# Operationalising resilience-based management at scale: a meta-adaptive blueprint from the Great Barrier Reef Crown-of-Thorns Starfish Control Program

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## ABSTRACT

Resilience-based management (RBM) has been widely adopted as a future focused extension of adaptive management to address mounting climate change impacts on coral reef ecosystems, yet there are few demonstrated examples of RBM operating effectively at large spatial and institutional scales. The Crown-of-Thorns Starfish (COTS) Control Program on the Great Barrier Reef illustrates how RBM can be operationalised by incrementally building new dimensions of the Program onto a simple foundation of direct management action. We term this approach meta-adaptive management: a deliberate process in which an intervention program incrementally expands its scope, sophistication and its capacity to adapt over time through stakeholder engagement, technical refinement, and effective governance. Rather than assuming a fully mature adaptive framework is in place from the outset, meta-adaptive programs build the institutional, social, and technical capacity required for RBM to function at scale while continuing to deliver operational outcomes. We describe how this approach has been applied in the COTS Control Program, with a specific focus on recent advances in reef prioritisation. We also distil eight transferable enabling components that are built over time—foundational research, systematic monitoring, technical efficacy, stakeholder and political support, governance and strategy, secure funding, decision-support systems, and robust prioritisation—and show how recurring decision points (e.g., annual prioritisation) create incentives for applied research and stakeholder alignment. This

perspective offers a practical blueprint for conservation programs facing dynamic threats and uncertain futures.

Keywords: Resilience-based management, adaptive management, conservation prioritisation, coral reef resilience, Crown-of-Thorns Starfish, Great Barrier Reef, iterative decision-making

# INTRODUCTION

## Conservation management in the Anthropocene

Ecosystems worldwide are experiencing profound transformations driven by climate change, habitat degradation, and intensified human activities (Crutzen, 2002; Hughes et al., 2017a). Coral reefs are among the first to confront existential versions of these challenges, facing recurrent and cumulative disturbances that threaten ecosystem resilience and functions (Bozec et al., 2025; Hoegh-Guldberg et al., 2018; Hughes et al., 2017b). Conservation managers must increasingly allocate limited resources under complex and uncertain future conditions, prompting the need for frameworks capable of anticipating, absorbing, and adapting to change (Anthony et al., 2015; Game et al., 2014; Wilson et al., 2006).

Adaptive Management (AM) (Holling, 1978; Williams and Brown, 2014), and, more recently Resilience-Based Management (RBM) (Anthony et al., 2015; Mcleod et al., 2019), have iteratively developed in recent decades as frameworks for addressing uncertainty and complexity. While AM emphasises structured experimentation and iterative learning, RBM extends this approach, placing greater emphasis on anticipating future disturbances and explicitly managing for socio-ecological resilience (i.e. the ability of a system to both resist and recover from disturbances; Holling, 1973; Hughes et al., 2005). Despite their theoretical appeal, and notable examples (e.g. AM - 2004 rezoning of the Great Barrier Reef Marine Park; Day, 2002; Fernandes et al., 2005; McCook et al., 2010; RBM - NOAA Coral Reef Conservation Program; NOAA, 2018) there remain significant challenges to overcome when attempting to operationalise AM and RBM interventions at large spatial or institutional scales (Walters, 2007). Such interventions may include reducing local stressors (e.g. Crown-of-Thorns Starfish (COTS) predation, land-based pollution, overfishing), implementing climate smart Marine Protected Areas, or emerging coral restoration and assisted-evolution (Mcleod et al., 2019). Programs attempting comprehensive, fully developed adaptive frameworks from the outset often stall, as complexity and resistance overwhelm institutional capacities and social acceptance (Rist et al., 2013). Moreover, a persistent research–implementation gap means even well-developed methods often fail to influence on-ground management actions (Dubois et al., 2020; Knight et al., 2008; Toomey et al., 2017).

## Operationalising resilience-based management: from theory to practice

Despite recent shifts in overarching governance to incorporate RBM in long term frameworks (Commonwealth of Australia, 2021; GBRMPA, 2024, 2017; NOAA, 2018) and growing scientific consensus, there remains a critical gap in successful operational implementation of RBM at large spatial scales (Shaver et al., 2022). We argue that a key missing step is to explicitly foster the enabling conditions for a program to adapt and to embed clear, operational decision points that incentivise applied research and cooperative governance. In this manner program-level adaptiveness can emerge, scale and adequately respond to dynamic environmental conditions.

Managing for uncertain futures is modern necessity and any operational implementation of RBM must be willing to start in an unoptimized state and progressively evolve alongside the compounding stressors that managers aim to mitigate. Moreover, the adaptiveness of the program cannot be expected to work “out of the box” and the most suitable approaches must be learnt and scaled over time. We use the term “meta-adaptive” to denote an extension of double-loop learning (Argyris and Schön, 1978; Williams and Brown, 2014) and deutero-learning or learning about learning (Argyris and Schön, 1978; Fabricius and Cundill, 2014) that focuses on building the program’s capacity to learn and adapt over time. Where double-loop learning leads to new approaches and challenges to existing methods, we posit that the meta-adaptive approach adds the deliberate buildup of enabling and operational capacity (i.e. funding stability, foundational research and monitoring, institutional processes, stakeholder and political buy-in, and recurring decision points) as the program and its adaptive capability expands. This extension of existing frameworks explicitly acknowledges that adaptiveness is an emergent property cultivated through cumulative iterative actions through which the decision points, planning cycles and culture of the program and partner organisations are aligned towards a shared approach and common goals (Kingsford and Biggs, 2012; Roux et al., 2022) . This approach is particularly important for RBM, where the objective is not only to manage adaptively, but to do so in ways that actively build long-term system resilience in the face of uncertain futures(Anthony et al., 2015; Mcleod et al., 2019)

## Crown-of-thorns starfish control: a model of meta-adaptive management at scale

The Crown-of-Thorns Starfish (COTS) Control Program on Australia’s Great Barrier Reef (GBR) provides a rare operational case study of an effective application of adaptive management to enhance ecosystem resilience (Matthews et al., 2024). The Program’s successes were realised incrementally, and progressively increased stakeholder buy-in, funding stability, research collaboration and institutional capacity. Outbreaks of the Crown-of-Thorns Starfish (*Acanthaster* cf. *solaris*, COTS) significantly threaten coral reef resilience in the Indo-Pacific, particularly on the GBR. Although COTS are a natural component of reef ecosystems, COTS outbreaks, amplified by their high fecundity (Pratchett et al., 2021b), nutrient enrichment of coastal waters (Fabricius et al., 2010), and depletion of key predators

(Kroon et al., 2021; Motti et al., 2022), can drive severe coral loss (De'ath et al., 2012; Kayal et al., 2012; Pratchett, 2010). Concern about the impact of these outbreaks motivated the establishment of the GBR's first systematic Long-term Monitoring Program (Emslie et al., 2020) in 1985, delivered by the Australian Institute of Marine Science. Analysis of that monitoring data has revealed that COTS outbreaks are estimated to account for up to 40% of historical coral decline on the GBR (De'ath et al., 2012; Emslie et al., 2024; Osborne et al., 2011) and remain one of the few major reef threats amenable to direct intervention at ecologically meaningful scales (Matthews et al., 2024; Pratchett et al., 2017; Westcott et al., 2020). The GBR COTS Control Program is one of the world's largest active coral reef interventions. Supported by federal policy and investment (GBRMPA 2017, 2024a; Commonwealth of Australia 2021, DCCEEW 2022), implementation of the program is guided by adaptive operational frameworks (Fletcher et al., 2020), integrated decision support systems (Matthews et al., 2025), and applied research programs (e,g., Fletcher et al. 2021, Bonin et al. 2022). This has enabled delivery of broadscale coral protection and ecosystem resilience benefits across the GBR with up to 6-fold reductions in COTS densities and 44% increases in live coral cover (compared 37% loss in previous outbreaks) across entire regions where timely and sufficient culling effort was applied (Matthews et al. 2024).

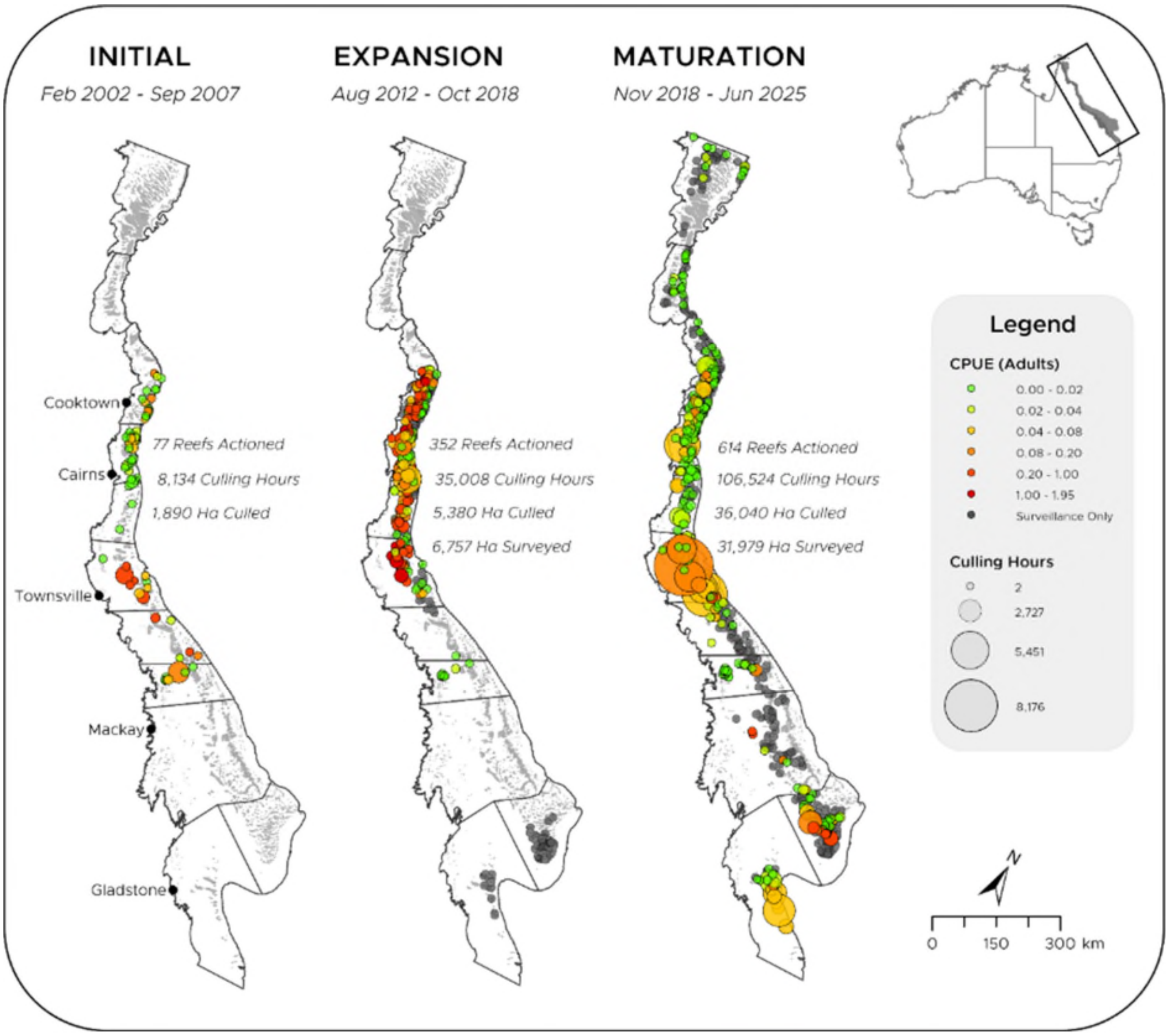


Figure 1 Evolution of the GBR COTS Control Program across three phases of maturity (2002–2025). Geographic expansion of control and surveillance effort (measured as CPUE: catch-per-unit-effort) across three operational phases: Initial (2002–2007), Expansion (2012–2018), and Maturation (2019–2025). Points represent reefs surveyed and culled, with symbol size and colour indicating culling effort starfish density (CPUE) respectively. Grey circles indicate reefs surveyed by both the COTS Control Program and the COTS Response Program operated by Queensland Parks and Wildlife Service where no culling has taken place.

The COTS Control Program illustrates how adaptiveness can be cultivated over time. Rather than attempting to implement a comprehensive framework from the outset, the Program evolved through successive iterations: reactive beginnings focusing on high value tourism sites (Matthews et al., 2024), early operational wins (Westcott et al., 2020), and gradual institutional embedding (GBRMPA, 2024, 2020, 2017). This enabled the incremental accumulation of the components that we contend are required for successful and durable RBM at scale: foundational research; systematic monitoring; technical efficacy; stakeholder support and political will; governance and strategy, secure funding, decision support and robust prioritisation (i.e. rigorous, practical and resistant to uncertainty; Fletcher et al., 2024; Hemming et al., 2022; Regan et al., 2005)).

In this paper, we present the COTS Control Program as a mature example of meta-adaptive management in action and offer a new paradigm for successful RBM via meta-adaptive principles. Specifically, we:

1. Trace the Program's evolution from small-scale tourism site stewardship actions to ecosystem-scale intervention, highlighting how incremental improvements laid the foundation for long-term adaptiveness and success.
2. Describe this evolution in terms of the core components for successful RBM and mark the key advancements
3. Detail the prioritisation framework that underpins where and when interventions occur, highlighting how adaptive decisions are made in an operational program.
4. Extract general lessons and recommendations for conservation initiatives seeking to build successful large scale adaptive programs under uncertainty.

By dissecting how the GBR COTS Control Program has become both adaptive and durable, we offer a rare, pragmatic model for other large-scale conservation and RBM efforts facing intensifying pressures and an uncertain future as climate change progresses.

# COTS CONTROL PROGRAM: FROM HUMBLE BEGINNINGS TO LARGE SCALE RESILENCE-BASED MANAGEMENT

Numerous small scale control efforts throughout the 1970s and foundational research into COTS outbreaks through a Cooperative Research Centre (CRC) for the GBR paved the way for the establishment of the first formal COTS Control Program in 2002 during the third recorded outbreak wave (Figure 1) (Woodley et al., 2006). Delivered by industry through the Association of Marine Park Tourism Operators (AMPTO), this initial control program focusing on manual culling via multi-shot sodium bisulphate injections of starfish at key tourism sites across 77 reefs (Figure 1). While effective in reducing starfish densities, these early interventions were not scalable due to program resource limitations and the time-intensive nature of the multi-shot method (Pratchett et al. 2017; Westcott et al. 2020). Despite their limitations, these early iterations developed key relationships between the tourism industry, government bodies and research groups, effectively setting the trajectory for increased stakeholder buy-in and social license for COTS control on the GBR (Bartelet et al., 2025; Lockie et al., 2024). In 2012, the Program was remobilised with increased resources in response to the emergence of the fourth outbreak wave and the devastating impact of a series of severe tropical cyclones (De'ath et al. 2012, GBRMPA, 2020). This marked the beginning of a more systematic and coordinated approach geared towards protecting ecosystem resilience in the face of mounting cumulative pressures. Critically, foundational research and iterative testing led to the development of 'single-shot' injection techniques using ox bile salts and later household vinegar, dramatically increasing diver efficiency and making large-scale control operations feasible (Rivera-Posada et al. 2014; Boström-Einarsson & Rivera-Posada 2016) (Figure 2, Table 2).

Initial responses to COTS outbreaks, while effective at smaller scales (e.g. individual sites on reefs), still followed a reactive cycle of crisis-driven attention and reactive intervention funding, a pattern consistent with the "issue-attention" cycle commonly observed in pest management with operational surges occurring only during acute outbreaks (Babcock et al., 2020; Downs, 1972; Hoey et al., 2016). However, these modest early successes were strategically designed to demonstrate effectiveness at smaller scales and were pivotal in garnering institutional support and providing the evidence base to attract sustained increases in operational capacity and targeted research investment. This included funding for the first dedicated COTS research program through Australia's National Environmental Science Program (NESP) that developed a new Integrated Pest Management (IPM) strategy to inform the effective scale-up of control efforts (Westcott et al., 2016). At the same time increasing management and political concerns around mounting climate change impacts and the urgent need for direct protective actions that could buy time for climate adaptation at seascape scales had been building in the lead up to the back-to-back coral bleaching events in 2016 and 2017 (GBRMPA, 2017).

Together, these developments underpinned substantially increased investment in COTS control in 2018 and marked the formal adoption of the IPM framework (Fletcher et al., 2020; Westcott et al., 2016) that was deployed to guide the program's research integration and operational processed. This transformative shift toward strategically targeted systematic COTS control on the GBR resulting in substantial funding uplift, a tripling of culling effort, a 60% increase in culling efficiency (Westcott et al., 2020) and consolidated shift from protecting small scale tourism sites, to protecting ecosystem resilience at broad spatial scales (GBRMPA, 2020; Matthews et al., 2024). Growing confidence in the Control Program's potential for scalable impact paved the way for ongoing sustainable funding through the Reef Trust Partnership (RTP), and the establishment of the COTS Control Innovation Program (CCIP) to sustain the research-management feedback loop (Bonin et al., 2022; DCCEEW, 2022; Fletcher et al., 2021; Great Barrier Reef Foundation, 2019; Pratchett et al., 2021a). Together, these investments enabled the expansion of a systematic monitoring toolbox (Chandler et al., 2023; Uthicke et al., 2024), further development and integration of ecological modelling, including larval dispersal and connectivity estimates (Choukroun et al., 2024; Rogers et al., 2024; Skinner et al., 2025) and ongoing improvements to decision support systems to enable RBM (Matthews 2019, Matthews et al 2025).

Today, the COTS Control Program operates across the 2,300 km length of the Great Barrier Reef, making it one of the largest-scale coral reef interventions in the world (Figures 1,2). It operates with longer term dedicated funding out to 2030 and is recognised as a foundational component of GBR management with the express purpose of protecting coral from COTS predation to support the Reef's resilience and adaptive capacity (GBRMPA, 2024, 2020, 2017). While significant resilience and coral protection benefits have been realised (Matthews et al., 2024), several studies have highlighted that much more benefit could be derived by increasing the scale, strategic targeting and complementarity of the Program with other emerging reef interventions (Babcock et al., 2020; Castro-Sanguino et al., 2023; Condie et al., 2021; Skinner et al., 2025). Furthermore, the current development of a bespoke monitoring program for COTS (Lawrence et al., 2025) alongside advancement of early warning systems within the Decision Support System (Matthews et al., 2025), will increase the ability of the Program to be responsive to changes in the system. These continual and incremental improvements underscore the benefits of the meta-adaptive approach embedded within the Program and among research and industry partners.

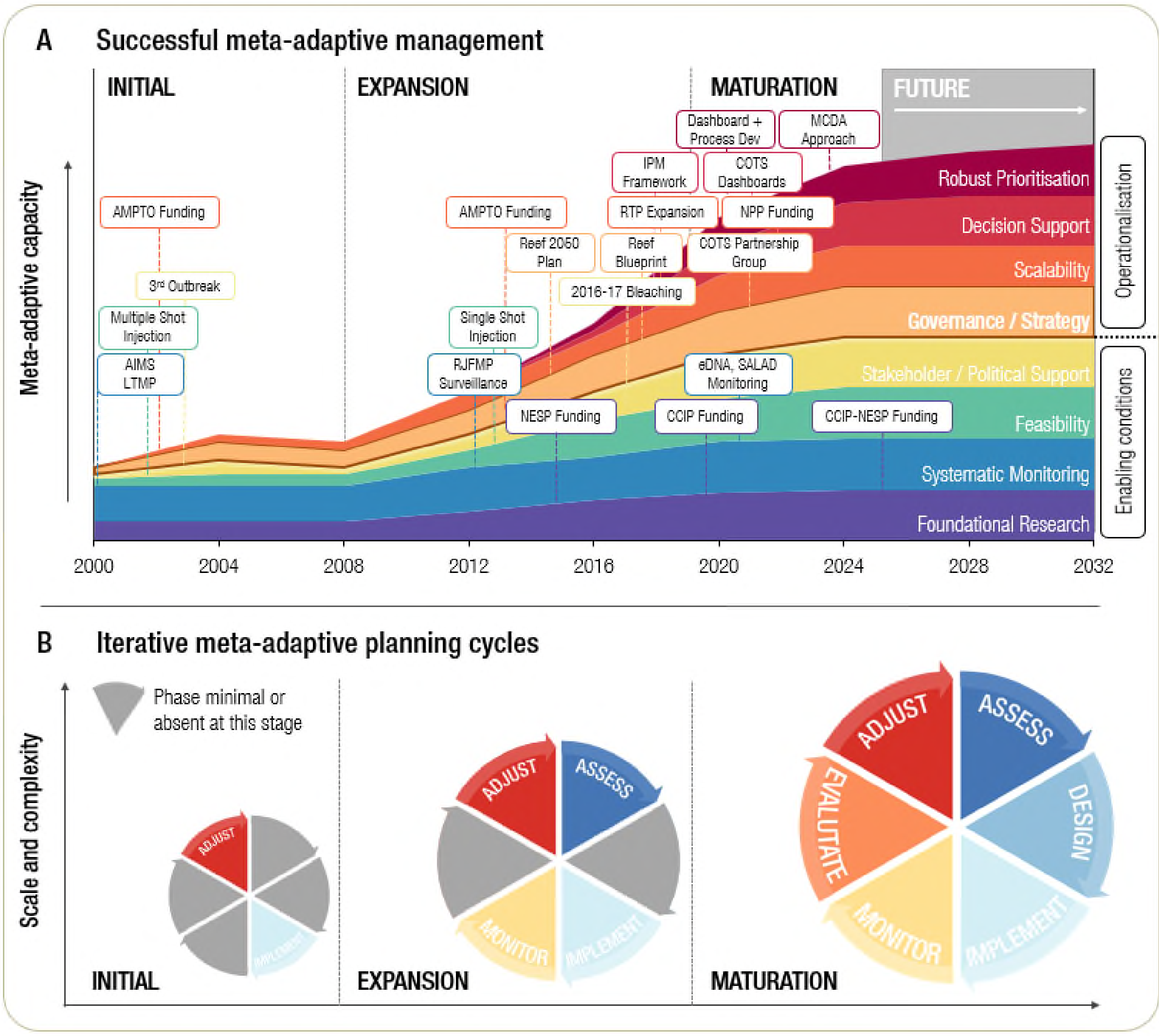


Figure 2 Panel A shows the cumulative development of eight core components underpinning successful meta-adaptive management of the GBR COTS Control Program, highlighting how capacity and complexity were built incrementally over time. Panel B illustrates how adaptive planning cycles (Assess → Design → Implement →

Monitor → Evaluate → Adjust) were repeated and expanded through time (Adapted from Matthews et al, 2025). Each cycle increases in size to reflect greater institutional capacity, integration of research, and decision complexity, and greyed segments indicates how different phases of the AM cycle were incrementally improved / included. This conceptual framework contrasts with traditional adaptive management models by emphasizing iterative scaling and emergent adaptiveness.

The evolution of the GBR COTS Control Program reflects a structured sequence through which the size, complexity, effectiveness and adaptiveness of the Program is being progressively enhanced via cumulative, reinforcing components (Figure 2). The cumulative layering of enabling conditions (Foundational Research through to Stakeholder and Political Support; Figure 2) has been catalysed into an operational program via strategic planning and effective governance. Rather than a static framework implemented wholesale, adaptiveness emerged through repeated decision cycles in which operational, institutional, and technical capacity were incrementally layered. These components, each contributed to building the conditions under which program adaptation could be sustained at scale (Figure 2). Each of these components were built up over the course of decades and sustained through tight integration between management and research, undergoing their own iterative cycle of inner loop learning and development. Some of the notable breakthroughs and promising new developments are depicted in Figure 2 and detailed in Table 2. Importantly, the meta-adaptive evolution and of the COTS Control Program and its sub-components, is consistent with broader climate adaptation planning where risks are identified based on future projections then iteratively improved based on empirical observations and continual model enhancements.

Table 1 Key examples of inner loop learning within each component of meta-adaptive management from the GBR Crown-of-Thorns Starfish Control Program. Each core component of the program's meta-adaptive trajectory (as shown in Figure 3) is supported by specific examples from the COTS Control Program.

| **Type** | **Meta-adaptive component** | **COTS Control Program example** |
|---|---|---|
| Enabling Condition | Foundational research | Decades of foundational COTS research (see Pratchett et al. 2014, 2017, 2021a) was continuously leveraged and refined over time in successive structured research programs (i.e. CRC, NESP, CCIP). Reef-scale connectivity and ecosystem models now guide where and when to intervene; network analyses identify source reefs and outbreak-risk pathways, while system modelling and monitoring show that sustained, large-scale COTS control can delay regional coral decline (Castro-Sanguino et al., 2023; De'ath et al., 2012; Matthews et al., 2024). |

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| | Systematic monitoring | The AIMS LTMP time series revealed the magnitude and causes of coral loss on the GBR and quantified COTS' contribution, establishing thresholds and priorities used by the Control Program (De'ath 2003, De'ath et al. 2012, Emslie et al. 2020). Current development in robotics and AI platforms for automated detection and monitoring (Bainbridge et al., 2025) alongside newer fine scale (Chandler et al., 2023) and eDNA (Uthicke et al., 2024) techniques are rapidly evolving the ability to detect emerging outbreaks and are part of an emerging bespoke COTS monitoring program (Lawrence et al., 2025). |
| | Technical Efficacy | Single-shot injections achieved high, rapid COTS mortality (first with ox-bile/bile salts; then widely available vinegar), providing a scalable, diver-deployable technique that underpins the modern program (Bostrom-Einarsson and Rivera-Posada, 2015; Rivera-Posada et al., 2014). New techniques of semiochemical attractants / dispersants are also being developed further increase the efficacy and efficiency of control methods (Harris et al., 2025). |
| | Stakeholder and Political Support | Early intervention was inspired by community awareness and demand for action, with initial Control Program efforts led by the GBR tourism industry. Today, national surveys demonstrate strong public support for large-scale COTS control on the GBR, reinforcing the Program's social legitimacy and political mandate (Bartelet et al., 2025; Lockie et al., 2024). This strong tourism and stakeholder support has underpinned the willingness of governments to invest significant public funds in ecosystem-scale culling efforts. Political will has been further reinforced by growing participation from Traditional Owner groups in both operational control and strategic governance, including through the expansion of Traditional Use of Marine Resource Agreements (TUMRAs) and increased participation in program decision-making. |
| Operationalisation | Strategy and Governance | The Program's strategic foundations matured through time with publication of the COTS Strategic Management Framework (GBRMPA, 2020) being a key milestone aligning COTS management within the overarching RBM policy set by the Reef 2050 Plan and Blueprint for Resilience (Commonwealth of Australia, 2021; GBRMPA, 2024, 2017). At the same time, 2020 saw the establishment of a two-tiered governance model to provide robust oversight and coordination across strategic and operational levels. The COTS Partnership Group (CPG) provides strategic direction, setting Key Performance Indicators, approving Annual Work Plans, and managing partnerships. The COTS Operations Group coordinates safe and effective on-water activities during |

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| | | implementation of Annual Work Plans and facilitates rapid knowledge sharing across delivery providers and stakeholders. |
| | Sustained funding | COTS control is now recognised as a core priority of both the Reef 2050 Plan and the Blueprint for Resilience (Commonwealth of Australia, 2021; GBRMPA, 2024, 2017) and has secured $161.4m Australian government investment in the Program from 2022 to 2030 (DCCEEW, 2022) as a direct reflection of the Australian Government's commitment to fund actions that support Reef resilience and climate adaptation. Ecosystem modelling indicates that only sustained, large-scale COTS control maintained over years meaningfully delays reef-wide coral decline, supporting further investment in the Program with potential expansion of fleet capacity (Castro-Sanguino et al., 2023). |
| | Decision support systems | An underpinning integrated pest management framework leverages surveillance to guide the effective allocation of culling effort during day-to-day operations so that efforts over months and years can achieve Program ecological outcomes, while collecting and interpreting program data to adaptively refine the efficiency of operations (Fletcher et al., 2020). Recent work validated operational density thresholds that underpin when to intervene (Rogers et al., 2024). These framework and rulesets are automated within the COTS Dashboard decision support system to support RBM decision making (Matthews et al., 2025). |
| | Robust prioritisation | Longer-term regional decision-making relies on long term projections assessing the relative efficacy of various control strategies under uncertainty (Castro-Sanguino et al., 2023; Skinner et al., 2025, 2024). Connectivity and spatiotemporal models identify source reefs and outbreak corridors and map dynamic risk, directly informing the Program's reef-level targeting and seasonal scheduling (Choukroun et al., 2024; Matthews et al., 2020). The annual selection of reefs is the key decision point for ensuring regional scale coral benefits are derived from the Program under uncertain futures. This prioritisation process is described in detail in the following section and supplementary information (S1. Annual Reef Prioritisation Procedure, Figure S1, Table S1) |

# COTS CONTROL PRIORITISATION PROCESS: AN EXEMPLAR OF META-ADAPTIVE MANAGEMENT PRINCIPLES

The GBR is vast (> 3,000 reefs, ~344,400 km²) and complex (GBRMPA, 2025). In any given year, only some reefs on the GBR are at risk from COTS outbreaks, and the resources available for COTS control mean that only a proportion of these can be actioned for surveillance and culling operations. The prioritisation of reefs for control carries profound ecological, operational, and reputational implications. Poor prioritisation could result in severe coral loss, heightened operational risk, or eroded political support, stakeholder trust and social license (Lockie et al. 2024). Consequently, the process to select target reefs for COTS control has evolved progressively from informal expert-driven decisions toward a structured, transparent, and repeatable approach. Here we detail the evolution of the process as an example of the meta-adaptive approach and highlight its importance as the COTS Control Program's central decision process.

## Current prioritisation process

Each year, the COTS Control Program applies a structured, transparent process to identify and rank target reefs for intervention. The prioritisation framework integrates ecological, economic, logistical, and stakeholder considerations through a two-stage multi-criteria decision analysis (MCDA, swing-weighting and linear additive models; Fletcher et al., 2024), underpinned by a decision-support dashboard and annual consultation cycle (Figure S1; see Supplementary Information S1 for full details).

Ecological value for each reef is derived from five normalised layers, COTS outbreak risk, coral source strength, marine park zoning, resilience, and outbreak history, while economic value is based on tourism visitation data. These scores are combined via additive utility, using stakeholder-informed swing-weighting (Fletcher et al., 2024). Median weights typically assign twice the influence on ecological over economic value. Resulting reef rankings are then reviewed and filtered through an operational feasibility lens (e.g. safe anchorage, crocodile risk). Traditional Owners are consulted on the target reef list to understand their views and identify any areas of cultural significance where activity should be prioritised or avoided. Finally, manual amendments to the reef list are permitted in response to emerging threats not accounted for by current data (e.g. primary outbreak risk; Chandler et al., 2023; Uthicke et al., 2024). Additional decision layers, such as reef workability and additional estimates of tourism value (Spalding et al., 2017), are in development for future planning cycles. The full process and criteria definitions are summarised in Figure S1 and Table S1.

While the Program has a rigorous prioritisation and annual planning process, it also has embedded flexibility evidenced by its responsiveness to emergent threats. For example, in 2021 early signals of a fifth outbreak wave detected using advanced fine-scale monitoring methods (Chandler et al., 2023;

Pratchett et al., 2022; Uthicke et al., 2024) triggered resource reallocation of COTS Control Program vessels to affected regions. Similar rapid adaptations occurred in response to outbreaks being detected in the remote Far Northern Management Area, where Traditional Owner-led teams were mobilised and repositioned, demonstrating operational adaptability informed by updated intelligence. Increasingly the Control Program has had to adapt its strategic and tactical targeting of reefs and regions of the GBR in response to wide scale disturbance events such as coral bleaching and cyclones.

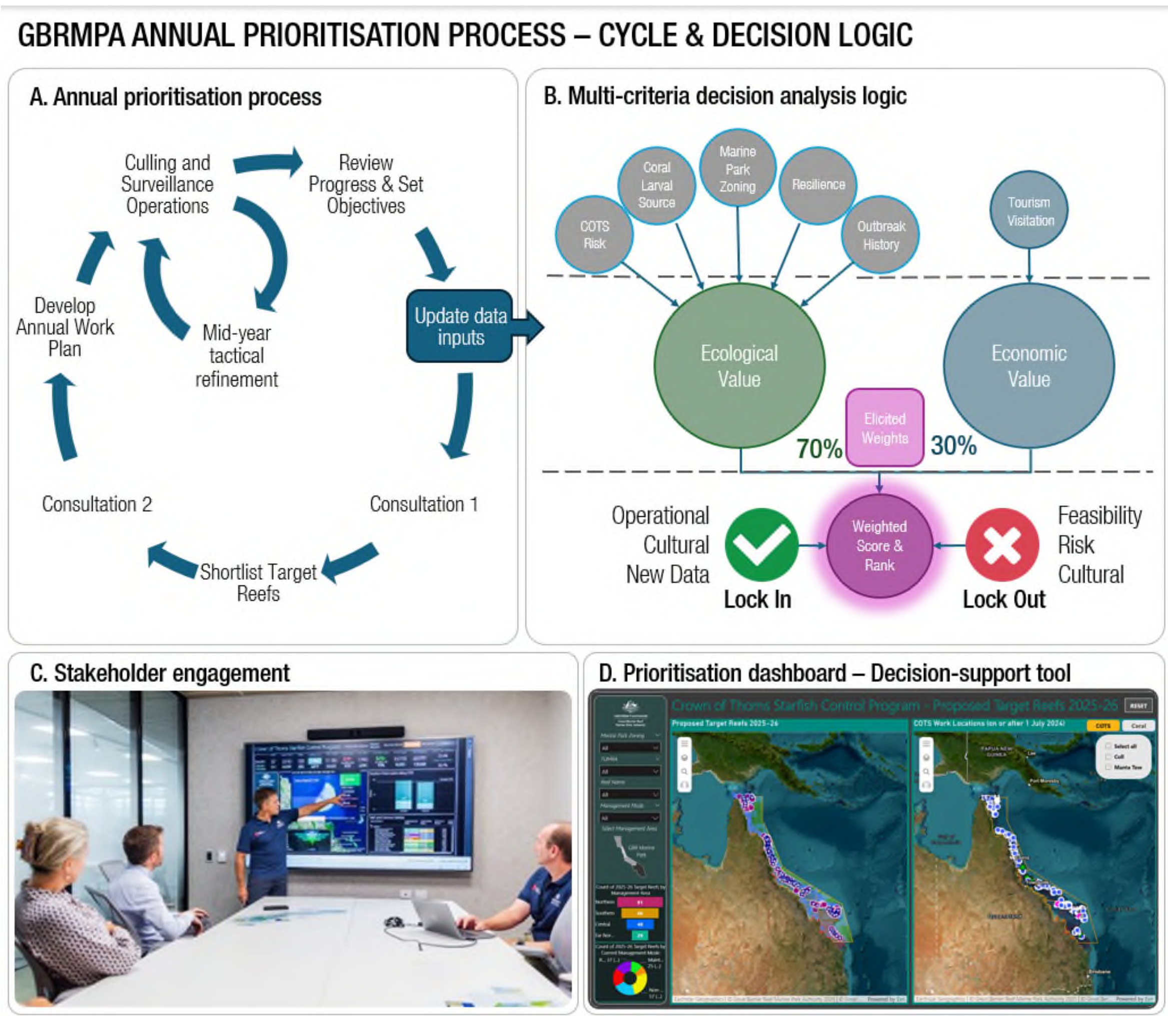


Figure 1 GBRMPA annual prioritisation process—cycle and decision logic. (A) Annual adaptive cycle linking operations, objective review, data updates, two consultation rounds, and short-listing of candidate reefs. This process involved a mid-cycle workshop to assess how the implementation is progressing and making tactical refinements. A more detailed description of this process is given in Figure S1 (B) Multi-criteria decision analysis (MCDA) used to rank reefs: Ecological and Economic values are first scored and ranked separately from their component indicators (Stage 1), then combined using swing-weighted preferences elicited during stakeholder workshops (Stage 2; current weights shown as 70/30). Post-scoring constraints implement operational and Traditional Owner considerations via lock-in (e.g. cultural significance) and lock-out (infeasible or unsuitable) gates. (C) Stakeholder engagement during annual workshops and bi-monthly operations meetings. (D) Decision-support dashboard that visualises candidate targets and current work locations, enabling stakeholder engagement

a workshop and intra annual updates. Images reproduced with permission of GBRMPA; example weights are illustrative and may vary by year.

## Evolution and meta-adaptations of the prioritisation process

Early prioritisation (2012–2018) relied predominantly on expert opinion, targeting high-value tourism reefs. Between 2014–2018, the Program expanded target zones beyond tourism reefs, incorporating initial larval connectivity estimates (Hock et al., 2014). From 2018 onward, the Program pivoted to a formal, transparent process aligned to its annual planning cycle. Between 2018–2020 threshold rules and initial weighting schemes were introduced; by 2021–2023 this matured into a multi-stage MCDA approach that (i) ranks reefs on ecological value (outbreak risk, coral source strength, resilience, zoning), and economic value (tourism visitation/value), then (ii) combines them via stakeholder-informed swing-weighting and (iii) applies a logistical feasibility filter (Fletcher et al. 2024). Importantly this process is conducted to identify both strategic Priority Reefs (long-term: ~500 reefs) and tactical Target Reefs (short-term: ~200 reefs). During this period prioritisation workshops were formalised and operationalised, providing a clear pathway for input from stakeholders, including Traditional Owners, tourism operators, and field teams to influence reef selection. Alongside these process-based improvements, advancements to decision-support tools were ongoing, enabling more complex approaches to be implemented in subsequent years and ensuring that results could be clearly shared among stakeholder groups to gain support for the process and its decision outcomes (Matthews et al. 2025). These improvements and evolutions of the prioritisation process are summarised in Table 3 to highlight their linkages with the eight core components of meta-adaptive management.

Table 2 Evolution and meta-adaptations of the Great Barrier Reef COTS Control Program reef prioritisation process, showing how eight core components of meta-adaptive management have been progressively embedded into the annual reef selection framework (see also Fletcher et al. 2024).

| **Meta-Adaptive Component** | **Integration within the Prioritisation Process** |
|---|---|
| **1. Foundational Research** | Decades of foundational research underpins models of COTS risk and connectivity which enabled a shift from expert opinion to structured, data-driven prioritisation. |
| **2. Systematic Monitoring** | Long-term monitoring datasets are integrated to identify both regional strategies and specific reefs / sites for control. Emerging tools like eDNA and fine-scale surveys were rapidly adopted to enhance detection and responsiveness. |

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| **3. Technical Efficacy** | Operational constraints (e.g. anchorage, crocodile risk, workability) have been increasingly integrated from 2020 onward to ensure field efficacy and safety. |
| **4. Stakeholder & Political Support** | Prioritisation workshops grew from ~6 experts to >30 participants (2012–2023), incorporating Traditional Owners, tourism operators, and delivery partners to build legitimacy and trust. This increased participations and robust governance (below) has grown in recent years and has helped build cross-institutional and political support. |
| **5. Governance & Strategy** | Prioritisation has become the core component of the COTS Control Program's formal Annual Work Plan, which is guided by the COTS Strategic Management Framework, endorsed by the COTS Partnership Group and enacted by control vessels and the COTS Operations Group. |
| **6. Sustained Funding** | Transparent prioritisation logic supported successful cases for funding to 2030 by demonstrating measurable outcomes, inclusivity and cost-effectiveness. In turn the sustained funding allows the Program to tackle COTS populations with longer term strategic objectives. |
| **7. Decision Support Systems** | A dynamic MCDA dashboard integrates datasets, applies weights and constraints, and enables near real-time updates and stakeholder consultation. |
| **8. Robust Prioritisation** | The current system balances long-term strategic and short-term tactical targets, serving as a central mechanism for research integration and adaptive learning. |

Of particular importance is how the prioritisation process has become the primary entry point for scientific information into strategic and tactical decision-making, creating a positive feedback loop between research and management. As the process matured, explicit decision points were established where new data could be trialled and incorporated. This has incentivised researchers to align their work with management needs and enabled managers to rapidly adopt advances such as improved connectivity models (Choukroun et al., 2024; Skinner et al., 2025, 2024), regional-scale outbreak simulations (Skinner et al., 2025, 2024), and novel monitoring methods (Chandler et al., 2023; Uthicke et al., 2022). This deliberate integration and alignment of research into decision-making processes reduces the research–implementation gap (Knight et al., 2008), and is a pragmatic and replicable template for large scale conservation programs with concurrent research initiatives.

## TRANSFERABLE LESSONS FOR ADAPTIVE MANAGEMENT AT SCALE

To support transferability, we distil these components into a set of eight generalisable lessons, each grounded in an operational principle derived from peer-reviewed evidence from the COTS Control Program (Table 2). Foundational research and long-term monitoring established the empirical base for action; early technical breakthroughs demonstrated efficacy and enabled scaling; strong stakeholder and public support enhanced political appetite and sustainable funding ensured continuity; and structured decision-support systems and prioritisation frameworks formalised learning and directed effort toward system-level gains. Together, these lessons highlight how adaptiveness can be cultivated deliberately through sequencing, institutional alignment, and iterative refinement.

The success of the GBR COTS Control Program highlights key principles for how adaptive capacity can be systematically built through the accumulation of core meta-adaptive components for large scale conservation programs. These components are split into categories of enabling conditions and operationalisation.

**Enabling Conditions:**

- **Foundational research -** Invest early in research that reduces key uncertainties and yields tools directly usable by managers.
- **Systematic monitoring** - Long-term, standardised monitoring provides baselines, detects change, and attributes causes—ensuring adaptive decisions are grounded in evidence, not anecdotes.
- **Technical efficacy** - Start with simple, robust, field-proven methods to build capacity and trust; scale up in size and complexity only as readiness increases.
- **Stakeholder and political support –** Build legitimacy and durable mandate through alignment with public values, industry needs, and Traditional Owner engagement. Broad societal support underpins sustained political commitment and large-scale public investment.

**Operationalisation:**

- **Governance and strategy -** Establish enduring, cross-institutional governance arrangements to coordinate delivery, ensure accountability, and embed adaptation into broader policy frameworks. Define clear objectives and establish durable coordination to connect daily operations to long-term goals. Without this, even well-resourced programs risk failure.

- **Sustained funding -** Multi-year, predictable investment is essential delivering measurable benefits at scale and for compounding gains across disturbance cycles and breaking the "issue-attention cycle".
- **Decision support systems -** Formalise choices using transparent, data-driven rules (thresholds, trade-offs, conservation logic), enabling field teams to act decisively. Concurrent development of decision support systems can act as research catalysing endpoints to both utilise and incentivise emerging research.
- **Robust prioritisation** - Target locations that maximally reduce system-level risk (e.g. highly connected reefs) and timepoints that maximise return on investment (e.g. neither too early or too late). Update priorities as new data become available and align research to reduce the research-implementation gap.

This synthesis complements and extends existing resilience-based management and adaptive management theory, offering a pragmatic, operational pathway for its realisation under conditions of uncertainty, complexity, scale, and contested values. Rather than treating adaptation as a prerequisite, it is shown here to be an emergent outcome, one that can be built, tested, and expanded through structured, evidence-informed practice (Figure 2; Table 2).

As climate change accelerates and ecosystems confront increasing variability, compounding disturbances, and uncertain tipping points, adaptive, resilience-based approaches are essential (Anthony et al., 2015; Mcleod et al., 2019; Shaver et al., 2022). Yet in practice, even robust RBM frameworks can falter if the enabling conditions for adaptiveness are absent. Meta-adaptive approaches to these problems are critical: they recognise that adaptiveness is not static or assumed but must be intentionally built, nurtured and iteratively expanded over time. Meta-adaptive systems cultivate the institutional, technical, and social architecture required for RBM to function embedding flexibility, formalising learning cycles, and aligning incentives between science and management. While such approaches cannot alone reverse the effects of climate change, they provide a useful and practical approach for climate adaptation planning. By fostering a culture of learning-by-doing, revisiting assumptions, and continually refining decision processes, meta-adaptive conservation programs can remain responsive, evidence-based, and durable in the face of accelerating change.

# CONCLUSION

The Great Barrier Reef COTS Control Program illustrates not only effective resilience-based management, but also exemplifies the concept of meta-adaptive management where the Program has incrementally learned how to become adaptive over time. Unlike many conservation programs that attempt to launch fully formed frameworks and stall due to complexity, resistance or an inability to demonstrate specific real-world impacts in the short term, the COTS Control Program began with simple, reactive processes implemented at appropriate spatial and temporal scales, and evolved iteratively through stakeholder input, empirical research feedback, and co-designed decision tools. This approach has gradually built institutional capacity, stakeholder and political buy-in, and technical sophistication, proving that large-scale adaptive management is often best achieved through sustained, practical improvements rather than grand initial designs. Critically, this model also helps close the persistent research–implementation gap. The initial design of the Program identified clear ecological objectives and leveraged the ecological insights available at the time to adapt into a program that has generated significant real-world outcomes. In turn, by providing researchers with clear, operationally influential decision points such as how to prioritise reefs or evaluate control thresholds, the Program creates tangible opportunities for further scientific input. This clarity incentivises researchers to align their work with practical needs, ensuring investment delivers usable knowledge, tools and outputs. In turn, management becomes more evidence-based, enhancing credibility and unlocking sustained support. The resulting co-evolution of science, operations, and governance exemplifies a meta-adaptive pathway for managing complex conservation challenges under uncertainty.

As coral reefs and other ecosystems face accelerating pressures, conservation programs must increasingly adopt frameworks that allow management practice to emerge, adapt and strengthen over time. The COTS Control Program demonstrates that iterative refinement through well-defined decision points and the gradual inclusion of more sophisticated research that aligns with operational and social capacity is key to conservation efforts remaining durable and effective. The success of the Program however has been hard won and will be easily lost and thus there needs to be continued demonstration of progress and coral protection to ensure the Program’s future. This model offers a pragmatic approach: start simple, stay flexible, and build adaptiveness over time through collaborative decision-making, trusted partnerships, and iterative refinement. More importantly however, the COTS Control Program provides an important global case study of the successful application of RBM and climate adaptation planning in a complex conservation setting.

# SUPPLEMENTARY INFORMATION

**S1. Annual Reef Prioritisation Procedure**

The Reef Authority (i.e. GBRMPA) annual reef prioritisation is an operational, multi-phase workflow that integrates modelled and empirical datasets with partner consultation and feasibility checks to produce a defensible list of target reefs for COTS control (Figures 2, S1). The process is run each planning year (July-June) and includes two consultation rounds, a shortlist, a consensus building "Prioritisation" workshop (April) and feedback loops to incorporate new field intelligence at a mid-year "Pre-Summer" workshop (November).

The prioritisation framework integrates ecological, economic, logistical, and stakeholder considerations through a two-stage multi-criteria decision analysis (MCDA), underpinned by a decision-support dashboard and annual consultation cycle. The prioritisation considers two value types at present—Ecological and Economic—with additional cultural value pathways under active development (Table S1). Ecological value is represented by five normalised layers: predicted COTS outbreak risk, coral source strength, zoning, resilience, and recent outbreak history. Economic value is currently represented by tourism visitation data using GBRMPA Environmental Management Charge data.

**Normalisation and aggregation**

Each criterion is either normalised to [0,1] or in some cases, such as visitation data, expressed as ranks to mitigate skew. Ecological scores are combined with equal weighting to create a single ecological score to be combined with the economic score. Rank transformation was explicitly adopted to standardise utilities and reduce outlier effects.

Ecological (E) and economic (B) scores are combined via an additive utility:

$$Ui \;=\; wE\,Ei \;+\; wB\,Bi$$

$$wE + wB = 1$$

Weights were estimated in two complementary ways:

1. **Swing-weighting survey (indirect elicitation).** Stakeholders rank and score scenario "swings" between worst/best cases for ecological vs economic benefits via an online instrument; responses are converted to weight distributions.

2. **Retrospective statistical inference (revealed preferences).** An additive benefit function is fitted to previous years' prioritisation decisions using repeated multi-start optimisation over ranked criteria. This yields weight distributions consistent with realised decisions.

Across analyses, ecological and economic contributions are approximately 2:1: a back-cast yielded $w_E \approx 0.62$ and $w_B \approx 0.38$, while stakeholder medians typically fall near two-thirds ecological and one-third economic (with 95% ranges: ecological 0.58–0.90; economic 0.10–0.42).

**Guardrails, feasibility, and mid-year adjustments**

Before finalising annual targets, post-scoring "guardrails" apply feasibility and rights-holder considerations: (i) threshold filters (e.g., distance to port, crocodile risk, safe anchorage/staging), (ii) lock-in/lock-out decisions made in workshops (e.g., cultural significance; infeasible sites), and (iii) mid-year reviews that allow manual amendments when new surveillance or operational information indicates emerging priorities or logistical constraints. These manual steps are documented in workshops and fed back to improve subsequent cycles and identify areas where new data layers may be able to incorporate considerations into the formal MCDA part of the process.

The cycle institutionalises two consultation phases each year, anchored by March–April prioritisation workshops (and a mid-year review). Engagement includes managers, on-water contractors, researchers, and increasingly Traditional Owners; 2023–2024 workshops also focused on formalising logistics data, connectivity use, effort prediction, and manual steps.

## Future improvements

Future refinements to the GBR COTS Control Program should be understood through the lens of meta-adaptiveness, learning how to become adaptive through implementation itself. Improvements span technical, ecological, social, and institutional domains, but not all changes are equally beneficial or adoptable. Strategic focus is needed to prioritise improvements that offer high value while reinforcing legitimacy, stakeholder buy-in and research integration and is guided by overarching governance frameworks (Commonwealth of Australia, 2021; GBRMPA, 2024, 2020, 2017).

(1) Technically, the prioritisation framework could benefit from more advanced optimisation methods, refined MCDA techniques, and integration of sensitivity analyses and formal feasibility metrics (Bode et al., 2024; Esmail and Geneletti, 2018; Yazdani et al., 2019). Emerging high-resolution monitoring tools and improved larval connectivity models (Choukroun et al., 2024) also provide important opportunities to strengthen the technical robustness of the process.

(2) Ecologically, incorporating projected bleaching risk and persistent thermal and cyclone refugia (Bozec et al., 2025; Cheung et al., 2025; Mellin et al., 2025; Sun et al., 2024) is increasingly critical to ensure gains of the control program can be preserved. Aligning COTS control with broader resilience goals, including coordination with the Reef Restoration and Adaptation Program (RRAP), will allow mutual reinforcement of protection and recovery efforts (Condie et al., 2021) and likely increase broad stakeholder support.

(3) Institutionally, priorities include a two-fold expansion of the operational program to reach optimal benefits (Castro-Sanguino et al., 2023), expanding engagement with Traditional Owners and local communities, more accessible decision-support (Artelle et al., 2018; Ban et al., 2018) and considerations of data sovereignty (Cannon et al., 2024; Reyes-García et al., 2022) as well as increased documentation and publication of outcomes (Fletcher et al., 2024). Governance structures should remain flexible enough to continue to accommodate iteration and avoid ossification, while robust enough to maintain confidence across partner agencies and funding bodies.

Ultimately, enhancements should be assessed for their ecological impact, adoptability, and ability to reinforce institutional legitimacy. Uncoordinated or overly complex changes risk eroding stakeholder buy-in and undermining operational delivery. Sustained success will depend on pacing innovation with organisational capacity, a core tenet of meta-adaptiveness.

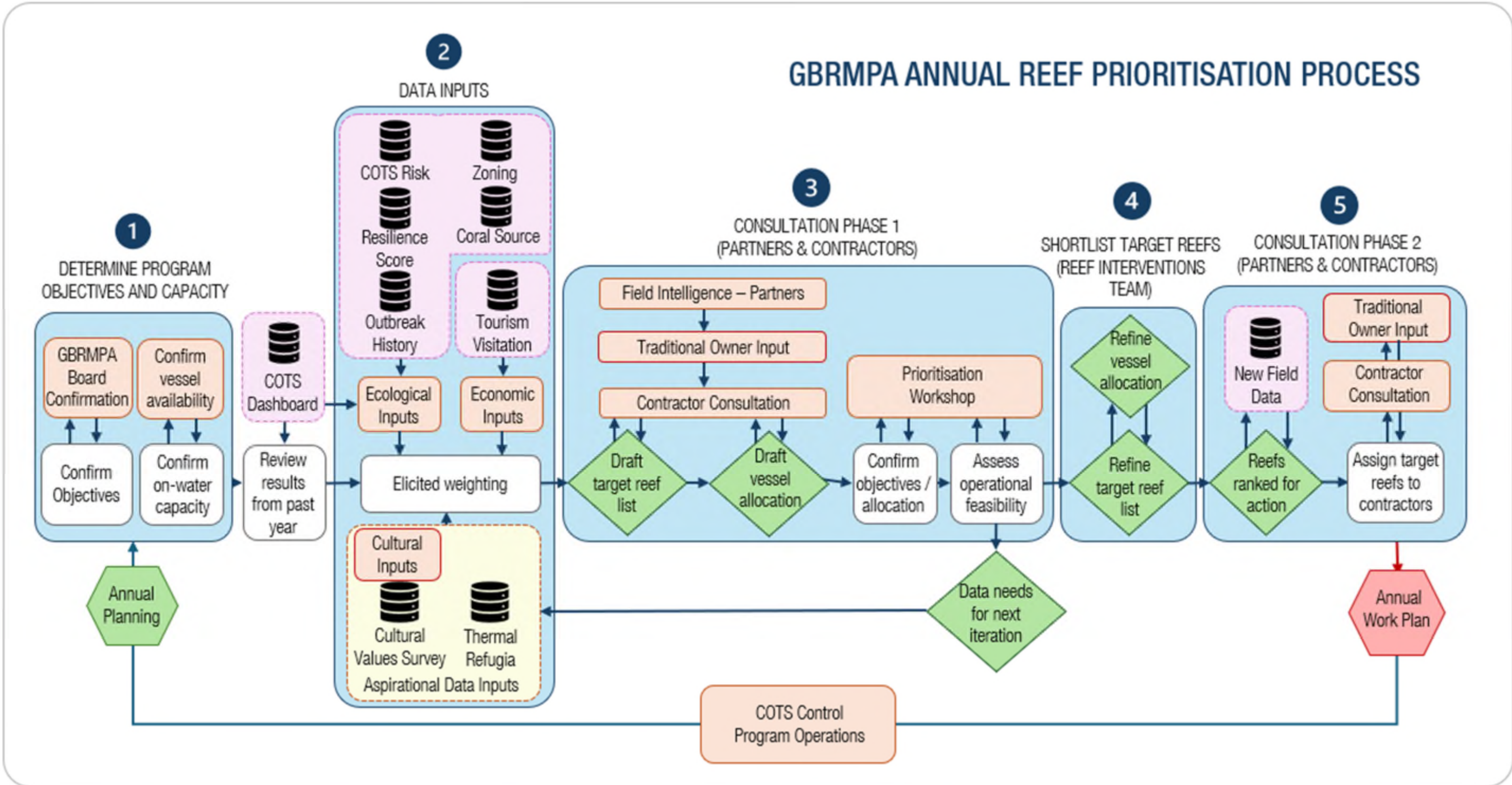


**Figure S1.** GBRMPA Annual Reef Prioritisation Process (diagram). The figure shows (1) program objectives and capacity; (2) data inputs; (3) consultation phase 1; (4) shortlisting by the reef interventions team; and (5) consultation phase 2 and assignment. (Image supplied with permission.)

**Table S3** Criteria and descriptions currently included within the COTS prioritisation process. Rows marked with * are in active development and to be included in 2026 decision processes

| Category | Criteria | Description | Weighted vs Threshold | Reference |
|---|---|---|---|---|
| Ecological | COTS Risk | Composite metric of ensemble weighted out-degree (as a percentile per sector) multiplied by predicted COTS density (scaled 0-1). Represents how well connected a reef is and how likely the reef is to have problematic COTS densities. | Weighted | (Choukroun et al., 2024; Hock et al., 2014; Matthews et al., 2020) |
| | Coral Source | Composite metric of coral weighted out-degree (as a percentile per sector) multiplied by predicted Coral Cover. Represents how well connected a reef is and how much coral is available to supply surrounding reefs. | Weighted | (Hock et al., 2017; Mumby et al., 2021) |
| | Zoning | Scored (0-1) for four categories of protection (Pink = 0; Blue = 0.5; Yellow = 0.75; Green = 1). Green zones are slightly upweighted to 1) uplift reefs that should be easier to control due to enhanced fish predators amplifying zoning protection; and 2) balance the implicit upweighting of blue zones through their more prevalent COTS outbreaks. | Weighted | (GBRMPA, 2004; Kroon et al., 2021; Sweatman, 2008) |
| | Resilience | Calculated as: Recovery Potential + (1-Disturbance Exposure). Included to give weighting to reefs that have avoided recent disturbances and have a higher chance of recovery. | Weighted | (Liu et al., 2017; Matthews et al., 2019; Puotinen et al., 2016) |
| | COTS Outbreak History | Scored 0-1 in five outbreak categories from previous 2 years of data (Severe = 1; Established = 0.75, Potential = 0.5; No Outbreak = 0.25; No COTS = 0). | Weighted | (AIMS, 2015; Emslie et al., 2024; GBRMPA, 2025a) |

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|---|---|---|---|---|
| | | Designed to upweight places where COTS outbreaks are known and thus give slight preference to empirical observations over modelled estimates. | | |
| Economic | Tourism Visitation | Number of visits, scaled (0-1), from the GBRMPA Environmental Management Charge (EMC) data 2019-2022. Best available proxy for tourism value. | Weighted | (GBRMPA, 2025b) |
| | Tourism Value | Estimated value (on reef and reef-adjacent) of coral reefs to the tourism sector. These values are taken from the combined value of on reef values and reef adjacent values, the former including recreational diving and snorkelling and the latter including the provision of calm waters, coral sand beaches, views and seafood. | *In progress | (Spalding et al., 2017) |
| Logistical Feasibility | Distance to major Port | Depending on the ports available to the current fleet, distance cut-offs are applied to ensure operational efficiency | Threshold | (GBRMPA, 2022) |
| | Crocodile Risk | Area deemed “high risk” (by proximity to the coast and high crocodile density areas) are automatically excluded and “medium risk” are flagged for individual risk assessments by operators | Threshold | (Queensland Government, 2019) |
| | Anchorage, Safe harbour, Staging Post | Some reefs offer significant advantages in terms of safe anchorage, shelter and work opportunities during bad weather or as a staging post to reach remote areas of the GBR. Some of these factors are known only to on-water operators and these reefs may be included via consensus at planning workshops. | Lock in/out via workshop consensus | - |
| | Workability | Derived from monthly trends in wave exposure data and dive success / cancellations to estimate workability at reef / site scales | *In progress | Bode et al (2025) |

| | | | | |
|---|---|---|---|---|
| Traditional Owner Perspectives | Cultural significance | Some reefs may be locked in or out of the target list via consensus during workshops due to the cultural significance of a reef. This may result in a reef being prioritised to protect the cultural values or to be left un-managed to keep the reef free from human intervention. | Lock in/out via workshop consensus | - |

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## Author Contributions

S.A.M., C.S.F, M.B. conceived the study, and designed the MCDA approach. S.A.M implemented and iterated the decision support tool and wrote the first draft of the manuscript, R.B., M.C.B. and D.H.W. guided the design and implementation of the prioritisation process. I.R. and J.W. further developed the decision support tool and contributed to figure preparation. All authors contributed to drafting and editing the paper.

## Competing Interests

The authors declare no competing interests

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