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 and knowledge systems, systematic monitoring, technical efficacy, social, cultural and political support, governance and strategy, sustained funding, decision-support systems, and robust prioritisation—and show how recurring decision points (e.g., annual prioritisation) create incentives for applied research, Traditional Owner partnerships 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, reef resilience, Crown-of-Thorns Starfish, Great Barrier Reef, decision support

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 various AM/RBM frameworks exist they typically involve six cyclical stages: (1) assessing the extent of the problem and setting objectives; (2) designing management actions; (3) implementation; (4) monitoring of outcomes; (5) evaluation and institutional learning; and (6) adjusting future actions based on predictive insights and emerging conditions (Gregory et al., 2006; Månsson et al., 2023; Matthews et al., 2025; Rist et al., 2013). RBM is a special case of AM, which extends the approach of iterative learning by 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). Finally, these frameworks typically centre Western science over Traditional Ecological Knowledge (TEK), despite long-standing recognition of the value of TEK in guiding biodiversity conservation and adaptive management (Berkes et al., 2000; Bohensky and Maru, 2011; Dorji et al., 2024; Wheeler and Root-Bernstein M, 2020).

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, social, cultural and political buy-in, and recurring decision points) as the program and its adaptive capability expands. In essence it is an approach and framework for successfully and incrementally building adaptiveness into a large scale RBM 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 increasingly 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).

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 Meta-adaptive Components (MACs, Table 1, Figure 2a) that we contend are required for successful and durable RBM at scale: foundational research and knowledge systems; systematic monitoring; technical efficacy; social, cultural and political support; governance and strategy; sustained funding; decision support systems; and robust prioritisation (i.e. rigorous, practical and resistant to uncertainty; Fletcher et al., 20242026; Hemming et al., 2022; Regan et al., 2005)).

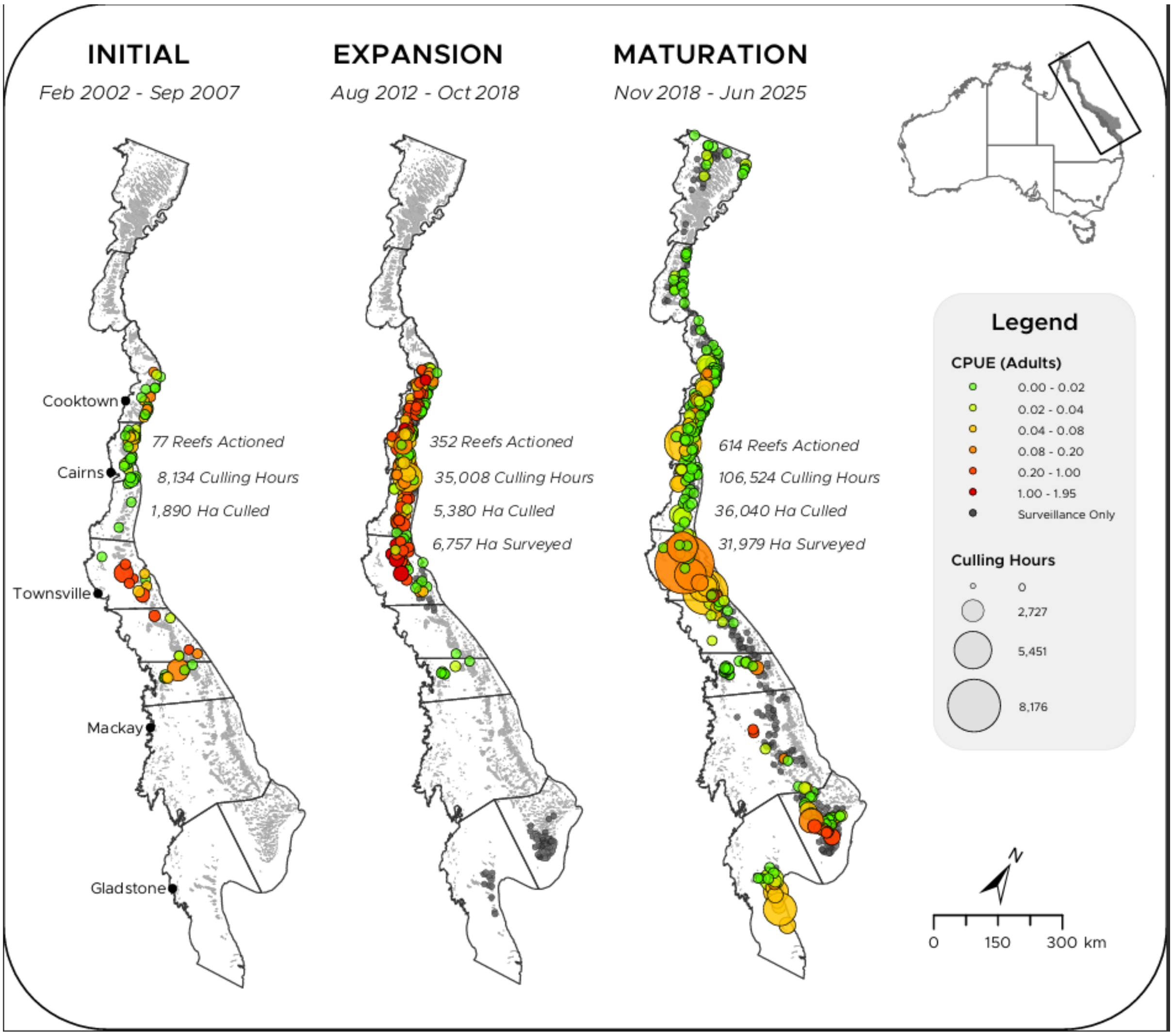

Figure 1 Evolution of the GBR COTS Control Program across three phases of maturity (2002–2025). Geographic expansion of control and surveillance effort (measured as CPUE: catch-per-unit-effort) across three operational phases: Initial (2002–2007), Expansion (2012–2018), and Maturation (2019–2025). Points 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.

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 focused on manual culling via multi-shot sodium bisulphate injections of starfish at key tourism sites across 77 reefs (Figure 1) and was mostly restricted to the RBM cycle stages of *Implement* and *Adjust* (Figure 2b). 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 (*MAC – Social, Cultural and Political Support*; Figure 2a, Table 1) (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 (MAC - *Systematic Monitoring; Governance and Strategy*) (De'ath et al. 2012, GBRMPA, 2020). This marked the beginning of a more systematic and coordinated approach, with more resources and greater synthesis of monitoring data the Program could begin to *Assess* and *Monitor* the outbreak and culling intervention. Critically, foundational research and iterative testing led to the development of 'single-shot' culling 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) (MAC - *Foundational research, Feasibility,* Figure 2a, Table 1). Moreover, from a Value of Information perspective (Helmstedt et al., 2025), during this program expansion phase monitoring data began being used to both diagnose the problem, and to direct intervention at site and regional scales. Long-term datasets such as the AIMS LTMP provided the regional context needed to allocate vessels according to outbreak phase and coral cover, while operational monitoring and surveillance (through the Control Program and Reef Joint Field Management Program (RJFMP)) has increasingly informed annual prioritisation of reefs and where culling should occur within and between trips. This period also marked a shift in focus towards protecting ecosystem resilience in the face of mounting cumulative pressures.

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 (MAC – *Feasibility, Sustained Funding*). 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 (MAC – *Foundational Research, Governance and Strategy*) (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 (MAC - *Social, Cultural and Political Support)* (GBRMPA, 2017).

Together, these developments underpinned substantially increased investment in COTS control in 2018 and marked the formal adoption of the IPM framework to guide research integration and operational planning (Fletcher et al., 2020; Westcott et al., 2016). This marked a shift from relatively localised, reactive control toward a more strategic program that strengthened the *Implement* phase of adaptive management and laid the foundation for more explicit *Design* and *Assess* phases at reef and regional scales (MAC – *Governance and Strategy, Feasibility*; Figure 2, Table 1). The 2018 funding uplift, which tripled culling effort alongside a 60% increase in culling efficiency due to adopting IPM principles (Westcott et al., 2020), consolidated a 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 (MAC – *Sustained Funding, Foundational Research and Knowledge Systems*) (Bonin et al., 2022; DCCEEW, 2022; Fletcher et al., 2021; Great Barrier Reef Foundation, 2019; Pratchett et al., 2021a).

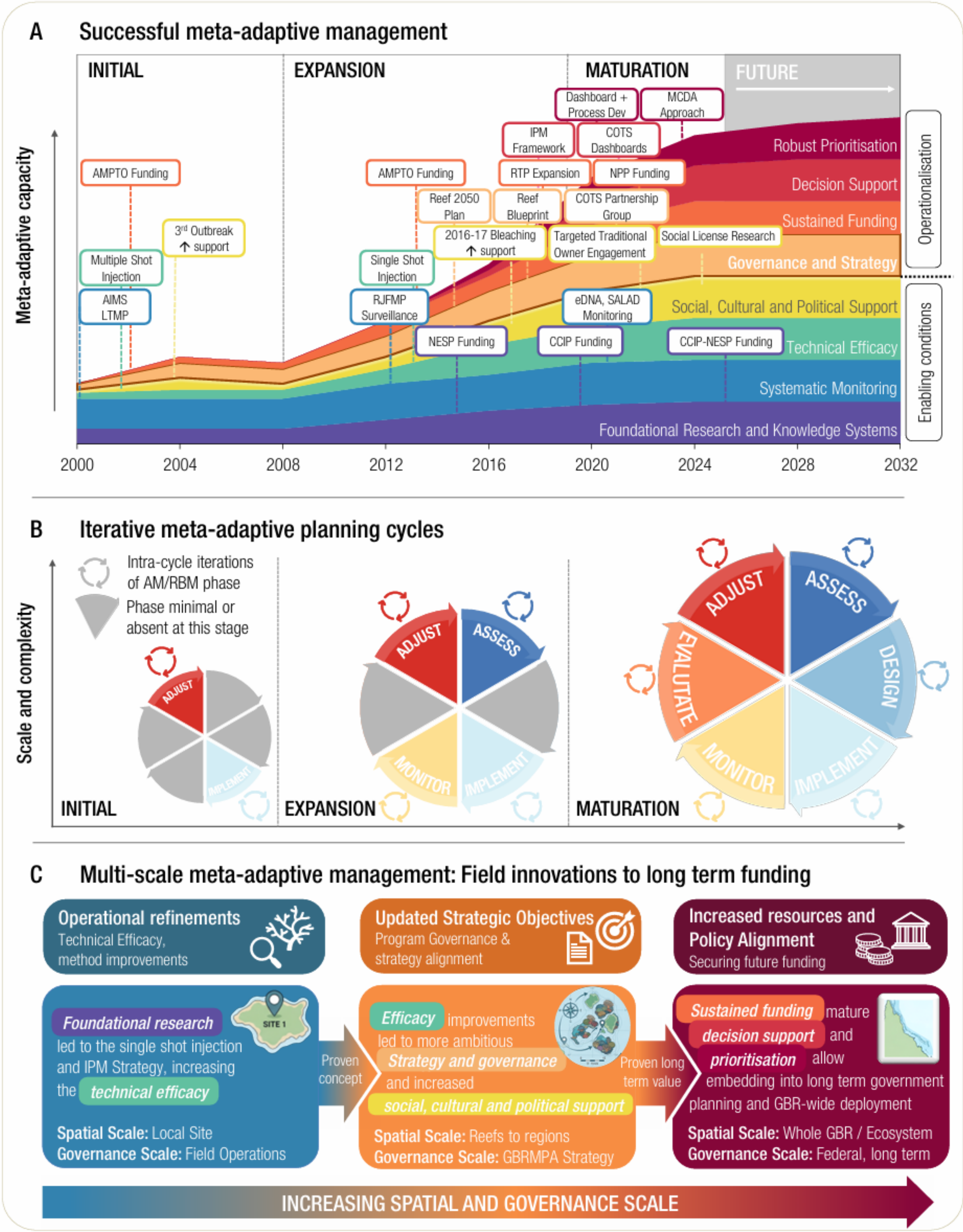

Figure 2 Panel A shows the cumulative development of eight core components underpinning successful meta-adaptive management of the GBR COTS Control Program, highlighting how capacity and complexity were built incrementally over time. Panel B illustrates how adaptive planning cycles (Assess → Design → Implement → Monitor → Evaluate → Adjust) were added, 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/RBM cycle were incrementally improved / included. Smaller coloured cycles indicate the iterations and improvements that were ongoing throughout each phase of the control. This conceptual framework contrasts with traditional adaptive management models by emphasizing iterative scaling and emergent adaptiveness. Panel C illustrates how meta-adaptive

learning operates across spatial and governance scales, showing how local operational innovations and improvements in technical efficacy can be translated into broader strategic objectives, strengthened governance, and long-term policy and funding support.

These investments also enabled the first research co-designed with Traditional Owners to assert their interests and aspirations in COTS control and research (Backhaus et al., 2025), the expansion of a systematic COTS 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). Collectively, these advances strengthened the Program's ability to *Evaluate*, *Monitor*, and *Adjust* management over time, while also supporting more structured *Design* through improved reef prioritisation (MAC – *Systematic Monitoring, Decision Support, Robust Prioritisation*; Figure 2, Table 1). In this sense, the Program reflects a practical value-of-information logic where monitoring is valuable to simultaneously reduce uncertainty, monitor trends, and actively guide tactical decision-making (Helmstedt et al., 2025). Some monitoring streams provide ecological context for regional planning and annual prioritisation, while others are integrated directly into the tactical decision-support system (Matthews et al., 2025) to guide day-to-day deployment of culling effort.

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), should further improve the Program's capacity to *Monitor, Evaluate* and *Adjust* in response to changing conditions (MAC – *Systematic Monitoring, Decision Support*; Figure 2, Table 21).

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 through cumulative, reinforcing components (Figure 2, Table 1). The cumulative layering of enabling conditions (Foundational Research and Knowledge Systems through to Social, Cultural and Political Support; Figure 2) has been catalysed into an operational program via strategic planning and effective governance. These core meta-adaptive components were built up over the course of decades and sustained through tight integration between management and research, and through their own iterative cycles of learning and improvement. Key breakthroughs and emerging developments in this meta-adaptive evolution are shown in Figure 2 and detailed in Table1.

However, this meta-adaptiveness does not operate at a single scale. Rather, it is expressed through nested adaptive loops. At the operational scale, field methods, surveillance, and control logistics are repeatedly refined; at the program scale, annual prioritisation, monitoring, and evaluation cycles are used to adjust where and how effort is deployed; and at the broader governance scale, research investment, funding models, and strategic frameworks are progressively revised to align the Program with GBR-wide resilience objectives and the interests of Traditional Owner rights-holders (Commonwealth of Australia, 2021; GBRMPA, 2024; Queensland Government, 2022).. The Program's adaptiveness has been built from a combination of bottom-up and top-down iteration and learning, where operational and strategic components have adapted in response to each other. For example, iterative improvements in culling methods and processes (i.e. single-shot injection and IPM strategy) increased efficiency and feasibility at the site and reef scale, and these operational gains were then translated upward into broader program redesign (GBRMPA, 2020). In turn, these strategic advances helped support expanded investment, more formal prioritisation, and a shift from ad hoc local protection toward GBR-scale resilience planning. This illustrates how adaptive learning within individual components of the Program can be embedded within larger governance frameworks and scaled up to deliver GBR-wide outcomes (Figure 2c).. . In this sense, the COTS Control Program reflects a broader climate resilience planning logic, in which management is progressively improved by linking fine-scale operational learning to higher-level strategic adaptation.

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, Traditional Owner and stakeholder considerations through a two-stage multi-criteria decision analysis (MCDA, swing-weighting and linear additive models; Fletcher et al., 20242026)), underpinned by a decision-support dashboard and annual consultation cycle (Figure 3; see Supplementary Information S1 for full details).

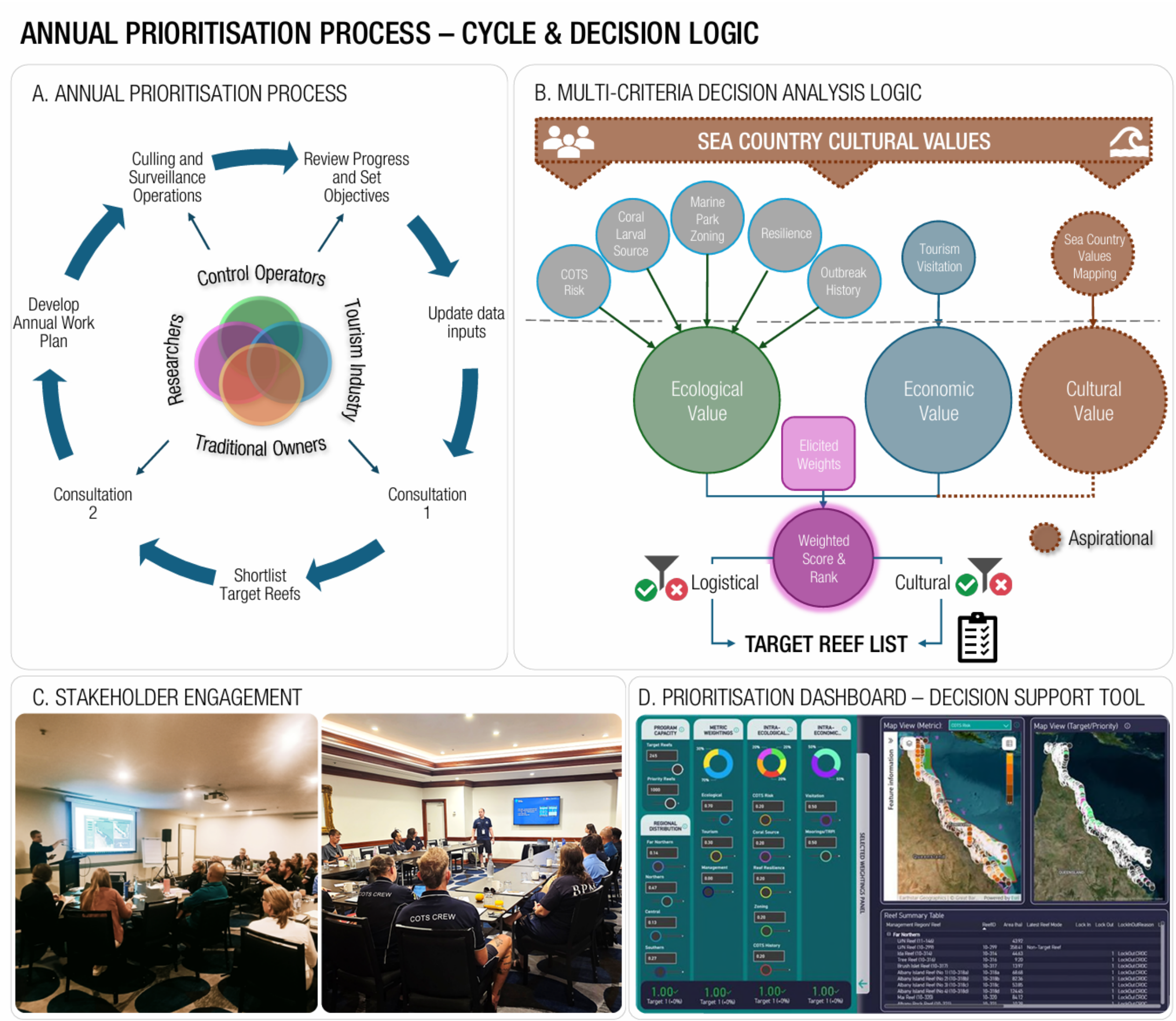

Figure 3 The COTS Control Program's annual prioritisation process. cycle and decision logic. (A) Annual adaptive cycle linking operations, objective review, data updates, two consultation rounds, and short-listing of candidate reefs and how various groups feed in to each of these stages. This process 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-ins (e.g. cultural significance) and lock-outs (infeasible or unsuitable). Cultural sea-country values are represented both as an overarching consideration in the decision framework and as a value to be included into the core MCDA model. Both are noted as 'aspirational' as they are not yet formally embedded at the outset; this is an important area to adapt and improve in the future. (C) Traditional Owner and stakeholder engagement during annual

workshops and bi-monthly operations meetings. (D) Decision-support dashboard that visualises candidate targets and current work locations, enabling engagement at workshops and intra annual updates. Images reproduced with permission of GBRMPA; example weights are illustrative and may vary by year.

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., 20242026)). 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). 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. In recent years, engagement of Traditional Owners in the prioritisation decision process has increased. Representatives from groups across the GBR are now routinely involved in the development of target reef lists, to understand their views and identify areas where COTS control activities should be prioritised or avoided across their Sea Country. While this is a start, these changes have historically lagged operational developments. There remain significant opportunities for the program to further adapt by more deeply considering Traditional knowledge systems and cultural values alongside Western science. Recent research co-designed and delivered with Traditional Owners has identified key priorities related to the prioritisation process, including the development of indicators for measuring the cultural value of reefs and methods for their consideration alongside ecological and economic decision criteria (Backhaus et al., 2025). Importantly, any such data sharing to inform reef prioritisation must be supported through arrangements that protect Indigenous Cultural and Intellectual Property (Backhaus et al., 2025). Key learnings related to Traditional Owner involvement and agency across the meta-adaptive management cycle and prioritisation process are highlighted in Table 1.

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, illustrating how new monitoring information is used not only to update understanding of outbreak status, but to directly redirect operational effort. Similar rapid adaptations occurred in response to outbreaks being detected in the remote Far Northern Management Area, where Traditional Owner-led businesses contracted within the Control Program 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.

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 (Figure 3) 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 Traditional Owner rights-holders and stakeholders, including tourism operators, researchers 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 1 to highlight their linkages with the eight core components of meta-adaptive management.

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, monitoring and management. As the process matured, explicit decision points were established where new modelling and monitoring data could be trialled and incorporated to direct where culling resources should deployed (Fletcher et al., 2026, 2020; Helmstedt et al., 2025). 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 1). Foundational research and long-term monitoring established both the empirical base for action and the information to inform strategic objectives, annual prioritisation, and tactical deployment.; early technical breakthroughs demonstrated efficacy and enabled scaling; strong stakeholder and public support, and increasing engagement of Traditional Owners, 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 successes and learnings of the GBR COTS Control Program has highlighted 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 and knowledge systems-** Invest early in research that reduces key uncertainties and yields tools directly usable by managers, as well as pathways for Traditional Ecological Knowledge to guide adaptive management.
- **Systematic monitoring -** Long-term, standardised monitoring provides the ecological context for planning and is directly linked to management action, ensuring adaptive decisions are grounded in evidence rather than 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.
- **Social, cultural and political support –** Build legitimacy and durable mandate through alignment with public values, industry needs, and meaningful and consistent Traditional Owner engagement. Broad societal and cultural support underpins sustained political commitment and large-scale public investment.

Operationalisation:

- **Governance and strategy -** Establish enduring governance and strategic frameworks that coordinate delivery, maintain accountability, and engage Indigenous rights-holder in decision-making at the outset. 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 for delivering measurable benefits at scale and for compounding gains across disturbance cycles to break 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. Importantly, prioritisation should encompass ecological, economic and cultural values.

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 1).

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.

LIMITATIONS AND FUTURE DEVELOPMENT: ECOLOLGICAL, ETHICAL AND SUSTAINABILITY CONSIDERATIONS

Early phases of the program were necessarily reactive and focused on proving that control was feasible at smaller scales. Over time, the Program became more strategic through clearer objectives, improved surveillance, formal prioritisation, and stronger links between monitoring, decision-making, and operations (Fletcher et al., 2026, 2020; GBRMPA, 2020; Matthews et al., 2025). This history highlights three lessons: (1) early reactive approaches carry ethical and ecological risks and may become entrenched unless they are deliberately revised; (2) operational feasibility alone is not enough, programs also need transparent decision rules, feedback loops, and explicit evaluation; (3) adaptive management should be judged not only by whether it responds to new information, but by whether it improves how decisions are made over time. Despite major progress, gaps remain. Trade-offs between ecological ambition, operational simplicity, logistics, ethical governance and limited funding cycles have not disappeared and thus strategic and governance frameworks should continue to evolve alongside the operational program.

Ethical governance and Traditional Owner partnerships

The Program has been strengthened by Traditional Owner partnerships over time, yet acknowledges that indigenous land- and sea-management systems have governed natural resource protection and use for millennia, long predating Western systems of adaptive management(Berkes et al., 2000). On the Great Barrier Reef, there are over 70 Traditional Owner groups with rights, interests, and aspirations in managing their Sea Country. Traditional Owner leaders have developed an Implementation Plan that outlines actions to achieve these aspirations as part of the Reef 2050 Plan (Queensland Government, 2022), including increased leadership in COTS management through governance, employment pathways, and fee-for-service arrangements.

In recent years, the COTS Control Program has adapted its governance and operations in line with these goals. Since 2022–23, a Traditional Owner representative has been included in the COTS Partnership Group, guiding the strategic direction of the Program. Operationally, two Traditional Owner-owned businesses are now contracted within the program following an open tender process, and all control vessels support Traditional Owner traineeships. Furthermore, cultural values and place-based knowledge are increasingly embedded into annual prioritisation through dedicated engagement phases and participation in planning workshops, supported by growing, trust-based relationships with Traditional Owner groups and TUMRAs. A key future evolution is the formal embedding of cultural

Sea-Country values strategic framework of the Program (GBRMPA, 2020) and the core MCDA prioritisation model (Figure 3). While this remains an active priority, it is currently constrained by the lack of consistent, GBR-wide cultural datasets.

While these recent developments represent important advances, they also highlight that earlier formal partnerships could have accelerated the integration of Traditional knowledge into the program's strategic direction and operations. A mature adaptive governance model must therefore continue to evolve beyond consultation toward earlier and deeper involvement in priority setting and clearer recognition of Indigenous knowledge.

Program costs, trade-offs, and long-term sustainability

Large-scale culling depends on substantial, ongoing investment in vessels, workforce, surveillance, analytics, and coordination. While formal cost-benefit analysis suggests that this investment is cost-effective and delivers a significant net benefit to the Australian people (Scheufele et al., 2025) as well as measurable coral protection benefits (Matthews et al., 2024), the investment may still carry opportunity costs within the broader GBR management portfolio and should continue to be weighed up alongside other available interventions(Castro-Sanguino et al., 2023; Condie et al., 2021). COTS control is therefore framed as one component of a wider reef resilience strategy, not as a substitute for emissions reduction, water-quality improvement, or other long-term actions(GBRMPA, 2024, 2017). It is a targeted intervention that can buy time, protect high-value reefs and provide region-wide benefits, but it does not remove the underlying drivers of reef decline. As outbreak drivers are not removed (nor fully understood) there is also a longer-term sustainability question, where continued benefits may depend on continued intervention. Ongoing research and strategic planning should therefore continually assess not only operational success, but also long-term cost-effectiveness, and whether the balance of benefits and trade-offs remains favourable through time.

Ecological risk

Two ecological risks have been raised in relation to sustained COTS control. The first is that suppressing a natural predator of fast-growing corals could alter coral assemblages and potentially reduce diversity if competitive dominants are released from predation pressure (Bellwood et al., 2024; Porter, 1972). The second is that repeated suppression may disrupt natural boom–bust dynamics and contribute to more chronic, lower-density infestations that still require ongoing control (Yamaguchi, 1986). These concerns should not be overlooked nor overstated. In contrast to previous large scale attempts in Japan, the Program targets outbreak suppression rather than eradication and focuses on early intervention rather than high cull numbers, and the emerging evidence strongly indicates that outbreaks cause major coral loss and that control can protect coral (of all functional groups) at ecologically meaningful scales (Matthews et al., 2024). It is also plausible that, because many corals preferred by COTS are also highly susceptible to bleaching (Keesing et al., 2019), COTS control may offset additional losses from coral bleaching and protect non-preferred prey after severe coral mortality events. These potential ecological risks do, however, warrant explicit monitoring and contingency planning as part of a mature program. This reinforces the need to evaluate the Program not only against short-term coral protection metrics, but also against longer-term outcomes for coral composition, and ecosystem functions.

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, social, cultural and political support, 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 and supports ongoing improvements to build Traditional Owner partnerships.. Although early iterations of the Program were reactive and opportunity-driven, it progressively leveraged emerging insights to define these goals over time, adapting into a program that now generates 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.

Looking ahead, the Program should increasingly be positioned as part of a broader GBR climate adaptation portfolio of interventions, rather than as a standalone intervention. This means adapting prioritisation and surveillance to climate risk, for example by protecting bleaching refugia and other reefs with strong recovery or connectivity value where COTS control is most likely to preserve coral and support recovery under increasing climate stress. 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.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process.

During the preparation of this work the authors used ChatGPT, Gemini and ScholarLabs to perform deep literature searches to highlight gaps and to critically review drafted text and figures to improve clarity and identify points of improvement. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the published article.

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FIGURE CAPTIONS

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.

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 added, 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/RBM cycle were incrementally improved / included. Smaller coloured cycles indicate the iterations and improvements that were ongoing throughout each phase of the control. This conceptual framework contrasts with traditional adaptive management models by emphasizing iterative scaling and emergent adaptiveness. Panel C illustrates how meta-adaptive learning operates across spatial and governance scales, showing how local operational innovations and improvements in technical efficacy can be translated into broader strategic objectives, strengthened governance, and long-term policy and funding support.

Figure 3 The COTS Control Program’s 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 and how various groups feed in to each of these stages. 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-ins (e.g. cultural significance) and lock-outs (infeasible or unsuitable). Cultural sea-country values are represented both as an overarching consideration in the decision framework and as a value to be included into the core MCDA model. Both are noted as ‘aspirational’ as they are not yet formally embedded at the outset; this is an important area to adapt and improve in the future. (C) Traditional Owner and stakeholder engagement during annual workshops and bi-monthly operations meetings. (D) Decision-support dashboard that visualises candidate targets and current work locations, enabling engagement at workshops and intra annual updates. Images reproduced with permission of GBRMPA; example weights are illustrative and may vary by year.

TABLES

Table 1 Key examples of inner loop learning within each component of meta-adaptive management from the GBR Crown-of-Thorns Starfish Control Program and how they have been integrated within the reef prioritisation process (see also Fletcher et al. 2026). 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 and summarised by the key principle.

Type	**Meta-adaptive component and transferable principle**	**AM/R BM Stage**	**COTS Control Program example**	**Integration within the Prioritisation Process**
Enabling Condition	Foundational Research and Knowledge Systems – *Research-informed readiness*	***ASSESS, DESIGN***	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). The program is largely founded on Western science and the embedding of Traditional Ecological Knowledge as foundational in guiding COTS control is a major gap and opportunity for the program going forward.	Decades of foundational research underpins models of COTS risk and connectivity which enabled a shift from expert opinion to structured, data-driven prioritisation (Fletcher et al., 2026) Recent work co-designed and delivered with Traditional Owners has called for dedicated investment to understand how TEK could inform strategies for COTS outbreak prediction, response, and reef prioritisation alongside Western science (Backhaus et al., 2025).

	Systematic monitoring – *Monitoring that informs action*	***ASSESS, IMPLEMENT, MONITOR, EVALUATE***	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). Recent development sin 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). These data help define outbreak phase, coral cover context, and regional priorities for vessel allocation, and are also used to detect emergent outbreaks and guide reef- and site-level deployment through the integrated Decision Support System (Matthews et al., 2025).	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.
	Technical Efficacy - *Field-proven scalability*	***IMPLEMENT, ADJUST***	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).	Operational constraints (e.g. anchorage, crocodile risk, workability) have been increasingly integrated from 2020 onward to ensure field efficacy and safety.

	Social, cultural and political support - *Legitimacy for long-term action*	***DESIGN, ADJUST***	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 and cultural legitimacy and political mandate (Bartelet et al., 2025; Lockie et al., 2024). Research shows that broadscale support for COTS control is shaped not only by perceived ecological benefits, but also by whether there is respect for Reef Traditional Owners as rights-holders and there are genuine pathways for co-benefit (Bartelet et al., 2025). To realise these co-benefits, Traditional Owner groups are becoming increasingly involved in both operational control and strategic program delivery , including through (1)) fee-for-service arrangements for COTS control vessels; (2) the expansion of Traditional Use of Marine Resource Agreements (TUMRAs) to include COTS control work and (3) increased training and employment pathways within the program.	Prioritisation workshops grew from ~6 experts to >30 participants in the expansion and maturation phases encompassing Traditional Owners, tourism operators, researchers and delivery partners to build legitimacy and trust. This increased participation and robust governance (below) has grown in recent years and has helped build cross-institutional and political support.

Operationalisation	Governance and Strategy - *Coordinated adaptation at scale*	***ASSESS, EVALUATE, ADJUST***	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 implementation of Annual Work Plans and facilitates rapid knowledge sharing across delivery providers, Traditional Owners and stakeholders. Traditional Owner involvement in governance and decision-making has also increased in recent years through representation on the COTS Partnership Group, and increased program engagement with TUMRA and local advisory committees.	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. Increasingly TO representatives from GBR Sea Countrys are involved in the annual planning workshops to set control priorities for the coming year, build networks with operators, and develop control capacity as part of their own Sea Country management plans.

	Sustained funding - *Predictable investment over time*	***IMPLEMENT***	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).	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.
	Decision support systems - *Operationalising data-driven decisions*	***ASSESS, DESIGN, IMPLEMENT, EVALUATE, ADJUST***	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).	A dynamic MCDA dashboard integrates datasets, applies weights and constraints, and enables near real-time updates in response to stakeholder, operator and Traditional Owner feedback. Importantly this tool can accommodate more formal cultural values mapping if Traditional Owners choose to share this information under arrangements that protect their cultural and intellectual property..

	Robust prioritisation - *Target effort where it matters most*	***DESIGN, ADJUST***	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)	The current system balances long-term strategic and short-term tactical targets, serving as a central mechanism for research integration and adaptive learning. Future iterations aspire to include Traditional knowledge and cultural values as a core component of the prioritisation framework (Figure 3).

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