfish size			BE-1
		Time in reproductive cycle			BE-1
	Feeding preferences	Availability of preferred species	De'ath & Moran (1998b); Pratchett (2007); Pratchett et al. (2009)	Acropora is most preferred	BE-1
		Coral symbionts	Pratchett (2001)	Presence of crustacean symbionts on coral influences feeding preference of COTS	
		Coral health and bleaching	Haywood et al. (2019)	COTS predation impede recovery following coral bleaching	PC-11
		Growth form	De'ath & Moran (1998b)		

		Chemical cues	Caballes (2009); Motti et al. (2018)		
		Sublethal predation			BE-1
	Depth distribution	Water movement			BE-4
		Habitat type			PC-13
		Temperature			PC-11
	Habitat preferences	Size	De'ath & Moran (1998a)		
		Rugosity			BE-4
	Longevity	Ageing methods	Stump & Lucas (1990, 1991, 1999); Souter et al. (1997); MacNeil et al. (2017)	Need to further validate ageing methods in wild populations	BE-2, BE-6
		Prey availability			
		Disease	Zann et al. (1990)		
	Pathogenesis	Density	Sutton et al. (1988); Rivera-Posada et al. (2011a, 2011b); Caballes et al. (2012)		
		Nutritional condition		Caballes et al. (In prep.)	PC-2
		Putative pathogens	Sutton et al. (1988); Rivera-Posada et al. (2011a, 2011b); Høj et al. (2018)		PC-2
		Transmission	Caballes et al. (2012)		
	Predation - lethal	Predators (lethal predation)	Cowan et al. (2017); Kroon et al. (2020)		PC-9
		Size			
		Fisheries protection	Sweatman (2008)		PC-9, PC-10
		Abundance of predators			PC-9
	Predation - sub-lethal	Predators (sublethal predation)	McCallum et al. (1989); Rivera-Posada et al. (2014); Messmer et al. (2017); Budden et al. (2019)		PC-9
		Size	Rivera-Posada et al. (2014); Messmer et al. (2017)		PC-9
		Fisheries protection	RIvera-Posada et al. (2014); Messmer et al. (2017)	Caballes et al. (In review)	PC-9
		Abundance of predators			PC-9
	Mortality rates	Predation	McCallum (1992)		PC-9, PC-14
		Temperature			PC-11
		Starvation			PC-2
		Disease	Pratchett (1999)		PC-2

Gametogenesis / Spawning	Fecundity / Reproductive output	Physiological condition			
		Size	Conand (1983); Kettle et al. (1987); Babcock et al. 2016; Pratchett et al. (2021)		
		Density			BE-3
		Sex ratio			BE-3
		Sublethal injuries	Budden et al. (2019)	Unpublished data from Messmer, Caballes, & Pratchett	
		Mode of spawning	Caballes et al. (2021)		
	Size at reproductive maturity	Sex		Caballes et al. (In prep.)	
		Population	Zann et al. (1987)		
	Sex ratio	Density		Caballes et al. (In prep.)	
		Post-spawning mortality			PC-2
		Proximity to spawning season		Caballes et al. (In prep.)	
	Spawning cues	Pheromones	Beach et al. (1975); Caballes & Pratchett (2017); Hall et al. (2017)		
		Presence of sperm in water column	Caballes & Pratchett (2017)		
		Temperature	Yasuda et al. (2010); Caballes & Pratchett (2017)		
		Phytoplankton concentration (Larval food)	Caballes & Pratchett (2017)		
	Spawning incidence (mass versus batch spawning)	Temperature change	Lucas (1973); Babcock & Mundy (1992b); Caballes et al. (2021)		
		Reproductive investment (Gonadosomatic index)	Caballes et al. (2021)		
	Spawning extent (proportion of gametes released)	Temperature change	Caballes et al. (2021)		
		Reproductive investment (Gonadosomatic index)	Caballes et al. (2021)		
	Time of spawning	Temperature	Babcock & Mundy (1992a,b); Yasuda et al. (2010); Caballes & Pratchett (2017); Uthicke et al. (2019)		
		Tides	Pratchett et al. (2014)		
		Lunar cues	Uthicke et al. (2019)		
	Spawning synchrony	Proximity of spawners	Babcock & Mundy (1992a); Babcock et al. (1994)	Need field-based studies of spawning aggregations and corresponding spawning	
		Spawning cues	Beach et al. (1975); Caballes & Pratchett (2017)		
	Post-spawning mortality	Reproductive output		Does the energy spent during gametogenesis and spawning influence post-spawning mortality?	PC-2

		Sex		Higher mortality among females observed after spawning	PC-2
		Metabolic rates		Differences in metabolic rates pre- and post-spawning	PC-11
		Temperature			PC-11
		Foraging behaviour		Do COTS become more cryptic and feed less after spawning?	PC-2
		Disease		Are COTS more susceptible to disease after spawning?	PC-2

The comprehensive and systematic gap analysis for biology and ecology showed that there has been extensive research on gametes and zygotes (e.g., Kamya et al. 2014; Caballes et al. 2017b; Hue et al. 2020), which provides extensive information across a broad range of different traits, including the effects of several different environmental factors such as temperature and partial pressures of CO_2 (pCO_2) on these traits. There is however, missing information and critical uncertainties across most other life stages. Most critically, there is very limited pertinent, field-based information on key demographic rates such as larval survival, settlement rates, and also early post-settlement growth and survival (***Table 8.1***). These critical life-stages may be fundamental in understanding the population dynamics of COTS (*sensu* Wilmes et al. 2018).

After finalising the gap analysis (***Table 8.1***), all BE PA team members were asked to consider Research Opportunities that would explicitly address one or more knowledge gaps. To avoid overlap (and potential conflict) among Research Opportunities, team members were asked to first submit a provisional title and list of relevant researchers for all potential Research Opportunities. These provisional ideas were then discussed during a joint meeting with the Proximal Causes Program Area on 15 January 2021 (via Zoom). The decision to hold a combined meeting was largely motivated by the considerable overlap in team members (6) between the two Program Areas (***Table 2.4*** and ***Table 2.5***), though an inevitable (but unexpected) outcome of this meeting was the realisation that many of the proposed Opportunities would be more appropriately placed in alternative Program Areas, and mainly Proximal Causes (Table 8.1). At this stage the BE PA team members had also already started completing the Opportunity Template (***Appendix D***), which inferred that the likely funding success of the proposed Opportunities would be conditional upon (among other things) an obvious *Path to Impact* and the *Ability to suppress or prevent COTS outbreaks*. This was somewhat at odds with the previously stated goals of the BE PA (e.g., to better understand, as opposed to controlling population outbreaks of COTS), but team members assumed that much of the relevant research needed to address the key knowledge gaps would have much greater traction if focused explicitly on addressing relevant putative causes of population outbreaks, and were therefore placed within the Proximal Causes Program Area.

8.2 Research Opportunity scoping

A total of 8 Opportunities were submitted (on January 30 January 2021) from the BE PA, which were then numbered sequentially from BE-1 to BE-8. Two of these initial Opportunities (BE-6 and BE-7) were then combined. Also, one project (BE-9) that was originally submitted as part of Proximal Causes was moved into the BE PA, because it did not clearly align with any of the general Topics (or hypotheses) being used to organize Opportunities relevant to putative or proximal causes of population outbreaks (see ***Section 7.1***). Consequently, 8

Research Opportunities were ultimately submitted on 10 February 2021 (***Table 8.2***), but we retained the original numbering such that there is no BE-7, and instead, the new additional proposal is assigned the coding BE-9. The provisional cost estimates for the 8 Opportunities ranged from $197,000 to $730,040, with a combined cost of $3,419,180 (***Table 8.2***).

Table 8.2 Summary of Research Opportunities (RO) submitted to the Biology and Ecology PA.

RO #	Opportunity Title	Objectives	Cost Estimate
BE-1	*In situ* feeding rates of crown-of-thorns starfish and fate of prey corals	To quantify feeding rates of COTS in the field, to better resolve ecological impacts of COTS on coral assemblages relative to the size and abundance of COTS as well as changes in prey availability (coral cover and composition) and seasonal variation in seawater temp.	$527,000
BE-2	Beyond eDNA: New genetic tools for COTS management and monitoring	To develop two further techniques (beyond eDNA monitoring technology) critical for understanding outbreak dynamics and improving monitoring, focussing on 1) estimating age of individual COTS (especially juveniles) and 2) measuring eRNA to provide increased information on structure of COTS populations, adding to quantitative estimates of individual abundance from eDNA sampling.	$197,000
BE-3	Supply-side ecology for crown-of-thorns starfish (*Acanthaster* cf. *solaris*): the link between larval supply, settlement rates and adult densities	Aim: To simultaneously assess 1) local densities of adults, 2) levels of larval supply and 3) rates of settlement for COTS across a range of reefs along the length of the Great Barrier Reef. This research, along with improved understanding of larval dispersal, settlement patterns, and post-settlement movement, will inform how COTS spread within and among reefs.	$730,040
BE-4	Inter-annual changes in density, distribution and demography for pre-outbreak populations of *Acanthaster* cf. *solaris* on Australia's Great Barrier Reef	Aim: To establish when and where population irruptions of COTS originate in the northern or far northern sectors of the Great Barrier Reef. We will use intensive annual surveys to test for changes in density, distribution and population replenishment of COTS populations at select reefs (n ≥ 18 reefs).	$645,000
BE-5	Inter-reef differences in the incidence of population irruptions of *Acanthaster* cf. *solaris*: testing the role of larval supply versus settlement substrates	Aim: To assess the mechanistic basis of striking and consistent differences in the incidence of population irruptions of COTS among reefs on the Great Barrier Reef. This project will quantify patterns of larval supply and settlement rates for COTS along cross-shelf gradients, while also considering changes in 1) abundance of adult COTS, 2) cover and composition of corals (adult prey), 3) cover and composition of coralline algae (juvenile prey), and 4) quality and quantity of settlement habitat.	$519,820
BE-6	Tagging and mark recapture of adults to determine a method to age COTS, case study with stable low-density population at One Tree Reef	Aim: Through a mark-recapture study, 1) verify the spine pigment bands as a tool to age COTS and as an aging method that can be used in the field and 2) characterise stable low density COTS populations and how their traits differ from those in outbreaking populations.	$275,380
BE-8	Recruitment of juvenile COTS to coral on modern reefs; how seaweed, coral cover, warming and predation inhibit and promote first coral feeding on COTS	Aim: To examine how recruitment of COTS onto coral is inhibited and promoted by factors that are prevalent on modern coral reefs.	$317,640
BE-9	Specialised traits of COTS larvae: resilience or starvation in tropical waters: maternal provisioning, larval energetics, when do they need to feed, microbiome facilitation, DOM and influence of cloning	Aim: To construct a comprehensive understanding of the nutritive energetics and feeding ecology of COTS larvae in nature and the specialised traits that facilitate their success.	$207,300

To demonstrate the connections and complementarity among the proposed Opportunities, they were organized into three broad categories (***Figure 8.1***): (a) Opportunities that to address fundamental questions in *Ecology*, explaining why the impacts and distribution of COTS populations vary spatially and temporally; (b) Opportunities that validate new *Methods*, showing how to improve monitoring of low-density populations and determine the age of COTS; and (c) Opportunities that are generally aimed to answer what are the salient features regarding *Biology* that lead to elevated rates of larval settlement and recruitment (***Figure 8.1***). The linkages among Opportunities were further considered based on the relevant life stages, as per the framework used to identify pertinent knowledge gaps (***Figure 8.1***).

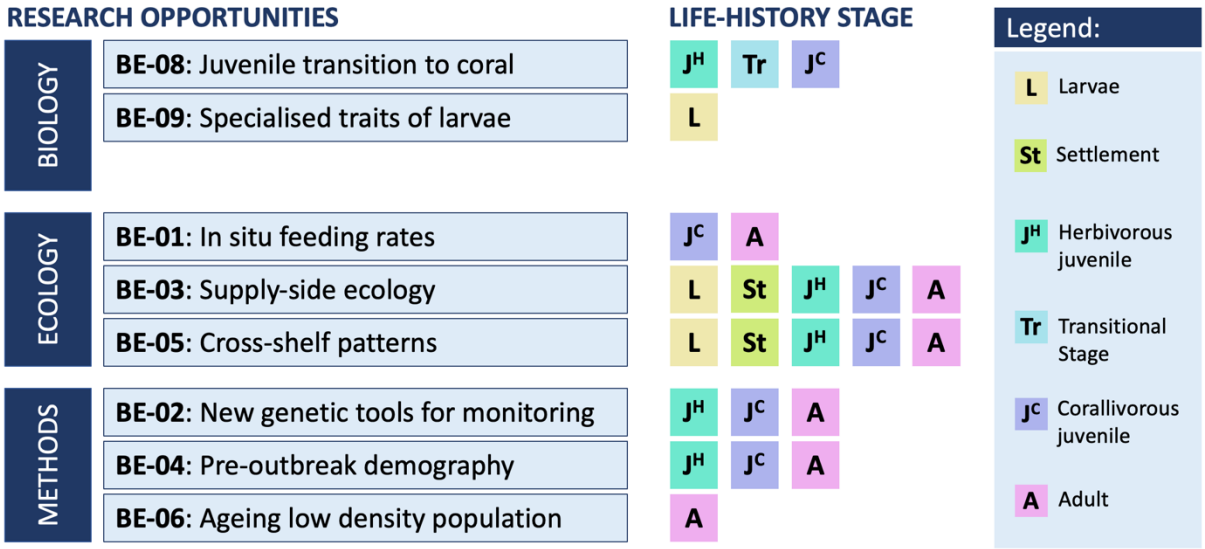

Figure 8.1 Alignment of submitted Research Opportunities and knowledge gaps within different COTS life history stages and processes. Colours of life history stages correspond with colours in Table 8.1 that indicate different life stages.

8.3 Research Opportunity assessment

Relevant research teams worked independently to formulate and outline each of BE PA Opportunities (8), by describing how the anticipated research would align with each 10 different criteria (***Table 3.1*** Evaluation Criteria and how they link to CCIP values*)*. These Opportunities were then independently assessed by all BE PA members, except M. Pratchett (who was at sea and out of contact throughout the entire assessment process). The results of the assessment were then presented and discussed on 5 March 2021 (via Zoom) at a joint workshop with the Proximal Causes Program Area. The final scores for each of the Opportunities (8) were very similar (***Figure 8.2***), with BE PA Opportunities generally scoring low (<5) to very low (<3) for 1) Path to impact; 2) Ability to suppress or prevent COTS outbreaks; 3) Co-benefits: ecosystem and coral health impacts; 4) Co-benefits: socio-economic impacts. In contrast, these Opportunities all scored reasonably well (>6) for 5) Time to viability; 6) Risks: research, economic, environmental, social, regulatory; 9) Synergies, overlaps and dependences with other opportunities. The main criteria that

distinguished the 8 Opportunities was 8) Innovation, where BE-2 “Beyond eDNA: New genetic tools for COTS management and monitoring” scored higher than all other opportunities (***Figure 8.3***).

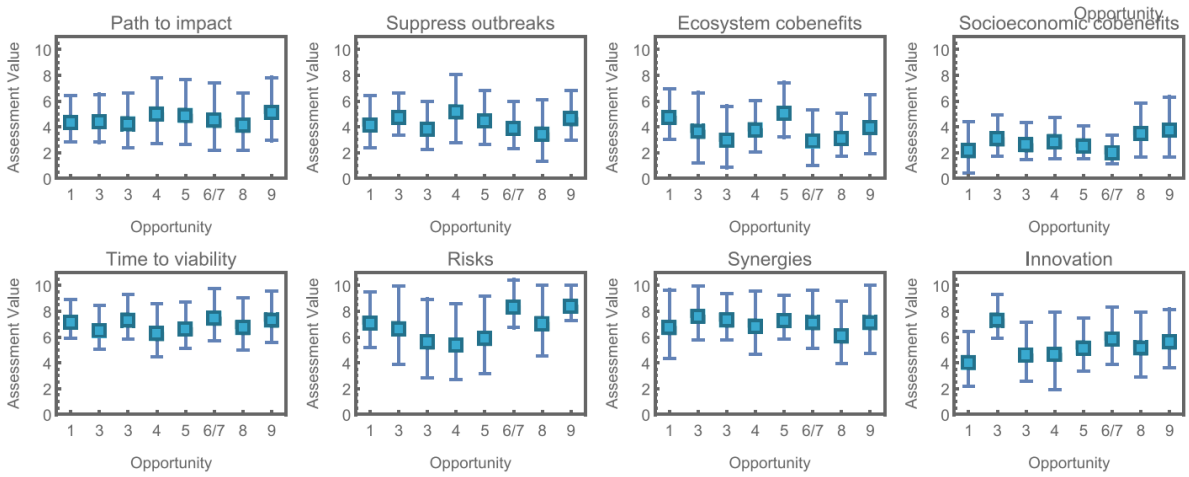

Figure 8.2 Assessments of the eight Biology and Ecology Research Opportunities across each Evaluation Criteria (all except research and implementation costs). Values are weighted means. Error bars represent standard deviation and are provided to give an indication of range of responses.

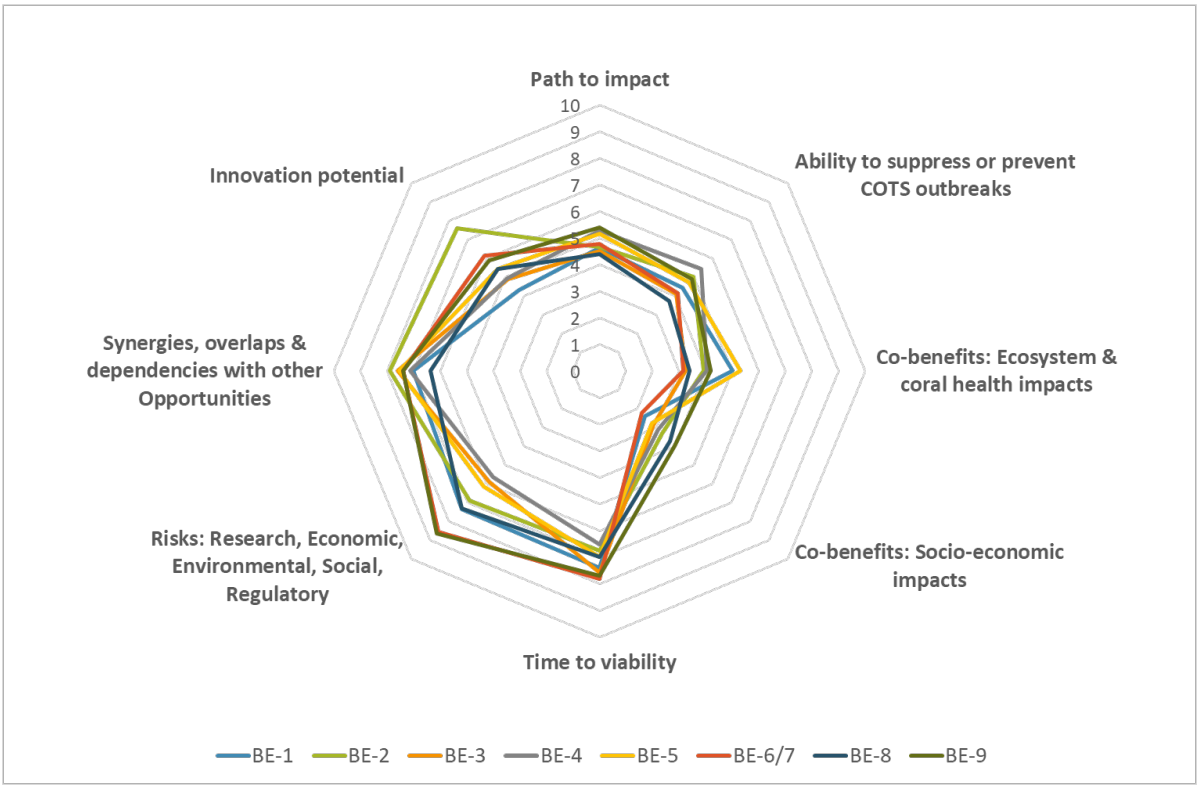

Figure 8.3 Spider chart highlighting differences in the weighted means of assessments against Evaluation Criteria across the eight Biology and Ecology Research Opportunities.

The consistently low scores for 1) Path to impact and 2) Ability to suppress or prevent COTS outbreaks by BE Research Opportunities (and especially compared to other Program Areas) was expected from the outset, and reflects that the proposed research is mostly about fundamental understanding, with limited direct or immediate applications to supressing

current or future population outbreaks. However, path to impact was proposed as the foremost assessment criteria to use in establishing which of the Opportunities presented should be given highest priority. Moreover, much of the criticism directed at the proposed Opportunities centred around the limited, unclear or indirect application of proposed research, or pathway to impact (***Table 8.3***).

Table 8.3 Summary of anonymous freeform feedback (and responses) on each Opportunity. See also elaboration of novelty and pathway to impact for each RO in section 8.4.

RO #	Opportunity Title	Feedback	Responses
BE-1	In situ feeding rates of crown-of-thorns starfish and fate of prey corals	1. Low risk approach with positive refinements for manual control at local scales, but unclear how this will scale up to COTS populations across GBR.	1. This extends the context – different contexts for coral consumption rates and these underly a lot of important model assumptions and management decisions.
		2. Important input for management models, but we already know a lot about predation on coral, what is the benefit of this additional information?	2. This project will measure feeding rates more accurately than what has been done previously and across different contexts, providing extensive information needed for modelling COTS impacts
		3. Could fieldwork be coordinated with other Opportunities to reduce costs?	3. Selection of field sites is flexible and fieldwork may be combined with other ROs
BE-2	Beyond eDNA: New genetic tools for COTS management and monitoring	1. There are examples of using this approach with vertebrates, but have there been any proof-of-concept for any aquatic invertebrate?	1. There are some examples with corals, but work has mainly been on terrestrial organism, so this is the proof-of-concept, which is low-cost and preliminary work has already been done
		2. Strong synergies with other eDNA ROs – is coordination and sharing of samples possible?	2. Uses genetic methods that are different to established eDNA methods, but open to coordinating with other genetics researchers
BE-3	Supply-side ecology for crown-of-thorns starfish (*Acanthaster* cf. *solaris*): the link between larval supply, settlement rates and adult densities	1. Would intensity of sampling be able to able to tease apart impacts and reach statistically significant conclusions with field sampling alone?	1. It is challenging because a lot of these assumptions have not yet been explicitly tested, so it will be hard to do a power analysis a priori.
		2. Can we use the existing control program to help collect more data from the field?	2. There is scope to use the control program to help with sampling
		3. Significant field costs – could these be reduced by coordinating across other projects?	3. This project will address fundamental ecological knowledge gaps and coordination with other ROs will reduce field costs
BE-4	Inter-annual changes in density, distribution and demography for pre-outbreak populations of *Acanthaster* cf. *solaris* on Australia's Great Barrier Reef	1. Should this be coupled to projects looking at fine-scale genetic structure (PC-1) and perhaps also BE-3?	1. BE-3 is more about fundamental ecological questions, whereas this Opportunity is more focused on monitoring pre-outbreak populations and delimiting the initiation box
		2. Utility of proposed methods (scooter surveys and eDNA sampling) may need to validated and sampling design refined accordingly	2. The variance and detection involved in the use of scooters for surveys in the field has been validated and the proposed eDNA sampling technique has been validated in the lab and ready for testing in the field
BE-5	Inter-reef differences in the incidence of population irruptions of *Acanthaster* cf.	1. This project explores cross-shelf variation and also tests juvenile habitat	1. Both components are essential in understanding population dynamics to

	solaris: testing the role of larval supply versus settlement substrates	cues, whereby second appears more innovative and has clear path to impact 2. Will the work that comes out of this be relevant for management?	identify settlement hotspots and how this relates to recruitment success 2. It is more relevant to understanding proximal causes, because understanding why settlement rates differ between inshore, mid-shelf and offshore reefs could help us understand why different reefs outbreak
BE-6/7	Tagging and mark recapture of adults to determine a method to age COTS, case study with stable low-density population at One Tree Reef	1. Is there an overlap with BE-2 (also doing ageing) ? Together, these projects could provide important information on age at size and ontogenetic shifts. 2. How would the technique be used in management context?	1. Both projects can collaborate, whereby samples are shared to cross-validate methods. 2. The capacity to reliably age individual COTS, especially during early life-stages, has major ramifications for processes that lead to initiation of outbreaks. This in turn, will inform relevant management.
BE-8	Recruitment of juvenile COTS to coral on modern reefs; how seaweed, coral cover, warming and predation inhibit and promote first coral feeding on COTS	1. Dummy COTS are innovative, but how are they surveyed? 2.Could the two components (settlement and predation) be considered separately?	1. Dummies have been used to study predation in terrestrial environments and are deployed in specific areas and then revisited to determine predation rates based on visible bites or loss of biomass. 2. The two components focuses on understanding recruitment to coral; but can be considered separately
BE-9	Specialised traits of COTS larvae: resilience or starvation in tropical waters: maternal provisioning, larval energetics, when do they need to feed, microbiome facilitation, DOM and influence of cloning	1. Opportunity addresses a recognised knowledge gap, but has no clear (independent) path to impact 2. It seems far too much for one opportunity; can this be broken up into two or three opportunities?	1. We need to understand this to determine if the investment on water quality improvement is well founded – maybe there is no direct link between water quality and COTS larvae 2. This can be broken up, but all the work can be done within the proposed budget

A key focus of the discussions among PA team members and the Steering Committee related to the apparent reliance on (and associated cost of) extensive field-based sampling, as for the Proximal Causes PA. However, the extensive need for further field-based research was explicitly highlighted by the knowledge gap analysis (***Table 8.1***). Critically, much of the detailed knowledge on the biology of COTS that currently exists (and especially existing insights on the early life-history stages) comes from experimental studies conducted under controlled laboratory conditions (e.g., Caballes et al. 2016; Pratchett et al. 2017; Deaker et al. 2020), and it is uncertain how the results of many such studies relate to the biology and ecology of COTS in reef environments. Given the intended application of biological and ecological knowledge for modelling natural populations, and informing field-based management and surveillance, it was considered a priority for many relevant biological and ecological traits to greatly expand on existing laboratory-based studies and conduct field-based studies. While there could be significant cost savings by conducting combined and collaborative research expeditions, such opportunities may be limited by differences in when and where the proposed research would need to be conducted. Nonetheless, PA team members were very willing to consider alternative funding arrangements, whereby the available funding would be used for resource specific expeditions (*cf*. individual projects) that allow for multiple projects to be conducted simultaneously. However, no further consideration

was given to optimizing use of available resources for widespread and extensive field sampling ahead of final decisions about which projects warranted funding.

8.4 Recommendations on priority Opportunities

Researchers were given an opportunity to revise Opportunities following the feedback and assessment provided to the CCIP Director and Steering Committee. Most importantly, there was a recognised need for all Opportunities to further highlight the key knowledge gaps that the proposed research addressed (as identified in ***Table 8.1***), and novelty of information arising, even though this did not clearly align with the assessment criteria. Where possible, researchers also tried to better articulate the pathway to impact (even if this was conditional upon other Opportunities), and further emphasise potential synergies across Opportunities. In addition to refining the Opportunities, these issues were also explicitly highlighted in the PA narrative, as presented below (***Table 8.4***).

Table 8.4 Post-assessment narrative for each RO submitted to the Biology and Ecology PA. For relevant knowledge gap(s), information (in brackets) indicates level of existing knowledge.

BE-1: *In situ* feeding rates of crown-of-thorns starfish and fate of prey coral	
Relevant knowledge gap(s)	COTS feeding rates (limited, based on one study using outdated methods); Coral mortality/recovery rates (zero); Shifts in coral assemblages (limited)
New information arising	Accurate measurement of COTS feeding rates and identify drivers of variation; Coral mortality and recovery rates; Shifts in coral assemblages following COTS predation
Path to impact	These information underly a lot of important model assumptions and management decisions and could significantly improve the ecological underpinning for COTS management; Could improve the performance of current control measures by improving models used to support management decisions and resource allocation
Synergies/Cost savings	$248K budget for fieldwork (vessel hire, bench fees, flights) can be significantly reduced if combined with fieldwork in PC-9, since similar field sites are proposed
BE-2: Beyond eDNA: New genetic tools for COTS management and monitoring	
Relevant knowledge gap(s)	COTS ageing techniques (very limited; existing methods unvalidated); Sex ratios and proportion of different ontogenetic stages in the field (zero)
New information arising	Develop molecular ageing marker (methylation load, telomere length); Estimate sex ratios and proportion of COTS at different stages of maturity using eRNA
Path to impact	Improved understanding of age and sex structure of population in order to identify drivers and justify management actions; Improve surveillance of COTS and enable more efficient and targeted control
Synergies/Cost savings	Low cost since funding will be supplemented by other sources. No fieldwork required – samples will be provided by other projects and sourced from aquarium-raised COTS
BE-3: Supply-side ecology for crown-of-thorns starfish (*Acanthaster* cf. *solaris*): the link between larval supply, settlement rates and adult densities	
Relevant knowledge gap(s)	Stock-recruitment dynamics (zero)
New information arising	Shed light on the 'black hole' of COTS ecology: high larval density = high settlement rate = high recruitment success and adult abundance
Path to impact	Provide foundational ecological underpinning for COTS management and new information pertaining to larval supply and connectivity, which is an important consideration in the strategic allocation of management effort
Synergies/Cost savings	Fieldwork component can be combined with PC-2
BE-4: Inter-annual changes in density, distribution and demography for pre-outbreak populations of *Acanthaster* cf. *solaris* on Australia's Great Barrier Reef	

Relevant knowledge gap(s)	Population dynamics of pre-outbreak populations (zero)
New information arising	Spatiotemporal dynamics in COTS densities; Determine when and where population outbreaks arise
Path to impact	Sampling techniques have already been validated in the field. Information will help establish early warning system for outbreaks and facilitate pre-emptive culling to suppress initial build-up of COTS populations
Synergies/Cost savings	Unique sites in the far north so difficult to combine; Two teams (MP/SU) already on board. May have potential overlaps with BE-2 and MS-5
BE-5: Inter-reef differences in the incidence of population irruptions of *Acanthaster* cf. *solaris*: testing the role of larval supply versus settlement substrates	
Relevant knowledge gap(s)	Cross-shelf patterns in outbreaks (very limited; only that less outbreaks in inshore reefs)
New information arising	Variation in larval supply and settlement rates between inshore, mid-shelf, and offshore reefs
Path to impact	Establish key environmental and habitat conditions that influence the likelihood of outbreaks, which are important when assessing dispersal and designing on-water control
Synergies/Cost savings	There are possible overlaps with other Opportunities, especially in mid-shelf reefs
BE-6/7: Tagging and mark recapture of adults to determine a method to age COTS, case study with stable low-density population at One Tree Reef	
Relevant knowledge gap(s)	COTS ageing techniques (very limited; existing methods unvalidated); Demography of low-density populations (very limited)
New information arising	Validate tetracycline technique; Identify specific cohorts within a population
Path to impact	Important for control efforts – if revisiting site, is it because populations are recruiting from existing juveniles
Synergies/Cost savings	Fieldwork at One Tree Island Research Station can be clustered with BE-8 and BE-9; Can share samples with BE-2 for method validation
BE-8: Recruitment of juvenile COTS to coral on modern reefs; how seaweed, coral cover, warming and predation inhibit and promote first coral feeding on COTS	
Relevant knowledge gap(s)	Transition from herbivory to corallivory (very limited)
New information arising	Drivers of diet shift; Role of proliferation of algae on the survival of juvenile COTS
Path to impact	If seaweeds weaken the defences of corals against juvenile COTS, could lead to integration of improved management of seaweed cover into existing decision-making tools
Synergies/Cost savings	Fieldwork at One Tree Island Research Station can be clustered with BE-6 and BE-9; Cluster with BE-9
BE-9: Specialised traits of COTS larvae: resilience or starvation in tropical waters: maternal provisioning, larval energetics, when do they need to feed, microbiome facilitation, DOM and influence of cloning	
Relevant knowledge gap(s)	Nutritive energetics (limited) and feeding ecology (limited) of larvae
New information arising	Microbiome facilitation and influence of cloning
Path to impact	Information important to understand if investment on water quality improvement is well-founded, in terms of its link to COTS outbreaks
Synergies/Cost savings	Fieldwork at One Tree Island Research Station can be clustered with BE-6 and BE-8; Cluster with BE-8

Aside from refining individual Opportunities the BE team members were also requested to effectively rank or prioritise the different Opportunities, and specifically distinguish those that are considered essential to the goals of CCIP ('must have'), versus those that we should

have or would be nice to have, should the funding allow. Notably, there was insufficient funding available to fund all of the Research Opportunities as currently represented and costed, within or across all Program Areas. However, the BE team had real difficulties in prioritising the 8 Opportunities, for several reasons. First, each of the Opportunities proposed addressed one (or more) distinct and fundamental knowledge gaps and there was very limited redundancy or overlap amongst them. Second, the Evaluation Criteria did not recognise the fundamental and supporting role of biological research, as opposed to affecting change in current management actions. Third, there were limited opportunities to really map outcomes and outputs of the proposed Opportunities with the biological and ecological data and information needed to support high priority ('must have') Opportunities proposed by other Program Areas. Undertaking sensitivity analyses using existing biological and ecological models would have been useful to identify what biological and ecological information (e.g., which traits) would be most important to prioritise, however this was not viable in the timeframes of this design process. BE team members were also insistent that all 8 Opportunities warranted high priority, albeit for different reasons. Consequently, all Opportunities were assigned the highest priority ('must have'), which in effect left decisions about the relative importance and prioritisation of Research Opportunities in the hands of the Steering Committee and CCIP Program Director.

9 RESULTS – SOCIAL ACCEPTABILITY, REGULATORY AND INSTITUTIONAL ARRAGEMENTS

As a cross-cutting program (see ***Section 2.2.6***) the overall objective of the social acceptability, regulatory and institutional arrangements Program Area was to support the development of publicly acceptable, cost-effective, and economically efficient management options. Note that the gap analysis for this Program Area was conducted differently to those within the other Program Areas. This is because, at the time of the analysis, there was no empirically sound knowledge base for how the general public and stakeholders perceived COTS as a native species, nor was there an understanding of how citizens perceived the need for the management of COTS using traditional and novel methods.

9.1 Gap analysis

The Social acceptability, Regulatory and Institutional Arrangements Program Area conducted a scoping review of potential considerations for social acceptability, a review of regulatory and institutional arrangements, a consideration of current COTS surveillance and control activities and identified a preliminary set of potential research areas for the 3-year R&D phase to follow. Specifically, we produced a summary review designed to identify gaps in the social science literature relevant to COTS control that complement the six key areas of population control identified by the Population Control Program Area to build a social science perspective around some of the control strategies identified in a review conducted by Høj et al. (2020).

The six areas of focus for the social science program, for the purposes of this review, were: (i) Manual COTS Control, (ii) Water quality improvement, (iii) Predators (conservation and augmentation approaches) and Coral-symbiotic fauna, (iv) Microbial agents, (v) Semio-chemicals and (vi) Genetic biocontrol. It is also anticipated that there may be other social science inquiries that are more tangential to these six proposed control strategies but are still required, to provide a holistic examination of the social environment with respect to COTS management.

This summary review will enable the future research, testing and implementation of innovations of the type identified in other Program Areas. The literature searches for this summary report were conducted between October and December 2020.

9.1.1 Method

Our initial scoping revealed that the literature on the social, economic, institutional, cultural and behavioural considerations relating to COTS and COTS control is fragmented with significant gaps evident.

At times, the published literature uses language that is inconsistent across fields in economics, social sciences and regulatory-related research. The authors applied a targeted, semi-systematic approach to identifying and synthesising the literature on a range of scientific approaches to the COTS control context. Semi-systematic literature searches are intended to synthesize current state of knowledge, identify gaps and generate insights for future research directions (Snyder 2019).

Our search commenced with the identification of several parameters recommended by subject matter experts (including David Westcott, Frederieke Kroon, Lone Høj and Cherie Motti). These conversations helped to establish some clarity and general agreement on first-order search parameters. Prior knowledge of GBR-specific studies related to COTS threat perceptions (e.g., Social and Economic Long-term Monitoring Program (SELTMP), Reef Restoration and Adaptation Program (RRAP)) and public attitudes research in relation to genetic technologies in the GBR (e.g., Synthetic Biology Future Science Platform (Synbio FSP)) also informed initial searches. Grey literature was consulted where relevant.

Next, several databases were used in the search for peer reviewed literature including: Scopus and the complete CSIRO, JCU and UQ library databases. Key search terms were used to create focussed search strings and initially included: “crown-of-thorns starfish"; “asteroid”; “sea star”; "great barrier reef". Search strings were then created according to the specific topic of enquiry (e.g., regulatory, economic, social, etc).

We did not explore Traditional Owner (TO) perspectives more fully than a cursory examination of the literature; this is because a lack of available literature, limited expertise within the research team, and unexpected delays in establishing appropriate contacts between the social team and the Reef Trust Partnership’s TO Component team due to unforeseen challenges in aligning our activity timelines. There is also an acknowledgement that the TO Component within the Reef Trust Partnership will more fully examine related issues to reef management more broadly.

9.1.2 Summary of gap analysis results

Public awareness and perceptions of environmental threats, and their understanding of the associated risks are an important factor affecting public support for mitigative policy and interventions (de Nooy 2013; Bennett and Dearden 2014). While recurrent population outbreaks of COTS are recognised by scientists and Reef managers as one of the leading causes of decline in hard coral cover across the GBR over the past few decades (De’ath et al. 2012; GBRMPA 2019), there is evidence that the significance of this threat is not widely recognised among GBR stakeholder groups and the wider public. In recent studies of public perceptions of threats and risks to the GBR, Taylor et al. (2019) showed that COTS were generally recognised among GBR region residents and Australians as ‘an environmental pest that negatively affects the health of the GBR’. However, COTS were found to be perceived among the “most serious threats” to the GBR by only a small proportion of GBR stakeholders, visitors, and coastal residents. In 2017, shortly after recurrent austral summers that resulted in mass coral bleaching in the GBR, only 8% of GBR coastal residents, 8% of domestic tourists, 12% of GBR tourism operators, and 3% of GBR commercial fishers identified COTS among the ‘three most serious threats to the GBR’ (Marshall and Curnock 2019a,b; Curnock and Marshall 2019). The “most prominent” threats, as perceived by these stakeholder groups in recent years, have been climate change, pollution, fishing, poor water quality and coastal development (Curnock et al. 2019; Thiault et al. 2020).

Public perceptions of environmental threats can and do change over time, in response to risk events (e.g., major disturbances and impacts), media representations, and the exchange of information within different social and cultural contexts (Kasperson et al. 1988; Thiault et al. 2020). Significant shifts in public perceptions of threats to the GBR have occurred over recent decades, with specific attributions given to media representations of high-profile development proposals (e.g., the Abbot Point coal terminal; Lankester et al. 2015) and major

environmental disturbances (i.e., mass coral bleaching; Curnock et al. 2019; Thiault et al. 2020). While many studies have shown a generalised lack of public trust in major news media networks, including among GBR communities (MacKeracher et al. 2018), the news media nonetheless retains a central position in the public discourse of environmental issues and events (Foxwell-Norton and Lester 2017). Media representations of the GBR in recent years have been dominated by stories of declining Reef health and mass coral bleaching attributed to climate change (Eagle et al. 2018). Similarly, an analysis of social media discourse of GBR threats over F.Y. 2017–2018 identified climate change, coral bleaching and mining as key topics (Taylor et al. 2019). The dominance of such coverage is considered likely to have had a 'crowding out' effect on public awareness of other serious and persistent threats, including COTS (Thiault et al. 2019).

The following sections will briefly summarise the social and economic science relative to six possible COTS control methods identified by Høj et al. (2020) and the Population Control Program Area. The summary and preliminary recommendations are also produced with some understanding of additional insights gathered from the other Program Areas within the CCIP. This will be followed by a summary of regulatory considerations for COTS control more broadly.

9.1.2.1 Manual COTS control programs

Based on a 2018 survey of (a) Australians' and (b) GBR residents' acceptance of a range of specific GBR interventions, Taylor et al. (2019) examined social acceptance related to several interventions in the GBR designed to mitigate coral loss and restore coral. One of the interventions examined was the manual removal of coral predators and pests, including COTS. The RRAP survey defined manual removal as "manual removal [of COTS] by divers with tools such as metal spears". The authors found that manual pest control was considered broadly acceptable by a majority of respondents from both populations. This level of acceptability was considered potentially attributable to familiarity with the existing COTS control program as an established and ongoing feature of GBR management. Additional findings from this survey included a prevalent perception that manual COTS control provides more benefits than risks; however, the authors cautioned that such views can change over time with exposure to debate over such risks and benefits in the media or other domains of public discourse (Taylor et al. 2019). A youth training program, administered by the Association of Marine Park Tourism Operators (AMPTO), has contributed to the development of a skilled workforce for COTS removal, whilst providing its own local social and economic benefits. The study by Jarvis et al. (2020) describes the training program, administered by AMPTO and funded by the Queensland Government's Skilling Queenslanders for Work (SQW) initiative, as having operated since 2010, producing 'several hundred' graduates to the present date. Stated aims of the program include the improvement of employment prospects and career aspirations for under and unemployed youths, including the enrolment of a high proportion of Indigenous trainees. Based on an online survey of graduates from the program, Jarvis et al. (2020) found significant increases in self-reported life satisfaction, confidence, self-efficacy, pride and stewardship sentiment for the GBR among graduates.

9.1.2.2 Water quality improvement programs

Social and economic research and monitoring associated with water quality improvement in the GBR catchment has focussed on policy reform (e.g., Kroon et al. 2014), cost-effective abatement methods (e.g., Roebeling et al. 2009), and the adoption of land management and

stewardship practices by agricultural producers in the region, under the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (Australian and Queensland Governments 2018b). This program has developed estimates of management practice adoption and annual practice change among a range of producers, including sugarcane, grazing, horticulture, grains and bananas, and has established a range of baseline 'human dimension' metrics for monitoring, evaluation, reporting and improvement. Despite the substantial investment into water quality improvement to date, monitoring of nutrient outflows and associated research on agricultural practice change have shown inadequate progress towards achieving the program targets (Kroon et al. 2016; Westcott et al. 2020; Taylor and Eberhard 2020). Ongoing effort and investment into the Reef 2050 Water Quality Improvement Plan is continuing, with evolving approaches to understanding and facilitating stewardship and practice change across multiple sectors (Taylor and Eberhard 2020; Great Barrier Reef Foundation 2020).

9.1.2.3 Predators and coral-symbiotic fauna

To date there has been no research encompassing any social or economic aspects of proposed COTS management interventions that aim to enhance populations of COTS predators per se, either through the reduction of extractive pressures (e.g., via Marine Protected Area zoning or other spatial or fisheries management tools) or through artificial population enhancement (e.g., via aquaculture breeding and release programs). However, the consideration of such interventions can potentially draw on lessons from the Representative Areas Program (RAP) that preceded the Great Barrier Reef Marine Park (GBRMP) rezoning in 2004, and from examples of native fish restocking programs in waterways elsewhere. For example, Cavasos and Bhat (2020), examined willingness to pay for restocking of staghorn coral (*Acropora cervicornis*), which provides essential habitat for fish and other organisms. Their research showed that public attitudes towards restocking were influenced by public perceptions of threats facing the reef and what the effects of restocking and protection might be. People were more willing to pay for restocking programs if they perceived staghorn coral to be under threat.

9.1.2.4 Microbial agents and semio-chemicals

No links have yet been made between microbial agents or semio-chemical methods of biocontrol and stakeholder views in the social science literature. However, chemosensation research is well established in insect ecology where some social science research, and public and stakeholder engagement has occurred. The use of attractants in managing Queensland fruit fly – a native pest species in Queensland but an alien invasive pest in other States – are relatively well accepted and many citizens are happy for such interventions to be installed in their backyards by external parties (e.g., Mankad et al. 2019). However, the chemical attractants used in controlling other pests are relatively static, semi-permanent objects installed in backyards. The use of a chemical released into the water brings with it an entirely different social risk profile, that is yet to be examined. What this means is that different factors and considerations will be important to people depending on the control context. For example, if we are talking about a static control that is placed in somebody's backyard, compared to a highly mobile chemical or organism floating around in the water, people will perceive a different level of susceptibility to harm between the two examples and this will influence decision making. This difference in decision making will not necessarily

correspond with the equivalent ecological risk, but rather a perception of risk aligned with different factors that may be important to individuals at any given time.

9.1.2.5 Genetic biocontrol

Several studies have explored public attitudes and 'social licence' considerations, as well as stakeholder perspectives, in relation to using genetic biocontrol techniques for managing invasive species in aquatic and terrestrial environments. To date, most of these have been conducted in the US, UK and European settings (for example, Sharpe 2014; Darling 2015; Kohl et al. 2019). However, work within an Australian context is emerging.

A recent Australian national survey conducted by CSIRO (Synthetic Biology Future Science Platform, 2020) examined the use and implementation of heat-tolerant coral developed using synthetic biology (Synbio) technology. While not specifically focusing on genetic biocontrol of crown-of-thorns starfish, the findings from this study examined public attitudes towards the use of a genetic intervention implemented in the GBR and the publics' intended engagement with the technology once introduced. Results from that study showed that around 90% of Australians moderately or strongly supported scientific development of Synbio coral for the purposes of restoring the GBR. When asked if they would visit areas of the reef where genetically modified coral had been introduced, only 12 % of the Australian sample indicated that they were less willing or not willing to visit parts of the GBR where Synbio coral had been introduced (SynBio FSP 2020). However, Australians did express concerns about associated consequences for humans and animals (84% at least moderately concerned), risks to the natural environment (86% moderately concerned) and whether the consequences arising from this technology could be controlled or managed (89% moderately concerned).

9.1.2.6 Economics summary

COTS outbreaks contribute significantly to the loss of hard coral of the GBR (e.g., Pratchett et al. 2014). This generates costs (lost benefits), which implies that a prevention of hard coral loss through COTS control interventions (avoided damage) would represent a benefit (increase in social welfare)[1]. Interventions use resources, which represents a cost (decrease in social welfare). Hence, an allocation of resources that maximises social welfare requires an assessment of social benefits and costs. Such an assessment is typically performed by a social cost-benefit analysis (CBA). In a social CBA, the costs and benefits generated by alternative interventions are assessed over a specified time period against a counterfactual, typically a business-as-usual scenario (e.g., Hanley and Barbier 2009; Boardman et al. 2018).

9.1.2.6.1 Benefits of interventions

The benefits of avoided damage are captured by the benefits society enjoys from the continued existence of healthy hard coral cover, which would be lost under a 'business-as-usual' scenario. That is, the benefit is captured as the additional benefits generated through COTS control interventions that prevent (or decrease) further hard coral loss. From an economic perspective, the generated benefits include both use and non-use values distributed across a range of beneficiaries (Tietenberg and Lewis 2008). Stoeckl and

[1] However, the costs of inaction are only equal to the benefits of action (control interventions) if they are completely effective, which is rarely the case.

Anthony (2019) identified, in the context of the Reef Restoration and Adaptation Program (RRAP), beneficiaries and a list of benefits enjoyed from healthy coral condition of the GBR measured in terms of a reef-condition-index (Anthony et al. 2019). Beneficiaries that are included in their assessment are residents within the GBR catchment (including the Torres Strait), traditional owners, reef tourists, reef fishers (commercial, recreational, or traditional), and other Australian stakeholders that enjoy benefits generated by the Great Barrier Reef (GBR).

Stoeckl and Anthony (2019) identified a list of benefits based on relevance to the GBR, the likelihood of being affected by climate change, and the likelihood of being responsive to a range of interventions aimed at reef restoration and adaption, including COTS control:

- Commercial fishing
- Coral harvesting
- Medicinal option values (reflecting biodiversity and gene pool values)
- Storm-surge protection
- Tourism
- Recreational fishing
- Learning and inspiration
- Non-use values (existence, bequest)
- Indigenous cultural values
- Relational values and other complex social goods

Market and non-market valuation methods (e.g., Alberini and Kahn 2006; Rolfe and Bennett 2006; Hanley and Barbier 2009; Hensher et al. 2015) can be used to estimate the benefits associated with coral condition. While for some benefits a monetary value may be attached directly to coral condition (e.g., non-use value), other benefits (e.g., commercial fishing) require quantifying a cause-effect relationship between coral condition and other variables (e.g., fish abundance).

The temporal and spatial trajectory of generated value is likely to differ across alternatives, potentially presenting trade-offs between the level of acceptable risk, benefit extent, and time of benefit realisation. For example, a low-risk method might generate limited value in the short-term, while a medium-risk method might generate substantive value in the long-term. Høj et al. (2020) provide timelines for ‘research, development and consultation’ and ‘implementation’ associated with the biologically based control methods considered in the CCIP, which indicate the temporal distribution of benefits across different methods.

Some COTS control methods (e.g., water quality improvements) are expected to generate benefits beyond COTS control associated with a general improvement of ecosystem health (De Valck and Rolfe 2018, Rolfe et al. 2018). For example, De Valck and Rolfe (2018) estimated values of benefits associated with mangroves, seagrass and coral reefs generated through water quality improvement programs in the catchment of the GBR. The presence of such co-benefits provides challenges in assessing the efficiency of COTS control effort. For

example, a cost-benefit analysis narrowly focused on the benefits associated with COTS control would result in a lower net present value than if these co-benefits were included.

9.1.2.6.2 Costs of interventions

The costs generated through COTS control interventions that prevent (or decrease) further loss in hard coral cover depend on the (combination) of control methods used and if (or how) they are linked with decision support tools as well as monitoring and surveillance systems.

Høj et al. (2020) provide an assessment of biologically based control methods against a set of criteria concerning effectiveness (short-term, long-term), risk (reversibility, specificity, spatial control, acceptability), and logistical constraints (scalability, revisitation rates, operational cost)[2]. The assessment provides information that assists in identifying cost categories and principal drivers of their extent. The costs of the control methods currently considered in the CCIP may be grouped into the following categories (adapted from Davis et al. 2019):

- Research and development
- Stakeholder consultation and engagement
- Implementation (costs of establishment, compliance, deployment, monitoring and surveillance, management, administration, and regulatory approval)
- Enforcement (costs of enforcing new regulations and associated litigation, prosecution, management, and administration)
- Adverse impacts (costs associated with environmental and health risks)

Timing of effort is crucial for the success of outbreak containment, with low success rates generating the need for further control effort (Bos et al. 2013; Dumas et al. 2016; Pratchett et al. 2017). Timing of effort also determines the temporal distribution of costs, which is linked to the concept of discounting applied in a CBA (e.g., Boardman et al. 2018). Costs (and benefits) generated over time are discounted to estimate their net present value. This implies that costs that occur in the future are valued less than those in the present. It is also critical to note that there may be significant opportunities to reduce cost through the realisation of infrastructure and deployment synergies across methods as discussed for the RRAP (Gibbs et al. 2019).

9.1.2.6.3 Allocative efficiency of COTS control

Allocative efficiency of COTS control would ensure that public investments maximise social welfare. Allocative efficiency is typically assessed by means of a CBA. In a CBA, the costs and benefits generated by alternative interventions are assessed over a specified time period against a counterfactual (e.g., Hanley and Barbier 2009; Boardman et al. 2018). Bowen and Sivapalan (2019) conducted a CBA under the RRAP based on scenarios that involved, among several other interventions, manual COTS control. Their analysis was based on the cost and benefit streams estimated under the same program by Gibbs et al. (2019) and Stoeckl and Anthony (2019), respectively. The simulated manual COTS interventions included the current Expanded COTS Control Program (Fletcher et al. 2020) and a

[2] Høj et al. (2020) emphasise that the assessment is based on the currently available best knowledge, which may change over time.

hypothetical scenario that implemented a gene drive eliminating future COTS outbreaks completely.

Bowen and Sivapalan (2019) find that, generally, implementing the hypothetical gene drive (instead of continuing the Expanded COTS Control Program) would generate net present value when assessed under different RRAP intervention scenarios simulated from 2020 to 2073 and assuming an effective gene drive from 2034 onwards. Given that the hypothetical scenario is underpinned by a high-level cost assessment based on a range of assumptions (Gibbs et al. 2019), these results may be considered a very first approximation.

For a considerably more detailed analysis of the economic considerations for all six COTS control methods examined in the social sciences program, please refer to the separate Literature Review document developed by the social and economic sciences Program Area (Carter, Curnock, Fidelman, Lockie, Scheufele and Mankad).

9.1.2.7 Regulatory considerations

The regulatory environment will impact, to a large extent, the feasibility and viability of alternative COTS control methods being considered in the context of CCIP. It will influence which, where, how and when control methods may be used. Further, such environment may underpin enabling conditions for COTS control by, for example, codifying scientific knowledge into COTS control standards, structuring process for community participation, mobilising financial resources and encouraging action. On the other hand, the regulatory environment may constrain the development and deployment of alternative control methods if it is not fit for the purpose of these methods, lacks the capacity to assess risks and impacts associated with the methods – particularly those based on emerging technologies (e.g., genetic biocontrol), or fails to provide regulatory guidance.

The regulatory environment directly or indirectly relating to COTS control involves several regulatory arrangements and entities pertaining to multiple levels, from local to international. Alternative control methods may trigger different regulations and policies depending on the nature of the method and its risk level. With exception of manual COTS control, all other methods being considered by CCIP are either high risk or very high risk. Control methods considered to be high risk (e.g., semio-chemicals) would involve tailored approaches to assessment and permit. These approaches are non-standard and involves such requirements as proof of concept, small-scale pilot study and joint risk assessment with scientists and regulators. For methods regarded as very high risk (e.g., microbial agents), given insufficient knowledge and significant uncertainty associated with them, the regulator is yet to identify an assessment approach. These methods would be unlikely to get a permission if an application was submitted at the present time.

The development and deployment of alternative COTS control methods will depend on an enabling regulatory environment that is able to address uncertainty and risks associated with these methods. An eventual regulatory component of CCIP should focus on the following areas:

- Engagement with regulators to help them understand the proposed COTS control methods and CCIP scientists understand the permission system;

- Identification of priorities to improve regulatory capacity to address different types of COTS control; this may include risk-based approaches that are better fit for the purpose of CCIP;
- Identification of what type of COTS control may be tested (and eventually deployed) and under what conditions (e.g., scale, location and timing) with the aim to inform relevant CCIP program areas;
- In collaboration with regulators, developing options to enhance the capacity of the regulatory system to effectively assess the range of risks and impacts associated with COTS control.
- Engagement with RRAP to explore co-learning opportunities and potential synergies with CCIP.

9.1.2.8 Gap analysis summary

To date, COTS researchers have predominantly relied on drawing parallels from social research in (perceivably) comparable Australian invasive biocontrol contexts - like common carp (*Cyprinus carpio*), wild rabbits, and mosquito (*Aedes aegypti*) outbreaks - to make sense of stakeholder perceptions and public attitudes towards COTS control in general (see for example, Høj et al. 2020).

While these studies may provide some general insights into, for example, the effectiveness of various public engagement methods or the robustness of specific scientific methods for capturing reliable data, caution is warranted if extrapolation of those past experiences is of interest. Directly translating findings from distinct biocontrol contexts across to the COTS scenario, given the complex interplay between stakeholder responses, control options, and unique social, ecological, economic and governance histories (Carter et al. 2020), can be an imprecise and potentially inconsequential exercise. Despite these limitations, though, it may be possible to draw some inferences from the few studies that do share key contextual similarities for the purpose of guiding the development of future research on stakeholder perceptions on the use of genetic biocontrol technologies for the management of COTS.

What these studies demonstrate, in the context of COTS control and innovation, is the need to conduct adequate groundwork to understand the implementation environment and prevailing sociocultural values and behaviours. This would ensure that any innovation to control COTS, whether it be a novel technology or whether an enhancement of current control/ management practises, would be designed with the end user in mind. This past research also highlights key psychosocial drivers of acceptance and support, such as perceived technology efficacy, clear messaging and a compelling articulation of the problem to be addressed.

In addition to existing empirical social research, other disciplinary approaches (like applied ethics, for example) have also made contributions to our understanding of common ethical arguments levelled against the development and use of genetic biotechnologies. Intrinsic objections such as Playing God arguments or appeals to ‘naturalness’ can reveal the presence of other, more tangible risks and concerns such as previous governance failures or discomfort with technology-driven approaches to complex problems (Carter et al., 2020, in review). This may have implications for science management, science communication and engagement with broader stakeholder groups.

Finally, it is important to note that stakeholder perceptions and attitudes may be sensitive to the control of species perceived as invasive, but which are in fact native, as may be the case with respect to the problem of COTS and its control. There are implications for science management and policy in relation to controlling native species invasions due to the potential emergence of diverse human values and their potential conflicts with conservation strategies (Schlaepfer et al. 2011; Shine and Doody 2011; Simberloff 2011; Carey et al. 2012).

9.2 Research Opportunity scoping

The social science research portfolio was designed to complement research within other PAs within CCIP, in particular the Population Control PA, to generate greater confidence among RTP and CCIP partners in their understanding of the risks, benefits and opportunities relating to CCIP interventions, the viable pathways to their implementation, and an improved understanding of the ongoing engagement requirements to achieve CCIP's desired impact.

In particular, the portfolio was to generate the following outcomes:

- Pathways to achieve increased TO, stakeholder and public trust in management institutions, regulatory and decision-making processes.
- Pathways to achieve increased engagement with reef managers and regulators.
- Guidance on the prioritisation of alternative COTS control interventions (with respect to social and regulatory feasibility).
- Guidance on targeted stakeholder consultation and engagement process customized to prioritised COTS control interventions.
- Support of the development of guidance on achieving more cost-effective and economically efficient COTS control interventions.
- Guidance on regulatory and policy best practices for innovative COTS control methods.
- Capability development of researchers identifying as Aboriginal and Torres Strait Islanders to support long-term engagement and implementation success.
- The building of early-mid career research (EMCR) capacity in participating research organisations via the employment of post-doctoral and research staff.

These outcomes were intended to support the development of an innovation pipeline to achieve sustainable long-term management of COTS (impact).

Research needs identified were:

- Assessment of the social acceptability of alternative COTS management options and the factors that influence acceptability.
- Development and testing of Traditional Owner and stakeholder engagement models that facilitate co-design of COTS interventions, the delivery of co-benefits from COTS management, and prospects of success for COTS management research.
- Investigation of policy and regulatory issues that may hinder R&D and deployment of innovative COTS control methods.
- Estimation of the economic value of benefits and cost generated through alternative COTS control interventions.

The core ideas from the Gap Analysis were used to shortlist eight separate, but conceptually linked, Opportunities. The Opportunities with a brief title are shown in ***Table 9.1***.

Table 9.1 Initial Research Opportunities scoped for the Social Sciences Program Area.

Opportunity ID	Opportunity title
SS-1	Understanding the preferences of and non-use benefits to the Australian public associated with COTS control methods.
SS-2	Understanding the costs of alternative (other than manual) COTS control methods.
SS-3	Policy and regulatory environment for COTS R&D
SS-4	Constructing COTS intervention scenarios and scoping associated social risks and opportunities
SS-5	Social acceptability of genetic biocontrol using incompatible male technique
SS-6	Public acceptance and preference for distribution of semio-chemical attractants for COTS management
SS-7	Public and stakeholder perceptions of COTS, COTS management and novel control techniques
SS-8	Biocultural values and governance assessment

After an internal assessment process, the social science team distilled the initial eight opportunities into five revised opportunities (***Table 9.2***). In that process, SS-4 was dropped as a viable opportunity, and SS-5 to SS-7 were combined into one larger offering (a new SS-4).

Table 9.2 Revised Research Opportunities scoped for the Social Sciences Program Area.

Opportunity ID	Opportunity title
SS-1	Understanding the preferences of and non-use benefits to the Australian public associated with COTS control methods.
SS-2	Understanding the economic costs of alternative COTS control methods
SS-3	Policy and regulatory environment for COTS R&D
SS-4 (new)	Public and stakeholder perceptions of COTS, COTS management and novel control techniques
SS-5	Biocultural values and governance assessment

The team then completed CCIP research opportunity templates for the five scoped opportunities. A brief summary of each opportunity is provided below:

SS-1: This Opportunity would conduct a discrete choice experiment to investigate the relative preferences of the general public of Australia towards different methods of COTS control on the GBR (including currently employed manual culling and potential alternatives considered within the CCIP) and estimate the associated economic value of generated non-use benefits. Both, relative preference strength towards alternative control methods and the generated economic value of non-use benefits the public attaches to generated outcomes are indicators

for the social acceptability of control effort, providing first insights across a range of alternative control methods.

SS-2: The aim of this Opportunity would be to estimate the economic cost of implementing (combinations of) alternative COTS control methods that can be used as inputs in cost-effectiveness and efficiency assessments.

SS-3: This project aims to: (i) Investigate the capacity of the existing regulatory and policy frameworks to address R&D and deployment of innovative COTS control methods; (ii) Scope which methods are permitted and under what conditions (e.g., scale, location and timing) with the aim to inform relevant CCIP program areas; and (iii) Help enhance the capacity of the regulatory system to assess the range of risks and impacts associated with R&D and deployment of innovative COTS control methods.

SS-4: The aim of this opportunity is to support the development and deployment of COTS management options that are perceived by the public and stakeholders as socially responsible and acceptable. It will achieve this through a combination of qualitative and quantitative research methods. Specifically, this project will identify and monitor public and stakeholder perceptions of COTS, COTS management and novel control techniques with a particular focus on attitudes and risk perceptions. There are many different potential delivery options to also consider, and evaluation of these different methods must be done in partnership with end users and those more proximally affected by such a release.

SS-5: The aim of this opportunity is to inform the development and deployment of COTS management options that reflect Reef Traditional Owner values and which support aspirations for collaboration with research institutions and meaningful involvement in program co-design and delivery. In part, this will be achieved by adapting research activities designed to monitor public and stakeholder perceptions of COTS, COTS management and novel control techniques to suit the preferences of Traditional Owners. Additional resources will be allocated to evaluating options for the involvement of Traditional Owners in the governance of COTS programs in collaboration with the RTP Traditional Owner Partnerships team.

9.3 Research Opportunity assessment

For each Program Area, the DSM Program Area Lead, Cameron Fletcher, provided preliminary analysis of the Pre-Workshop Assessment data (within-team assessments) and then facilitated the Assessment Workshop around the results from that preliminary analysis. Similar to all other Program Areas, the Social Science PA participants scored Research Opportunities across standard Evaluation Criteria (***Table 3.1***) using an online survey form.

Discussions during the workshop were facilitated to focus on:

- Relative assessments between Opportunities
- Consensus between assessments for each Opportunity
- Discussion of questions and feedback raised in anonymous comments.

Within the small team, relative assessments between Opportunities provided little discriminatory power because the SS Opportunities tended to share common characteristics that led to similar Evaluation Criteria Assessments (***Figures 9.1*** and ***9.2***). In general, Social Science Opportunities had moderate scores for path to impact and innovation, low risk and high synergies (***Figures 9.1*** and ***9.2***). Most team members chose not to assess the SS Opportunities across two of the evaluation criteria, namely Ability to Suppress or Prevent COTS outbreaks and Ecosystem co-benefits, because these were considered not suitable for assessing research across the suite of social, economic and regulatory science areas. This was reflected in the distribution of assessment values for those criteria, with some outliers.

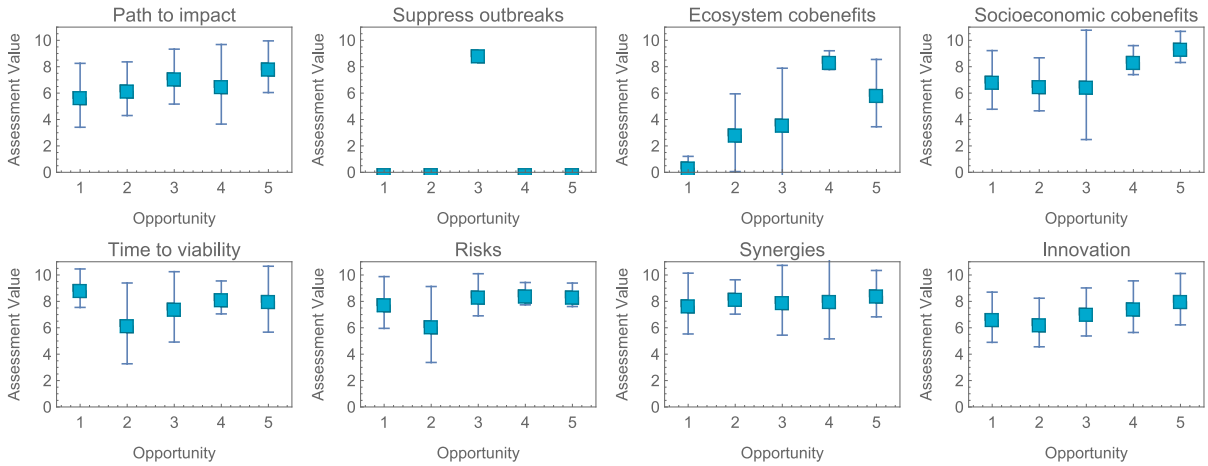

Figure 9.2 Assessments of the five Social Science Research Opportunities across each Evaluation Criteria (all except research and implementation costs). Values are weighted means. Error bars represent standard deviation and are provided to give an indication of range of responses.

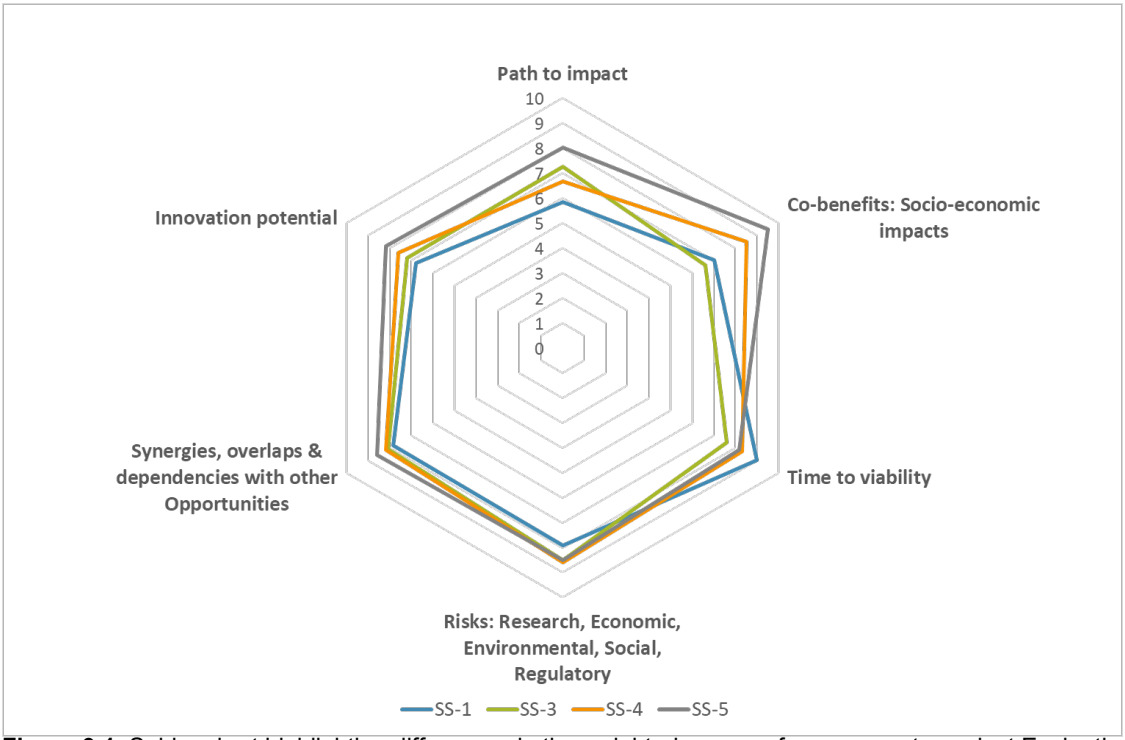

Figure 9.1 Spider chart highlighting differences in the weighted means of assessments against Evaluation Criteria across the five Social Science Research Opportunities.

9.4 Recommendations on priority Opportunities

The Social Science PA recommended funding four complementary Opportunities (***Figure 9.3***) because they would address the most pressing research needs to achieve the outcomes listed in ***Section 9.2***.

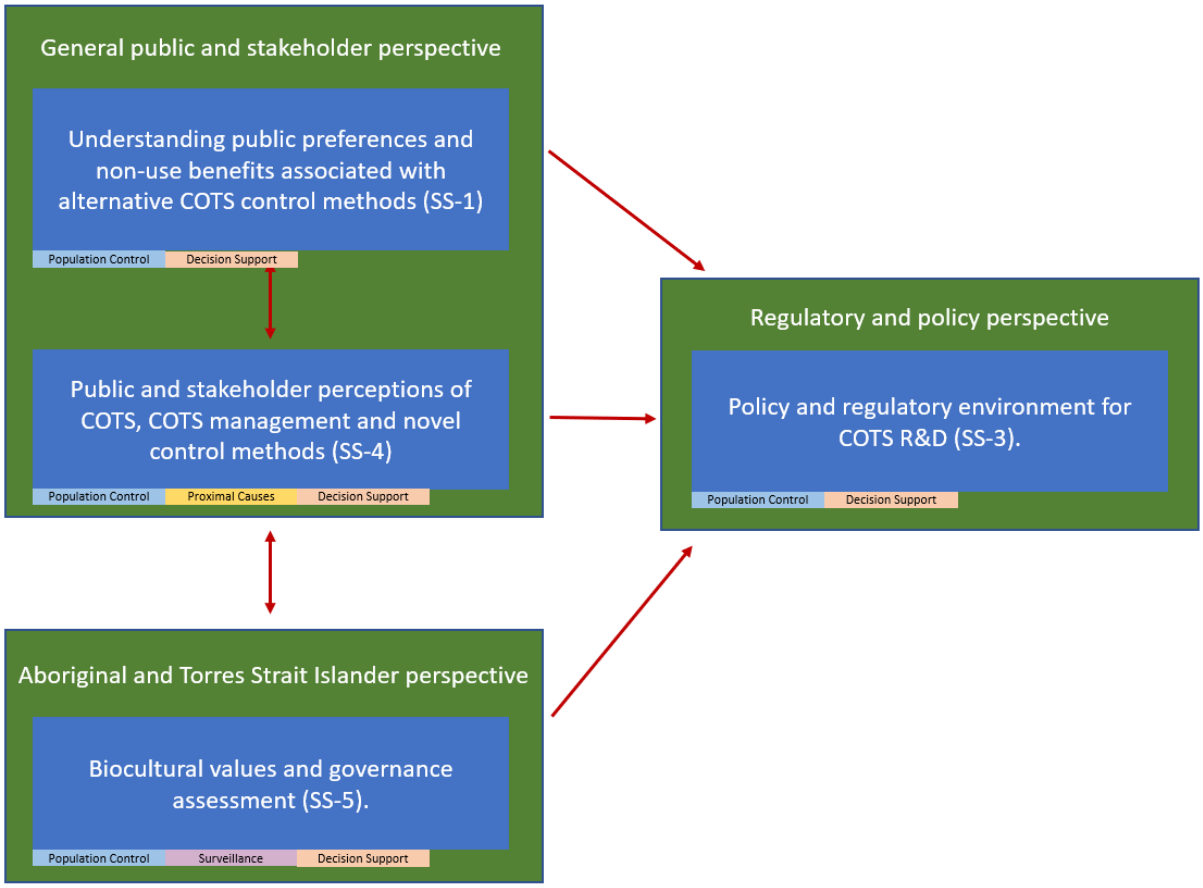

Figure 9.3 Diagram showing the four Research Opportunities recommended by the Social Science PA and how the relate to one another.

All four Opportunities were assessed to fall into the 'must have' category (***Figure 9.3***) to gain insights into the social and regulatory feasibility of alternative COTS control interventions.

CCIP has an opportunity to invest in a well-articulated and impactful social science program that is fundamental to understanding how technological advancements in COTS control influence the triple bottom line while to preserving existing reef partnerships and building trust.

The economic value of non-use benefits is estimated together with an assessment of public preferences associated with alternative control methods. A precision improvement of economic value estimates of other benefits categories (e.g., tourism, fishing, traditional owner values) would require additional investment, which may not be warranted in this 3-year period of CCIP given the recent estimation of benefit streams associated with coral cover under the RRAP and potential further investment in this regard by other programs and initiatives that may be usable within the CCIP. Any economic analysis undertaken within the

3-years research period under the CCIP would therefore rely on the economic values estimated under the RRAP (which can be seen as a first approximation surrounded by high levels of uncertainty) and other value estimates that may become available. At a later stage, additional and targeted investment in economic valuation may be valuable to improve the precision of economic assessments. Such investment should, however, be coordinated with investments of other programs to avoid unnecessary duplication.

Some of the Opportunities require intensive relationship and trust building, engagement and partnering. This involves considerable investment of time and people. However, there may be scope within specific opportunities to reduce staffing resources while acknowledging the consequent and necessary reduction in scope if reduction is favoured. For example, given the heightened research activity within the GBR region the quantitative survey activity within SS-4 (years 2 and 3) could be removed, thus also removing the need for the second postdoctoral research fellow (scenario development and quantitative expertise) and mid-career scientist/ quantitative specialist to reduce the budget.

9.4.1 Synergies

The SS PA has the potential to generate synergies within and beyond CCIP. A common component of SS-1, SS-3 and SS-4 (and potentially also SS-5) is the construction of realistic management intervention scenarios in which proposed CCIP control methods are deployed in the GBRMP and/or catchment. In reality, CCIP interventions will not be deployed independently of other management objectives and initiatives (e.g., those under RRAP), and thus this scoping component can provide valuable insights to the wider community of scientists, managers and partners working within the RTP. Key questions that would be addressed by this component include: (i) how would the novel control method be deployed, (ii) what are its effects in the environment, (iii) where would it be trialled/deployed (including Traditional Owners' land and sea country), (iv) at what scale, (v) involving whom, (vi) what regulatory and policy requirements are involved, (vii) what engagement/ inputs are required, (viii) who might benefit, (ix) who might be at risk, and so on. Generating these synergies is based on a meaningful integration of these Opportunities into the broader CCIP. This requires effective communication and collaboration within and across PAs as well as beyond CCIP facilitated by a '*knowledge and partnership broker*', ideally employed by CCIP.

9.4.2 Dependencies

This PA is dependent on outputs generated by PA Decision Support and Modelling, PA Monitoring and Surveillance as well as PA Population Control. In addition to the two-way transfer of information between program areas, the PA is critically dependent on fostering closer collaborations with the broader program. Such a role can be the dedicated task of the '*knowledge and partnership broker'* who is able to bridge disciplinary, stakeholder and knowledge boundaries to ensure that information and engagement needs are being met for all parties. This role is not synonymous with program co-ordination and relies on being effectively resourced to ensure expected outcomes are met. Whether proposed staffing arrangements share this role or whether it is the designated role of one individual, it must be sufficiently resourced. Given the CCIP is highly dependent on the outcomes of this PA being embedded/adopted by the broader program, serious consideration of resourcing such a role is recommended.

9.4.3 Risks

The Opportunities within this portfolio are low risk. Foreseeable risks include:

- Regular risks associated with research (e.g., sample recruitment, disruptive events)
- Regular risks associated with any social and economic research, which would be managed using standard human ethics approvals.
- Specific risk associated with the Opportunities in this portfolio is a perception risk associated with the idea of potentially controversial control methods being applied on the GBR becoming publicly known and potentially generating significant public concern.
- Risk associated with failures in communication and collaboration across program areas resulting in poor integration of this PA's findings.

The overall objective of the proposed social science portfolio is to support the development of publicly acceptable, cost-effective, and economically efficient management options. From the results of this process, it is clear that without a social science portfolio proposed under this PA, CCIP would need to rely entirely on other research activities (e.g., RRAP) to make inferences about social aspects of COTS management. Given COTS is a native species its management is likely to evoke different stakeholder responses to those evoked by other invasive species and higher levels of expectation in relation to engagement and involvement in decision-making.

Further, the regulatory and policy environment may prove critical in determining the feasibility and viability of novel COTS control methods in the GBR, particularly those involving unconventional technological interventions. If the capacity of the existing policy and regulatory frameworks to address those interventions is limited, delays in the assessment of permits for certain control methods may occur and/or permit approvals may be granted mostly for methods of low risk and small-scale. An important question warranting attention is which methods would be permitted and under what conditions (e.g., scale, location, and timing) with the aim of informing relevant CCIP program areas.

The four Social Science Research Opportunities recommended by this PA will generate greater confidence among RTP and CCIP partners in their understanding of the risks, benefits and opportunities relating to CCIP interventions, the viable pathways to their implementation, and an improved understanding of the ongoing engagement requirements to achieve CCIP's desired impact.

10 CONCLUSIONS

Outbreaks of COTS cause significant damage and are a major threat to the long-term health of the Great Barrier Reef (the Reef). Controlling these outbreaks is considered one of the most scalable and feasible direct management interventions available today to enhance the Reef's resilience in the face of climate change (GBRMPA 2017, GBRMPA 2020). With a current outbreak still spreading across the Reef, and the next outbreak already potentially developing, there is an urgent need to invest in research that improves our ability to manage COTS outbreaks at scale.

To manage COTS outbreaks at scale, the CCIP has been designed as a scientific consortium of core research partners working together to create a step change in the development and uptake of innovative methods that of COTS surveillance and control. This report has outlined the researcher-led component of the CCIP Feasibility and Design Phase, which was structured to identify and prioritise Research Opportunities for investment during the CCIP Research and Development Phase.

The researcher-led component of the CCIP Feasibility and Design Phase was structured around six Program Areas: PA 1) Population Control, PA 2) Monitoring and Surveillance, PA 3) Decision Support and Modelling, PA 4) Proximal Causes of outbreaks, PA 5) COTS Biology and Ecology, and PA 6) Social Acceptability, Regulatory and Institutional Arrangements. Each PA team completed three key pieces of work: a researcher-led Gap Analysis, the identification and scoping of Research Opportunities for consideration under CCIP, and an Assessment process to refine and provide initial prioritisation around these Opportunities. This culminated in a series of recommendations from the PA to the CCIP Program Director and Steering Committee about priority areas of research.

10.1 Knowledge gaps

Each PA identified and summarised key knowledge gaps that could inform knowledge of COTS or control methods, refining the general framework in response to disciplinary needs, so that information could be captured around why each gap was important, what existing knowledge was available to address each gap, the residual gap that remained given existing knowledge, what research would be needed to fill those gaps, and links to other Program Areas.

The Population Control Program Area built its gap analysis on two recent reports, identifying 85 knowledge gaps across six control types. The Monitoring and Surveillance Program Area built off a recent report summarising monitoring and surveillance needs, identifying 24 knowledge gaps across different phases of the outbreak and monitoring needs. The Decision Support and Modelling Program Area identified 86 knowledge gaps across nine broad areas, which were further refined to 52 sub-classes. The Proximal Causes Program Area identified 52 knowledge gaps across four major drivers of primary and/or secondary outbreaks. The Biology and Ecology Program Area built on several recent reviews on the state of biological understanding of crown-of-thorns starfish, identifying 71 key traits across ten distinct life stage and processes. There was little existing literature or empirical evidence relating to public perceptions of COTS or control methods. Therefore, the Social Acceptability, Regulatory and Institutional Arrangements Program Area conducted a thorough review of related literature, aligning their review to six areas of research identified by the Population

Control Program Area as potentially important to implementing further COTS control research.

10.2 Research Opportunities

Research Opportunities were then prepared and refined within each Program Area, based on the extensive knowledge of experts in the team. The CCIP Program Director worked with Program Area Leads to define a decision frame and values linked to the CCIP and RTP COTS Component goals. These were, in turn, used to define Evaluation Criteria, against which Research Opportunities were characterised for their relative ability to contribute to the spread of goals sought under the CCIP.

The Population Control Program Area generated four Early Investment Opportunities and seven Research Opportunities. The Monitoring and Surveillance Program Area initially identified 14 Research Opportunities, which were then further refined so that 10 Opportunities went through the assessment process. The Decision Support and Modelling Program Area generated 17 Research Opportunities, some of which were then merged, leaving 10 for assessment. The Proximal Causes Program Area proposed 14 Research Opportunities, which were further refined to provide 12 Opportunities for assessment. The Biology and Ecology Program Area synthesised a range of studies across multiple knowledge gaps to identify eight Research Opportunities. The Social Acceptability, Regulatory and Institutional Arrangements Program Area identified five Research Opportunities related to the six core areas identified in the gap analysis.

10.3 Assessment and Recommendations

Program Area teams assessed each Research Opportunity proposed within their Program Area based on the Evaluation Criteria. The assessment followed a three-stage process: individual anonymous scoring against established Evaluation Criteria using an online survey tool, followed by a detailed workshop discussing the outcomes of this assessment process, finalised in a series of recommendations provided by each Program Area to the CCIP Program Director and Steering Committee about priority areas of research.

In many cases, the individual anonymous assessment against Evaluation Criteria did not provide strong discriminatory power between Opportunities within a Program Area, and in some cases, most notably the Social Acceptability, Regulatory and Institutional Arrangements Program Area, the Evaluation Criteria were not well matched to the disciplinary background being assessed. However, even where the absolute discriminatory power of assessment scores was limited, they did provide a basis for the Assessment Workshop discussions amongst experts within each Program Area, in particular providing useful information around the consensus across Program Areas, as well as free-text anonymous feedback, which was discussed by each Program Area to reveal potential to further refine, combine, and prioritise Research Opportunities.

The outcomes of these discussions were summarised as Program Area narratives outlining the priorities for research within each Program Area, and opportunities to scale or refine those opportunities.

10.4 How this information was used

The outcomes of the Program Area process, encompassing the Gap Analysis, Opportunity scoping and Assessment, was fed into the Portfolio Design process run by the consultant and reported in the companion report (Sivapalan 2021). The outcome of both the researcher-led and Portfolio Design processes were then reviewed by the CCIP Program Director and Steering Committee. Following this review, on 30 April 2021 the CCIP Program Director and Steering Committee provided guidance to each Program Area on which Opportunities would be targeted for investment during the CCIP Research Phase, where Opportunities should be combined, and a fixed Program Area budget envelope and approximate target budgets for each Opportunity. Program Area Teams reviewed this guidance and prepared formal project proposals and budgets within these recommendations. These were submitted to the CCIP Program Director on 26 May 2021. The final research program design is outlined in the CCIP Investment Plan (Bonin et al. 2022).

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APPENDIX A – EVALUATION CRITERIA

Background information for Program Area leads

Evaluation Criteria provide a means to compare Opportunities as part of a Structured Decision-Making process. In developing these Evaluation Criteria, the goal has been to make them high-level enough that we don't get caught up in the details, while making the Evaluation Criteria, and especially the scales against which they are Assessed, tangible enough that they maintain their connection to on-ground implementation and impact.

It is important to note that the Evaluation Criteria Assessment process is not the prioritisation process, but it does provide a structure for the expert assessment and discussion around the relative benefits, costs, and risks associated with proposed Research Opportunities. Ultimately, the goal of the CCIP Feasibility and Design Phase is to propose an investment plan for an integrated portfolio of research. Individual Research Opportunities do not necessarily need to achieve specific assessment values for every Criterion in order to be included as part of a balanced research portfolio. The final portfolio of research priorities may cover a range of Assessment values in a range of Evaluation Criteria.

Opportunities within each Program Area will be Assessed against the Evaluation Criteria by members of that Program Area. Assessment Values from each Program Area will then be leveraged by the Program Director, the Program Area Leads and an external consultant to build Portfolios of Research Opportunities to be prioritised and discussed at the face-to-face GBRF CCIP meeting in Cairns at the end of March 2021. The aim, therefore, is to define the Evaluation Criteria and Assessment Value scales to be as generally applicable as possible across the Program Areas, to provide consistency, while making them specific enough to be relevant within each Program Area.

It is not necessary that every Assessment Value on every scale is used: for instance, we include a value of 0 on the "Path to Impact" Evaluation Criteria for an Opportunity that has no possible path to impact, even though we might hope that only Opportunities with at least some path to impact will be submitted. It is also not important that values are linear (i.e., that a value of "4" indicates twice the performance of a value of "2"), or that they match up between categories (i.e., that a value of "5" in "Ability to suppress or prevent COTS outbreaks" and a value of "5" in "Co-benefits: Socio-economic impacts" both indicate "average" performance). What is important is that we define clear categories for each value on the scale of an Evaluation Criterion.

Ideally, the values would:

1. be relatively objective, in that two people provided the same information about an opportunity would score it similarly
2. be relatively orthogonal, in that the same trait of an opportunity is not scored in two different Evaluation Criteria
3. add value, in that there is no point asking people to make an "Assessment" of something that is already objectively quantifiable

We aim to get close to the first of these aspirations by defining the example scales against which Evaluation Criteria should be Assessed. We aim to get close to the second by clearly defining the Evaluation Criteria to focus on different traits of Opportunities. We aim to achieve the third by only assessing Evaluation Criteria where it's necessary to leverage the expert knowledge of the Program Area team to interpret the Opportunity.

This document presents an outline of Evaluation Criteria definitions and example scales to underpin this discussion. These have been developed with the input of the Decision Support & Modelling Team, with input from the Program Director and with input from an independent external consultant experienced in this style of elicitation and prioritisation. They may be further refined before the assessment workshops. PA Leads can provide refinements and recommendations that would improve the fitness-for-purpose of the scales for each EC within their PA.

Proposed Assessment process for Research Opportunities

The proposed process for scoring Research Opportunities against these Evaluation Criteria is:

1. Program Areas collate Research Opportunities on Research Opportunity Templates (10 February 2021)

2. Prior to Program Area workshops in the last week of February, the Research Opportunity Templates for each Program Area are distributed to their respective Program Area teams

3. Each team member reviews each Research Opportunity submitted within their Program Area, they provide Assessment Values anonymously against the eight Evaluation Criteria requiring assessment using an online survey system, providing a minimum and maximum Assessment Value based on their certainty, and a few brief dot points of factors that influenced their Assessment Value.

4. The Assessment Value ranges and contributing factors for each Research Opportunity are accumulated across each Evaluation Criteria by the DS&M team prior to the Program Area Assessment Workshop.

5. During the Program Area Assessment Workshop, the DS&M team present the key results from the Assessment process, noting common and exceptional factors that contributed to the Assessment Values provided. PA team members are provided an opportunity to amend their Assessment Values based on what they've heard

6. This is combined with a facilitated discussion within the Program Area of research priorities, based on both the expertise of people in the room, and the relative Assessment Value received by Research Opportunities in each category.

7. The outcome of the assessment workshops is list of the Research Opportunities within each Program Area that have been assessed by the experts in that field.

This assessment data from within each Program Area will be used to generate a series of potential research portfolios for R&D investment, which will be evaluated and discussed at

the whole-of-CCIP prioritisation workshop. An independent consultant, Mayuran Sivapalan, will be facilitating this final prioritisation step, working closely with Program Director and team at the International COTS Forum in March 2021.

APPENDIX B – ASSESSMENT VALUE SCALES FOR EVALUATION CRITERIA

Note: *we do not define Assessment scales for Research or Implementation costs, because these are already quantitative estimates*.

EC Assessment Scale: 1 Path to impact										
EC Question: Does this Research Opportunity provide a pathway to deliver innovative COTS control outcomes, in alignment with CCIP vision and values, and how direct is the pathway to impact?										
Advice: Consider whether the research could be directly implemented into current COTS management, whether it would improve current management; whether it would require operationalisation before it could be implemented;										
0	1	2	3	4	5	6	7	8	9	10
No path to impact	Relatively indirect – the research would have to be completed, then further research on its implementation would be completed, then implemented			Fairly direct – once the research was completed, it would have to be implemented into the control program			Relatively direct - once the research was completed, it would fit within the existing control program			Completely direct – there is no difference between completing the research and generating the impact on water

EC Assessment Scale: 2 Ability to suppress or prevent COTS outbreaks										
EC Question: How significantly would realising this Opportunity improve our ability to prevent or suppress COTS outbreaks?										
Advice: Consider how the proposed research could improve the current state of COTS management, in which Outbreaks on the GBR occur every 15 – 17 years; outbreaks occur across 10 - 15% of reefs across the GBR in any one year; and outbreaking reefs experience COTS densities of 15 – 1000 COTS/ha. Would the current technique reduce the frequency of Outbreaks on the GBR? Would it decrease the proportion of individual reefs experiencing outbreaks? Would it decrease the density of COTS at outbreaking reefs?										
0	1	2	3	4	5	6	7	8	9	10
No benefit to outbreak suppression or prevention	Low benefit, meaning 15% improvement in outbreak frequency, proportion of outbreaking reefs, or density on outbreaking reefs (e.g., Outbreak frequency 18 - 19 years; outbreaks at 9 - 12% of individual reefs; peak COTS densities reduced by 15%)			Moderate benefit, meaning 30% improvement in outbreak frequency, proportion of outbreaking reefs, or density on outbreaking reefs (e.g., Outbreak frequency 22.5 years; outbreaks reduced to 6 - 9% of individual reefs; peak COTS densities reduced by 30%)			Significant benefit, meaning 50% improvement in outbreak frequency, proportion of outbreaking reefs, or density on outbreaking reefs (e.g., Outbreak frequency 30 years; outbreaks reduced to 4-6% of individual reefs; peak COTS densities reduced by 50%)			Highly significant benefit (e.g., no COTS Outbreaks on the GBR)

EC Assessment Scale: 3 Co-benefits: Ecosystem and coral health impacts										
EC Question: Would this research deliver positive coral health impacts on the Great Barrier Reef above and beyond those provided by more effective reduction of COTS impact, and how significant would those benefits be?										
Advice: Consider factors such as water quality improvements for COTS control that simultaneously support coral health; rezoning or protection of reefs; or monitoring methods that improve our knowledge of coral										
0	1	2	3	4	5	6	7	8	9	10
No coral health improvement other than that due to reduction in COTS	Low benefit (e.g., additional non-COTS protection of coral habitat at < 10 individual reefs)			Moderate benefit (e.g., additional non-COTS protection of coral habitat at 10 – 100 individual reefs; potential to increase average GBR coral cover by 1 – 2%)			Significant benefit (e.g., additional non-COTS protection of coral habitat at > 100 individual reefs; potential to increase average GBR coral cover by 2 – 5%)			Highly significant benefit (e.g., additional non-COTS all coral on the GBR protected; potential to increase average GBR coral cover by > 5%)

EC Assessment Scale: 4 Co-benefits: Socio-economic impacts										
EC Question: Would this research provide positive socio-economic outcomes for Traditional Owners, communities, and/or Reef-based industries beyond that generated by suppressing or preventing COTS outbreaks, and how significant would it be?										
Advice: Consider socio-economic impacts beyond those specific to COTS control, such as new income streams, employment, or other social benefits, for both Indigenous and non-Indigenous communities, and consider the potential impact of these benefits, relative to other opportunities available to these communities.										
0	1	2	3	4	5	6	7	8	9	10
Provides no socio-economic benefit (other than the benefit derived from culling COTS)	Low benefit (e.g., this research offers limited potential socio-economic benefits to communities, Traditional Owners, and/or reef-based industries)			Moderate benefit (e.g., this research provides some potential opportunities to communities, Traditional Owners, and/or reef-based industries, and these are quantifiable)			Significant benefit (e.g., provides clear pathways to enhance economic opportunities for communities, Traditional Owners, and/or reef-based industries, and these are quantifiable)			Highly significant benefit

EC Assessment Scale: 5 Time to viability										
EC Question: What is an approximate time estimate for this research to generate on-water impact reducing the impacts of COTS on the GBR?										
Advice: Consider the various factors that will affect how long this research will take to: 1) deliver the proposed research outcomes; 2) deliver outcomes that can be applied to suppress COTS outbreaks; 3) operationalise for on-water use; 4) deliver reduced frequency or intensity of COTS outbreaks on the GBR. If the research does not directly influence COTS, consider the time required for any additional research necessary to generate on-water impacts.										
0	1	2	3	4	5	6	7	8	9	10
Very long timeframe (20+yrs, not by this outbreak or next)	Long timeframe (10-20 years, by 2040 outbreak)			Moderate timeframe to implementation (5-10 years, before 2040 outbreak)			Short timeframe to implementation (3-5 years, by next outbreak 2025)			Very short timeframe (2 years or less, before next outbreak)

EC Assessment Scale: 8 Risks										
EC Question: How significant are the research risks associated with this Opportunity, including economic, environmental, social and regulatory risks?										
Advice: Consider the risk that research will not generate the outcomes expected, or that the outcomes will not generate the impacts expected even if the research is successful. Consider: economic risks (e.g., risk that the cost of implementing the technique would prevent its application); environmental risks (e.g., potential for non-target species impacts); social risks (e.g., potential for insufficient stakeholder engagement to prevent uptake); and regulatory risks (e.g., risk that regulatory approval will not be given for the methods being research to be applied).										
0	1	2	3	4	5	6	7	8	9	10
Significant regulatory risks that may degrade general public acceptance of COTS control	Significant risks that may prevent research or implementation even if research is successful			Economic, environmental, social or regulatory risks that are likely to be acceptable but are likely to impose additional risk management costs (e.g., funding for regulatory compliance, public education campaigns)			Potential for economic, environmental, social or regulatory components of research that would require awareness and proactive management.			No other risks

EC Assessment Scale: 9 Synergies with other opportunities										
EC Question: How does the proposed Opportunity interact with other potential research in CCIP? Is it primarily dependent on other research, does it overlap with other research, or does it enable other research?										
Advice: Consider synergies between the Opportunity and the current Control Program, or other research that may be proposed as part of CCIP by Program Area (e.g., would the proposed Opportunity benefit from innovations in surveillance or, alternatively, could the proposed Opportunity create benefits for surveillance?). Consider competitive overlaps with other research that may be proposed as part of CCIP (e.g., a biocontrol technique may replace culling completely; biological research into COTS larval settlement may or may not overlap with larval survival studies). Consider any research dependencies that would be required for this Opportunity to generate impact.										
0	1	2	3	4	5	6	7	8	9	10
This Opportunity directly overlaps with other Opportunities that could provide the same outcome, or it is heavily dependent on multiple other opportunities being successful to generate impact	This Opportunity is dependent on one or more other opportunities to generate impact, and is not synergistic with other Opportunities.			This Opportunity neither synergises nor overlaps with any other Opportunities, or is moderately dependent on one other Opportunities being successful to generate impact			This Opportunity is highly synergistic with other Opportunities, amplifying their impact, but is dependent on one or more other opportunities to generate impact			This Opportunity is highly synergistic with other Opportunities, amplifying their impact, and is not dependent on other opportunities to generate impact

EC Assessment Scale: 10 Innovation potential										
EC Question: Overall, what is the potential for this Research Opportunity to deliver innovation in COTS surveillance and/or control?										
Advice: If we define innovation as the implementation of a new idea, tool or approach that improves outcomes, consider the extent to which the proposed Opportunity can deliver innovation that transforms COTS surveillance and/or control on the Great Barrier Reef.										
0	1	2	3	4	5	6	7	8	9	10
No influence on COTS surveillance or control	This Opportunity has potential to deliver limited innovation in COTS surveillance and/or control			This Opportunity has potential to deliver moderate innovation in COTS surveillance and/or control			This Opportunity has the potential to deliver significant innovation in COTS surveillance and/or control			This Opportunity would completely transform COTS surveillance and/or control

APPENDIX C – CCIP FEASIBILITY AND DESIGN PHASE INFORMATION

Background and objectives of the COTS Control Innovation Program

Outbreaks of coral-eating crown-of-thorns starfish (COTS) are a major cause of coral decline on the Great Barrier Reef and future COTS outbreaks are almost certain. Managing these damaging outbreaks is a critical priority to improve the health of the Great Barrier Reef World Heritage Area. Effective COTS outbreak management is also a necessary complement to research and innovation that helps the Great Barrier Reef resist, adapt to, and recover from the impacts of climate change.

The COTS Control Innovation Program (CCIP) is being delivered as multidisciplinary collaboration with cross-institutional teams focused on designing (phase 1, 2020-21) and delivering (phase 2, 2021-24) a research and innovation program, with a total investment of $9.8m through the Reef Trust Partnership.

The overarching goal of the CCIP is to create a step change that will accelerate the development of innovative control and surveillance methods, while continuing to improve the efficacy and efficiency of current methods.

Achieving this goal will require targeted research that drives progress while also managing cost and risk. The problem at hand is that there are a wide range of Research Opportunities that could potentially contribute to delivering on CCIP goals. Moreover, the feasibility and benefit of many Research Opportunities in delivering innovative COTS management outcomes is not well understood. Consequently, we are faced with a complex problem in deciding which Research Opportunities warrant investment through the CCIP.

The structured decision-making process

In the CCIP Feasibility and Design Phase a structured decision-making process (SDM) is being used to inform decisions on which research and innovation opportunities will be invested in during the three-year research program. The intention is to deliver insight to decision makers about how well the goals and values of the CCIP will be met through a systematic assessment of the various investment options.

Structured decision-making is an organised, inclusive and transparent approach to understanding complex problems and evaluating alternative options to address them (Keeney 1982, Gregory et al. 2012). It is based on the concept that quality decisions are those which are based on values (i.e., understanding what's important) and consequences (i.e., understanding what's likely to happen). It is useful when different disciplines need to work together to develop solutions to complex problems that are rigorous, inclusive, defensible and transparent.

The CCIP Program Director and Program Area leads developed the following values statements to underpin decision-making when designing the portfolio of research for investment:

1. maximises the benefit to coral (i.e., minimises loss and/or enhances resilience);

2. maximises the potential for future prevention of COTS outbreaks on the Great Barrier Reef;
3. maximises the capacity for early warning and effective suppression of the next outbreak;
4. able to be safely deployed in the Marine Park with risks minimised and/or manageable;
5. provides socio-economic benefits to communities and/or Reef-based industries;
6. maximises complementarity across Research Opportunities, capitalising on synergies, and;
7. delivers value for money when considering the costs of research, development and deployment.

Development of Research Opportunities & next steps

At this point, CCIP Program Area teams have considered gaps in knowledge within their work theme and this can now be used as a basis for development of Research Opportunities.

Using the template attached, please summarise the research to be conducted and provide information on the various positive impacts, costs, risks, and timelines relevant to each proposed Opportunity.

Your Program Area team will use this information as a basis for evaluating the feasibility and benefit of potential Research Opportunities within your Program Area prior to and during an assessment workshop in February 2021. During the assessment, team members will consider the information provided in the template and, through a facilitated process, anonymously score each Research Opportunity across a set of Evaluation Criteria aligned with CCIP's values and objectives. The process of considering the characteristics of each Opportunity in order to score it, as well as the scores themselves, will assist your team to identify the most critical Opportunities within your Program Area.

The scoring data generated by this assessment process will subsequently be used to develop integrated research portfolios composed of Opportunities from across the Program Areas. These integrated portfolio options will then be considered and assessed jointly by all Program Area teams coming together at a whole-of-CCIP prioritisation workshop to be held 31 March 2021, in Cairns alongside the COTS Forum.

APPENDIX D – OPPORTUNITY TEMPLATE

Opportunity Title	
Opportunity Proponent	
CCIP Program Area	

Opportunity Outline 100 – 300 words	Outline the proposed Research Opportunity, including the aim, what will be done, the time frame, and an approximate estimate of resources required (e.g., staff time, operating costs, facilities or special equipment etc.).

1. Path to impact	**Describe the impact pathway** (100 – 200 words) How does this Research Opportunity provide a pathway to deliver innovative COTS control outcomes, in alignment with CCIP vision and values? Describe the pathways to creating real-world impact (i.e., a tangible change in the way COTS impacts are managed on the GBR). If the outcomes of the proposed research: • could be directly integrated into existing COTS management, e.g., refinement of existing decision support tools, explain how; • could improve the performance of the current control measures, e.g., improved surveillance enabling more efficient targeting of control, explain how; • could improve the ecological underpinning for COTS management, e.g., improved biological understanding, explain what difference the improved understanding would make In addition, if the research will require further steps to generate impact, such as: • operationalisation, e.g., rolling out new population control methods, note this and provide details • the success of additional research, e.g., regulatory approvals for biocontrol would require biocontrol methods to be created and implemented, note this and provide any details possible Comment on multiple potential pathways where they exist.
	Certainty of impact (10 – 50 words) Comment on the certainty of achieving this impact and note any factors that might influence this

2. Ability to suppress or prevent COTS outbreaks	**Describe the ability to suppress or prevent outbreaks** (100 – 200 words) Would realising this Opportunity improve our ability to: • prevent GBR-scale Outbreaks? • prevent outbreaks at individual reefs? • suppress the intensity of outbreaks? • suppress COTS at ecologically important places (e.g., super-spreader reefs)? • suppress COTS at ecologically important times (e.g., prior to spawning)? For Opportunities that indirectly suppress or prevent COTS outbreaks, comment on the ability of the entire impact pathway proposed in section 1 to suppress or prevent COTS outbreaks. Describe the ability of the Opportunity to suppress or prevent COTS outbreaks at a scale consistent with the costs included in sections 6 and 7, and the time included in section 5.
	Certainty (10 – 50 words) What factors influence the certainty of achieving these benefits?

3. Co-benefits: Ecosystem and coral health impacts	Does this Opportunity generate positive ecosystem or coral impacts beyond that generated by suppressing or preventing COTS outbreaks? If no, move to section 4 If yes, answer following parts of section 3
	Describe positive ecosystem or coral health impacts (100 – 200 words) How would this research deliver positive coral health impacts on the Great Barrier Reef above and beyond those provided by more effective reduction of COTS impact, e.g., water quality improvements for COTS control that simultaneously support coral health; or monitoring methods that improve our knowledge of coral? Describe the ecosystem or coral health impacts at a scale consistent with the costs included in sections 6 and 7, and the time included in section 5.
	Certainty (10 – 50 words) What factors influence the certainty of achieving these impacts?

4. Co-benefits: Socio-economic impacts	Does this Opportunity generate positive socio-economic impacts beyond that generated by suppressing or preventing COTS outbreaks? If no, move to section 5 If yes, answer following parts of section 4
	Describe positive socio-economic impacts (100 – 200 words) How would this research deliver positive socio-economic outcomes? Would it build trust, transparency amongst stakeholders? Would it increase the likelihood of uptake by stakeholders or social acceptability in coastal communities? Would it provide positive outcomes for Traditional Owners, communities, and/or Reef-based industries beyond that generated by suppressing or preventing COTS outbreaks? What Opportunities would be provided by the research itself? What Opportunities may be enabled during implementation? Describe the socio-economic impacts at a scale consistent with the costs included in sections 6 and 7, and the time included in section 5.
	Certainty (10 – 50 words) What factors influence the certainty of achieving these impacts?

5. Time to viability	**Describe factors contributing to time to viability of research and generation of impacts** (100 – 200 words) What factors will affect how long this research will take to: • deliver the proposed research outcomes? • deliver outcomes that can be applied to suppress COTS outbreaks? • operationalise for on-water use? • deliver reduced frequency or intensity of COTS outbreaks on the GBR? Provide time estimates for those components relevant to the proposed Opportunity, relative to the impacts described in sections 2, 3 and 4.
	Certainty (10 – 50 words) What factors influence the certainty of this time to viability?

6. Research cost	**Describe factors contributing to the research cost of this Opportunity** (100 – 200 words) What are the factors that will determine the research cost to deliver this Opportunity? Consider the full range of costs involved in conducting the research (e.g., personnel, facilities, fieldwork, consumables, travel). Provide approximate (± 25%) quantitative dollar estimates where possible. Comment first and in most detail on the research proposed as part of this Opportunity. If the Opportunity relies on other research to derive impact, comment briefly on what costs this research may involve. Summarise the costs to complete the research to the standard required to generate the impacts described in sections 2, 3 and 4.
	Certainty (10 – 50 words) What factors influence the certainty of these cost estimates?

7. Implementation cost	**Describe factors contributing to the implementation cost of this Opportunity** (100 – 200 words) What are the factors that will contribute to the costs of implementing the outcome of this research to generate the real-world impact outlined in section 1? Are there likely to be significant labour costs (e.g., the current Control Program); production costs (e.g., attractant baits); stakeholder payments (e.g., water quality); or compliance costs (e.g., those associated with demonstrating biocontrol standards are being maintained)? Outline factors that may apply. If possible, provide approximate (± 50%) dollar estimates at the scale most relevant to the Opportunity (e.g., per reef, over the entire GBR, per year)? Summarise the costs to generate the impacts described in sections 2, 3 and 4.
	Certainty (10 – 50 words) What factors influence the certainty of these cost estimates?

8. Risks • Research • Economic • Environmental • Social • Regulatory	**Describe any significant risks that may prevent this Opportunity from generating the impact outlined in sections 2, 3 and 4** (100 – 200 words) Describe the research risk associated with this Opportunity (e.g., the risk that research will not generate the outcomes expected, or that the outcomes will not generate the impacts expected even if the research is successful). If applicable, describe any: economic risks (e.g., risk that the cost of implementing the technique would prevent its application); environmental risks (e.g., potential for non-target species impacts); social risks (e.g., potential for insufficient stakeholder engagement to prevent uptake); or regulatory risks (e.g., risk that regulatory approval will not be given for the methods being research to be applied).
	Certainty (10 – 50 words) What factors influence the certainty with which we can predict these risks?

9. Synergies, overlaps and dependencies with other Opportunities	Does this research have any: 1) synergies; 2) competitive overlaps; or 3) dependencies with any other research that might be part of CCIP? If no, application is completed If yes, answer following parts of section 9
	Describe any: 1) synergies; 2) competitive overlaps; or 3) dependencies with any other research that might be part of CCIP (100 – 200 words) Describe synergies between the Opportunity and the current Control Program, or other research that may be proposed as part of CCIP by Program Area (e.g., would the proposed Opportunity benefit from innovations in surveillance or, alternatively, could the proposed Opportunity create benefits for surveillance?). Describe any competitive overlaps with other research that may be proposed as part of CCIP (e.g., a biocontrol technique may replace culling completely; biological research into COTS larval settlement may or may not overlap with larval survival studies). Provide as much detail as possible on any research dependencies identified in section 1 or throughout the Opportunity proposal that would be required for this Opportunity to generate impact.
	Certainty (10 – 50 words) What factors influence the certainty with which we can identify synergies, overlaps and dependencies?

APPENDIX E – RESEARCH OPPORTUNITY ASSESSMENT INSTRUCTIONS

Introduction

This document lays out the instructions for how to assess Research Opportunities using the web survey, a recommended workflow, and advice on how to score each Evaluation Criteria.

Recommended Workflow

The email invitation to the assessment survey included two documents:

- These CCIP Research Opportunity Assessment Instructions
- The pack of Research Opportunities for your Program Area

It is strongly recommended that you read both sets of documents thoroughly before beginning the online assessment process. The assessment process is straightforward but takes time, and it will be easier to apply a consistent approach to assessment if you have an overview of the Opportunities.

Our testing of the assessment approach suggested that *if pre-reading had already been completed* each Opportunity is likely to take 10 – 15 minutes to assess.

You access your personal survey in the SurveyMonkey system via the button contained in the email invitation. The survey will automatically save your responses as you progress. You can leave the survey page, return via the button in your invitation email, and pick up where you left off or amend previously entered responses. In order to facilitate this functionality, this invitation email is linked to a single respondent; please don't forward it to anybody else.

Please note that in some cases the wording of the “Opportunity Title” within the template files inside the Research Opportunity pack vary from those listed in the survey – please reference the Opportunity Numbers (e.g., DSM-1) in the filename of the Opportunity template file and the page title of the survey page to ensure you assess each Opportunity in the appropriate place.

Surveys will be open from Monday 15th February, and will close at 5pm AEST on Friday 19th February.

Advice on assessment

The assessment process is designed to characterise each Opportunity against a range of eight Evaluation Criteria representing important attributes for research under CCIP. It is not a simple scoring system, in that an assessment value of 8 is not necessarily “better” than a value of 2. Please consider each Evaluation Criteria independently; for instance, the cost of an Opportunity should not affect your assessment of its Path to Impact.

The assessment process is designed to leverage the expert opinion of people within CCIP to help complete this characterisation, through a two-step process:

- Individual online Assessment (what you’re being asked to do now)
- Group Assessment Workshop discussion (within the next two weeks)

This structure means that individual assessments do not have to be precise or certain. We are looking for the range encompassing your best estimate with uncertainty, based on your experience and knowledge, of your assessment of each proposed research Opportunity against each Evaluation Criteria.

The fact that we ask for a “range” of values for each Evaluation Criteria both reduces the importance of you selecting a precise number, and provides additional information about the certainty of your assessment. The fact that this information gets accumulated across a number of people in each Program Area provides for diverse input and reduces the sensitivity of the process to the precise value of any one assessment. Moreover, the subsequent Assessment Workshop will provide an opportunity to discuss the outcomes as a group, highlight missed factors or information that might have influenced assessments, and provide the chance to revise assessments in light of the discussion.

As a consequence of these factors, we recommend that you don’t obsess over the exact value with which you assess each Opportunity against each Evaluation Criteria, but that you instead focus on getting values that are ***reasonable in both an absolute and a relative sense***.

To help achieve absolute assessment, we provide a range of scales below that indicate roughly what each value (0 to 10) should correspond to. Please reference these scales each time you make an assessment. Provide your assessment as a range of values based on your certainty. For instance, if you believe Opportunity 1 has a “moderate” ability to suppress or prevent COTS outbreaks and you are relatively certain of that, you might select assessment values of 4 and 5. If you feel Opportunity 4 also has a “moderate” ability to supress or prevents COTS outbreaks at best, but you are much less certain of that outcome, you might select assessment values of 2, 3, 4, 5, and 6.

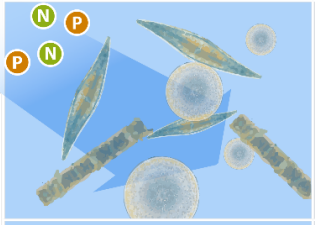
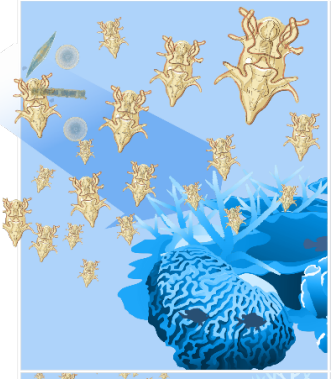
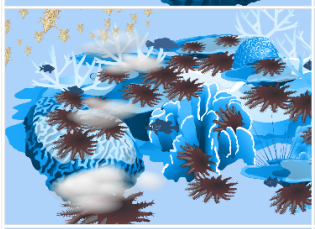
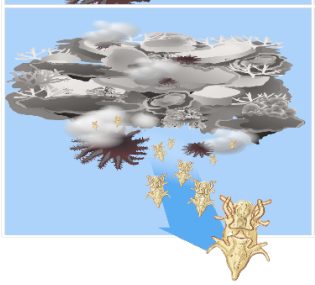
If you feel that a Criteria does not apply to the Opportunity in question, please select "Not Applicable". If you feel that you do not have the expertise to provide any comment, please select "No Idea".

The scales do not provide precise definitions for every value. This is to allow some latitude for relative assessment. As you complete your assessments, please keep in mind how earlier Opportunities were assessed and adjust your values for the current Opportunity relative to those. For instance, if both Opportunity 1 and Opportunity 4 have a “moderate” ability to suppress or prevent COTS outbreaks, but you feel Opportunity 4 has a greater ability than Opportunity 1, you may value the upper limit of Opportunity 4 as a “6” and Opportunity 1 as a “5”.

Once you have assessed all the Opportunities, we recommend that you review the relative values for each Opportunity against each Evaluation Criteria, and refine assessments as necessary. This is because it can be hard to hold many previous assessments in mind while assessing new Opportunities, but a direct comparison of relative assessments can be easier.

APPENDIX F – SCHEMATIC OF THE NUTRIENT HYPOTHESIS

The Nutrient Hypothesis In Relation to CoTS outbreaks

	STEP	MECHANISM	EVIDENCE	KNOWLEDGE GAP *Research proposed here (in italics)*
	Change in land use and management increases sediment and nutrient runoff	Soil destabilisation Fertilizer application	Land use and management data Catchment modelling Fertilizer usage End of river monitoring	
	Runoff increases sediment and nutrients in coastal waters (e.g. N, P, Si, Fe)	Pulse delivery through river input, specifically after long droughts	Marine monitoring Modelling	*Which nutrients are enhanced, and where?* *Are other potential food sources enhanced?* *Nutrient transformation and availability in coastal waters?* *Do increased nutrients reach 'initiation box'?*
	Increased nutrients increase phytoplankton	Plankton is assumed limited by individual or combined nutrients	Some inshore offshore comparisons Limited flood plume monitoring	*Which plankton group/size class increased by which nutrient constituent?* *Specific plankton groups/species enhanced in December/January?* *Do increased plankton/other food sources reach "initiation box"?*
	Increased phytoplankton leads to higher survival rates of CoTS larvae and thus increased recruitment	More and better fed larvae survive planktonic phase and settle. Development is faster and thus overall mortality lower	**Temporal:** outbreaks did appear after "drought breaking" flooding **Experimental:** larvae do grow faster to settlement with more algae food	*What are the "threshold values" for enhanced larval survival? Currently these are only known in terms of chlorophyll values. These are based on lab experiments with artificially high larval densities and in batch mode. Cell specific chlorophyll values unknown for natural phytoplankton.* *Is chlorophyll a good measure of nutritional value for CoTS larvae?* *Do CoTS thrive on the actual phytoplankton species enhanced in initiation zone?* *Does time and location with nutrients/ plankton blooms agree with spawning times and initiation box?*
	Higher recruitment increases adult populations **(primary outbreaks)**	More recruits result in more adults	Mechanism seems common sense, but are other drivers involved?	Early life history of settlers? Predators of larvae, recently settled juveniles and adults?
	High densities in initiation box lead high larval output and **secondary outbreaks**	More larvae through positive feedback (eg higher fertilisation) Outbreaks on reefs further south	Monitoring	*Do nutrients also promote/exacerbate secondary outbreaks*

Evidence key:
- sufficient evidence
- some gaps
- significant gaps

COTS Control Innovation Program | A research and development partnership to better predict, detect and respond to crown-of-thorns starfish outbreaks

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