From Business Intelligence to Conservation Intelligence: Operationalising adaptive pest control to protect the resilience of the Great Barrier Reef

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ABSTRACT

Resilience-Based Management (RBM) is crucial for enhancing outcomes in conservation interventions as the climate changes. To be effective it requires continuous modelling, assessment, evaluation and adjustment. Here, we adapt established Business Intelligence software into Conservation Intelligence tools to provide the near real-time analytics and a decision support system necessary for effective RBM. This approach is demonstrated using the Crown-of-Thorns Starfish Control Program on Australia's Great Barrier Reef where integrated visual dashboards were developed to assess outbreak severity, prioritize control actions, evaluate effectiveness and incorporate emerging research to close the research-implementation gap. The flexibility of Business Intelligence software allows these Conservation Intelligence tools to be built and maintained 'in-house', meeting the Reef Authority's explicit needs and reducing dependency on external developers or researchers. Conservation Intelligence tools can synthesize complex spatial-temporal data into flexible, user-friendly platforms specifically targeting stages of the RBM cycle that enable rapid iterations as programs and ecosystems adapt to climate change. This approach is readily transferable to other conservation challenges, particularly in government-led programs where enterprise software licenses may already exist and is particularly useful in ecologically complex but data rich environments.

RESILIENCE-BASED MANAGEMENT AND CONSERVATION INTELLIGENCE

Resilience-based management is increasingly recognised as best practice for conservation in rapidly changing environments, offering an iterative framework of forecasting, planning, action, monitoring, and adjustment specifically aimed at preserving and enhancing ecosystem resilience (i.e. the ability of a system to both resist and recover from disturbances (Holling, 1973; Hughes et al., 2005)) under uncertainty (Anthony et al., 2015; Holling, 1978; Mcleod et al., 2019; Schuurman et al., 2022; Walters, 1986; Westgate et al., 2013). The adaptive management framework typically involves six cyclical stages: (1) assessing the state of the system and extent of the problem; (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; Rist et al., 2013). By continuously integrating new information about ecosystem states, processes, and future scenarios (e.g. climate change), managers can proactively refine interventions to better anticipate and respond to disturbances (Gunderson and Holling, 2002; Walters, 2007). Extending this framework to RBM requires greater focus on planning for uncertain futures, and application of intervention strategies that boost resilience by mitigating disturbance impacts or enhancing recovery (Anthony et al., 2015)

Operationalising RBM however remains challenging. The burden of continual evaluation, stakeholder engagement and re-assessment of ecosystem state and resilience often slows or halts conservation outcomes (Anthony et al., 2015; Gregory et al., 2006; Rist et al., 2013). Financial and logistical lags commonly delay the acquisition of monitoring data or delivery of interventions (Downs, 1972; Hoey et al., 2016), and the substantial effort required to process, analyse, and communicate results creates bottlenecks that undermine the practical implementation of RBM (Anthony et al., 2015; Månsson et al., 2023; Mcleod et al., 2019; Rist et al., 2013; Williams and Brown, 2014).

Conservation interventions in complex ecosystems demand tools that can synthesise diverse data streams to successfully support resilience-oriented actions and stakeholder engagement throughout the RBM process (National Academies of Sciences Engineering and Medicine 2019; Mcleod et al. 2019). Decision-support software, such as Marxan, have been developed explicitly for tasks like designing marine reserves and have contributed significantly to spatial conservation planning globally, including the rezoning of the Great Barrier Reef Marine Park (Ball et al., 2009; Day, 2002; GBRMPA, 2004). While such purpose-built tools are invaluable for specific applications, their task specific-design limits their scope and flexibility to new decision-contexts. Bespoke, research-led decision support tools are often built to address emerging questions but suffer from a lack of long-term support once project-specific funding ends, or the mis-alignment with objectives of end users (Gibson et al., 2017; McIntosh et al., 2011). These issues often stem not from the software's immediate functionality, but from organizational constraints, a lack of personnel and funding to support long-term technical maintenance, or strict organizational IT policies (Curtice et al., 2012; Pınarbaşı et al., 2017) thereby hindering their long-term application and integration into practical RBM programs. There is a clear need for decision-support tools that are flexible enough to continuously adapt alongside the iterative cycles inherent to RBM frameworks and that help close the gap between researchers, conservation planners and decision-makers (Ferraz et al., 2021; Knight et al., 2008; Walsh et al., 2019). Addressing this challenge requires either substantial ongoing funding and collaboration for maintenance and development, or the use of platforms that conservation practitioners can sustainably manage themselves.

Here we describe ‘Conservation Intelligence’ as the adaptation of enterprise Business Intelligence tailored specifically for RBM decision-making, providing a robust alternative for decision support in conservation. Interactive and informative data visualisations create active engagement and knowledge generation amongst stakeholder groups (Keller and Tergan, 2005); improving decision quality (Howard, 1988; Spetzler et al., 2016) and speed (Eberhard, 2023); and provide a vehicle for knowledge transfer between science, management and policy (McInerny et al., 2014). Originally developed for finance and enterprise analytics, BI systems can ingest disparate data sources, automate data refreshes, and generate interactive visualisations without extensive programming skills (Gonçalves et al., 2023; Murugesan and Karthikeyan, 2016; Ul-Ain et al., 2019). Critically, these business intelligence systems benefit from sustained commercial development, cloud scalability, and user support which can enhance the sustainability and ongoing development of tools as conservation interventions and management needs evolve. Importantly, these attributes substantially lower barriers to entry, enabling in-house development of decision-support tools that are fit for their given purpose, resilient to research funding shortfalls, and adaptable to the iterative requirements of RBM frameworks (Figure 1).

COTS CONTROL AND CONSERVATION INTELLIGENCE ON THE GBR

The Great Barrier Reef (GBR) illustrates both the promise and the challenge of implementing RBM at scale (Day, 2022). Over recent decades, pioneering management measures, including extensive zoning (GBRMPA, 2004; McCook et al., 2010), strong legislative protections, and systematic and comprehensive ecological monitoring (Emslie et al., 2020) have strengthened local stewardship of the GBR. Nevertheless, the GBR continues to experience an increasingly severe and cumulative disturbance regime, driven by mass coral bleaching, cyclones, and recurrent irruptions of the coral-eating crown-of-thorns starfish (CoTS) (Emslie et al., 2024; Hughes et al., 2017; Mellin et al., 2019; Ortiz et al., 2018). Irruptions of CoTS alone account for approximately 40 percent of historical (1985-2012) coral loss on the GBR, and remains the only major and persistent cause of coral mortality that is amenable to direct and immediate intervention (De'ath et al., 2012; Matthews et al., 2024; Pratchett et al., 2017; Rivera-Posada et al., 2011).

Since 2012, the Great Barrier Reef Marine Park Authority's (GBRMPA) CoTS Control Program has scaled from localised demonstrations of a proof-of-concept (Westcott et al., 2016, 2020) to a comprehensive resilience-focussed operation to protect coral habitats across the Reef, employing multiple vessels and trained dive teams to cull CoTS across a network of highly connected reefs with high ecological and economic value (Fletcher et al., 2024; Matthews et al., 2024; Westcott et al., 2016, 2020). Over a decade, this program has shifted towards an integrated RBM approach, driven by continuous collaboration between GBRMPA, industry, researchers, on-water operators, and Traditional Owners, in order to deliver an increasingly integrated and innovative pest management approach to CoTS Control (Fletcher et al., 2024, 2020; Westcott et al., 2021) Since tripling its operational capacity in 2018, the program has produced unprecedented spatial and temporal data on CoTS outbreak severity, culling effort, operational efficiency, and coral health and recovery (GBRMPA, 2025). The program has delivered significant coral protection and resilience benefits (Matthews et al., 2024), by directly removing a major vector of coral mortality and thereby promoting faster recovery on reefs affected by other disturbances. The growing scale and inherent complexity of CoTS dynamics necessitate sophisticated data tools capable of: (1) synthesising these datasets into actionable resilience-focused management insights; (2) adapting flexibly to integrate emerging scientific research and evolving management priorities; and (3) actively engaging stakeholders throughout the RBM process. These tools need to be able to serve operational and strategic planning concerns as well as stakeholder engagement and public communications.

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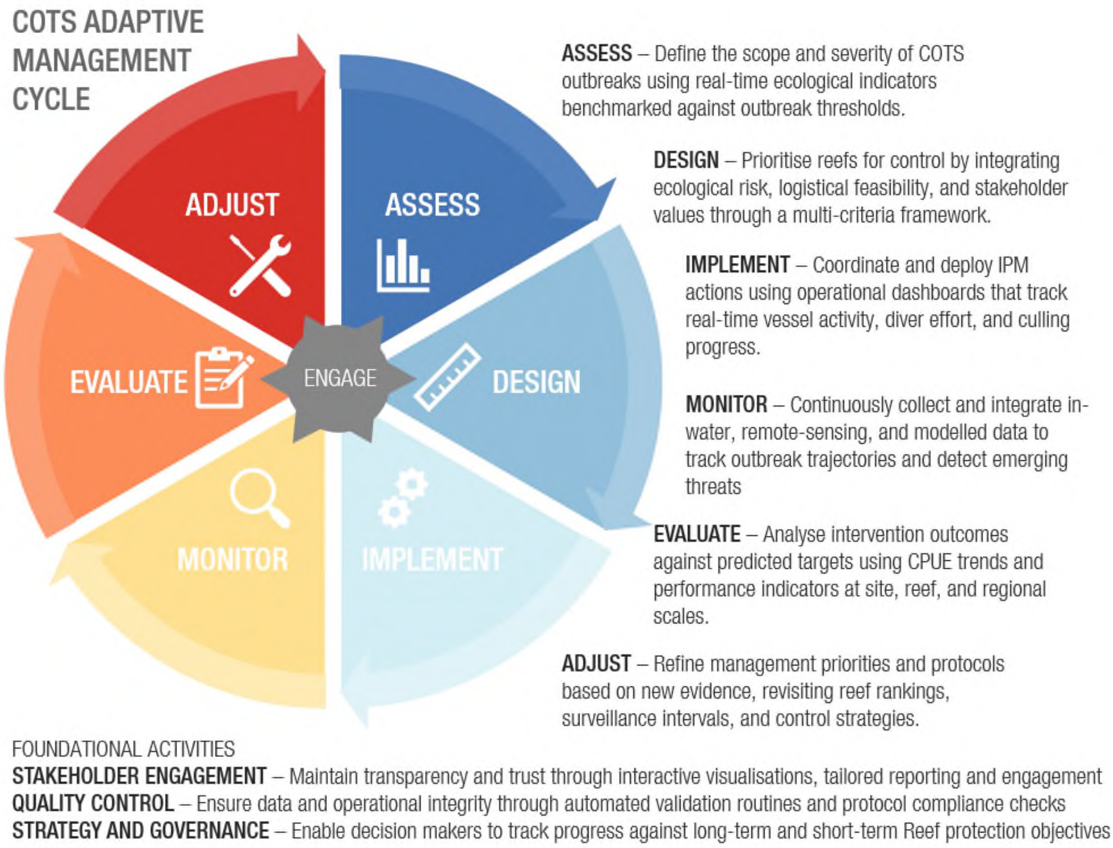

Figure 1 Adaptive management cycle for the GBR Crown-of-Thorns Starfish Control Program and its alignment with Conservation Intelligence decision-support tools. The cycle iterates through six phases—assess, design, implement, monitor, evaluate and adjust—centred on ongoing engagement and underpinned by stakeholder participation, data quality control, and strategy and governance to enable timely, transparent and evidence-based response to COTS outbreaks.

RBM explicitly focuses on delivering coral protection and enhancing recovery from disturbances. To this end, the CoTS Dashboard suite was developed as a visualisation and reporting tool to track outbreak severity and extent in near real-time and to monitor the progress of interventions against stated resilience goals. This tool was initiated in late 2017, growing as the program scaled and is now firmly embedded within GBRMPA's operational workflows and infrastructure. The dashboard integrates and synthesises monitoring and operational data from the program and its partners (Queensland Parks and Wildlife Services, Australia Institute of Science Long Term Monitoring Program, Marine Monitoring Program), early detection data, environmental data, prioritisation-specific measures (connectivity and resilience metrics), on-vessel reporting and quality assurance data into a unified interface that supports all phases of the adaptive cycle. Interactive visualisation, analysis and exploration capabilities, and automation of data workflows, enable managers to detect emerging irruptions, evaluate the efficacy of culling interventions in near real time, adjust actions, and generate customised reports and visualisations for diverse stakeholder groups. Crucially, embedding the dashboard within the agency's information infrastructure ensures long-term maintenance, fosters institutional learning, and enhances transparency and engagement among stakeholders. At a strategic level, the dashboard suite underpins Program governance, enabling decision makers to track progress against long-term and short-term Reef protection objectives, and evaluate and adjust the Program strategy as required. The strategic and tactical adjustment opportunities provided by the dashboard suite of tools also enable integration with other Reef protection initiatives consistent with the overarching goals of the Reef 2050 long-term sustainability plan (Commonwealth of Australia, 2021).

In this paper, we describe the design, implementation, and operational impact of the CoTS Dashboard. We highlight how the development of user-driven dashboards can support each stage of the RBM cycle, reducing decision lag, improving resource allocation, data quality, research collaboration and strengthening stakeholder engagement. This case study illustrates the potential for Conservation Intelligence platforms to be more widely used in conservation programs, and to act as a crucial enabler of climate adaptation through adaptive management in complex ecological systems.

DESIGN AND GROWTH OF THE COTS DASHBOARDS

Data collection and sources

The CoTS Control Program integrates multiple streams of field data collected by dedicated control vessels and monitoring teams (Figures 2,3). Each reef visit involves three distinct activities that yield different types of data and information. (1) *Manta Tow Surveys*: an observer is towed around the reef perimeter to assess coral cover and CoTS presence at broad spatial scales. Under the Integrated Pest Management protocol (Fletcher et al., 2020; Westcott et al., 2021), detection of adult CoTS or feeding scars triggers active culling. (2) *Culling Operations*: divers lethally inject CoTS and record counts by size class alongside diver effort (minutes). Reefs are subdivided into ~8–10 ha culling sites, which are “opened” when CoTS are detected and “closed” once catch-per-unit-effort (CPUE) falls below 0.04 CoTS per diver-minute (Babcock et al., 2014; Plagányi et al., 2020). Sites may be re-opened if subsequent manta tows (every 3–6 months) detect resurgence. (3) *Reef Health and Impact Surveys (RHIS)*: divers assess fine-scale coral condition and CoTS impacts at culling sites through 5 m radius spot checks (Beeden et al., 2014). Together, these methods provide complementary broad- and site-level data to support targeted and adaptive intervention.

Additional monitoring data from partner agencies are integrated into the CoTS Dashboards to support strategic decision-making. The Reef Joint Field Management Program (RJFMP), led by GBRMPA and QPWS, conducts independent manta tow and RHIS surveys, while the AIMS Long Term Monitoring Program (LTMP) provides long-term reef condition data (including data on CoTS abundance from comprehensive manta tows conducted annually at subset of reefs) that contextualise current and historical CoTS dynamics (Emslie et al., 2020, 2024). These datasets are combined with Control Program data to inform tactical and strategic objectives, prioritise reefs for intervention, and evaluate program effectiveness. Recent research initiatives, including the CoTS Control Innovation Program

(Bonin et al., 2022; Fletcher et al., 2021; Great Barrier Reef Foundation, 2019) ongoing investments from the National Environmental Science Program, have added novel data streams aimed at improving outbreak detection and refining prioritisation. For example, eDNA sampling (Uthicke et al., 2024) and Scooter-Assisted Large-Area Diver (SALAD) surveys (Chandler et al., 2023; Pratchett et al., 2022) enable early detection of low-density CoTS populations, facilitating more efficient control responses. Environmental variables such as chlorophyll, temperature anomalies, salinity, (e.g. eReefs (Steven et al., 2019), NOAA Coral Reef Watch (Liu et al., 2017; Skirving et al., 2020)) and larval connectivity outputs (Choukroun et al., 2024; Hock et al., 2017, 2014) are also integrated into the early warning component to further guide timely and targeted interventions (Figure 2).

Data integration and dashboard architecture

One of the most important features of CI tools like the CoTS Dashboard suite is the capability for flexible data Extraction, Transformation, and Loading (ETL). The CoTS Dashboard was built using Microsoft Power BI, which provides robust data connectivity, automation and preparation capabilities (via Power Query) to integrate numerous data sources and reshape them for analysis and visualisation. Within the platform, data from the various monitoring and culling activities are automatically cleaned, merged, and loaded into a relational data model, allowing different survey methods (manta tow, culling, RHIS, etc.) to be linked by common spatial and temporal identifiers (e.g. Reef ID, date) (Figure 3). This relational database approach ensures that all dashboards in the suite share a consistent, up-to-date data model and relationship structure. Importantly, data cleaning and merging are handled within the ETL pipeline with additional visual Quality Assurance / Checking (QA/QC) checks enabled via dedicated dashboard pages. These processes ensure that anomalies or errors in incoming data can be flagged and corrected before analysis and reporting (Figure 3).

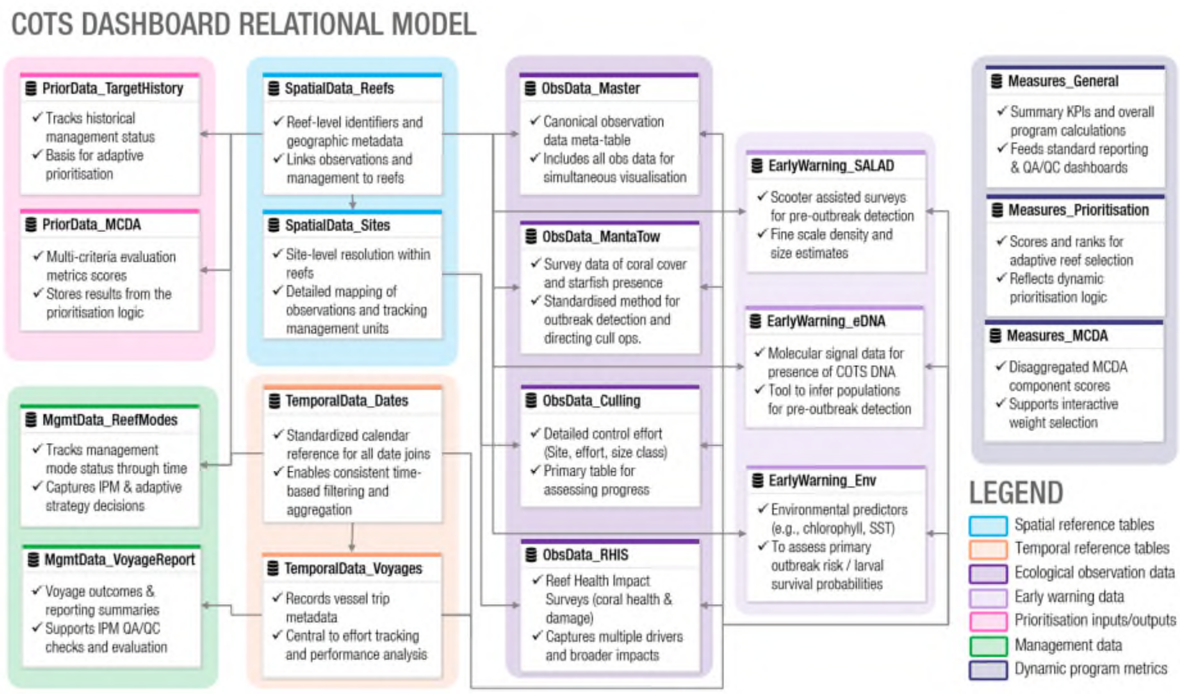

Figure 2 Simplified representation of the relational database structure constructed within the CoTS Dashboard. Data tables are linked to spatial and temporal references tables to enable the interactivity of the Dashboard. Colours represent groupings of tables reflecting their use. The vast majority of the program data is collected and stored through the Reef Authority's Eye-on-the-Reef system which also includes large amounts of tourism collected surveys used within the Dashboard model for early detection of outbreaks

As the system has expanded, a cloud-based data pipeline has been implemented to enhance automation and scalability (Figure 3). Newly developed Application Programming Interfaces (APIs) facilitate direct retrieval of raw data from Progressive Web Apps (PWAs) in the Eye on the Reef (EotR; GBRMPA, 2025) system (including broader EotR network tourism and citizen surveys used in early detection of outbreaks and external data systems (i.e. RIMRep DMS; (Australian Government and Queensland Government, 2023). These feeds are processed through automated routines using Databricks to avoid manual handling and enable quality control checks to ensure data is updated in near-real time to decision makers and on-water operators. This shared data infrastructure produces five distinct interfaces to support various components of the adaptive management cycle: Quality assurance/checking, Outbreak and Coral Cover Status, Early Warning, Prioritisation, Operations, Reporting and Evaluation (Figure 4) meaning improvements to data processing or new data streams are immediately available across the suite.

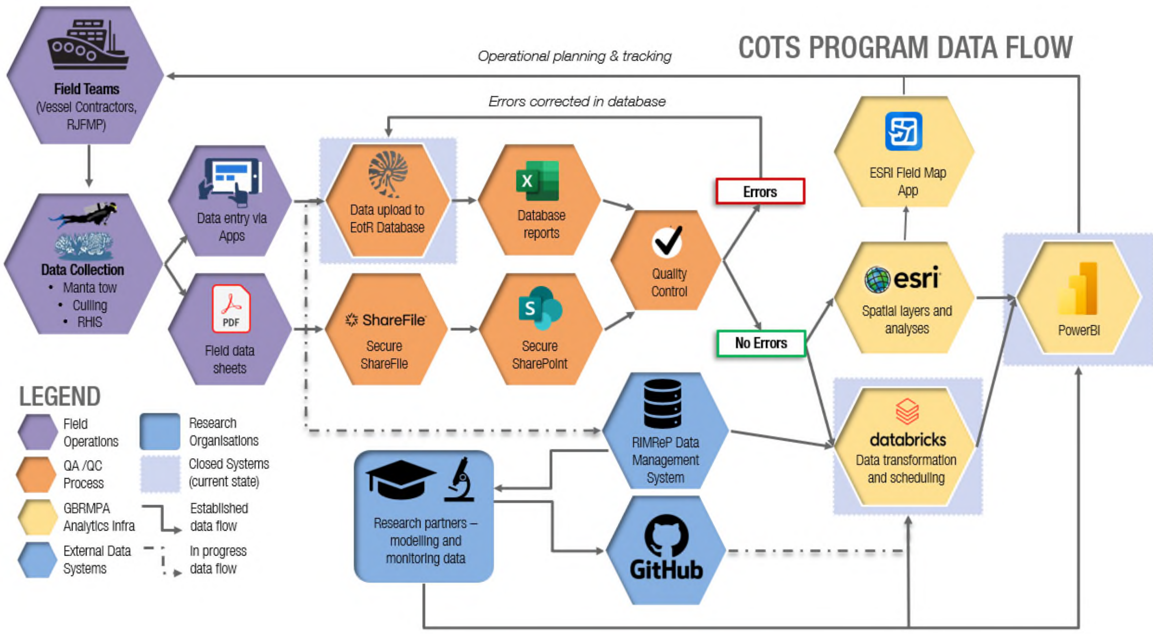

Figure 3 Overview of the CoTS Control Program data flow architecture, from field collection through validation, transformation, and delivery of analytics products. Field operations (purple) collect ecological data via in-water surveys and app-based tools, which are uploaded into the EotR database (orange) and subjected to QA/QC processes. Following verification, data are passed into analytics pipelines hosted in Databricks (yellow) and visualised through Power BI dashboards. External data systems (blue), contribute to proposed researcher led model integration and code management. Solid arrows denote active data pipelines; dashed arrows represent integration points under development.

ENABLING AND ACCELERATING ADAPTIVE MANAGEMENT

Assess – Severity, Extent and Early Detection

Adaptive management begins with a rigorous assessment of the ecological problem and the explicit formulation of objectives (Walters 1986; Gregory et al. 2006). In the context of CoTS control, this stage centres on quantifying outbreak and coral status across GBR reefs and articulating measurable objectives. The CoTS Control Program aims to maintain CoTS densities below the ecological threshold at which coral growth can outpace predation (Plagányi et al., 2020), at reefs conferring the highest ecological and economic value to the system (Matthews et al. 2025, Fletcher et al. 2024). Manta-tow densities, diver culling counts and feeding-scar prevalence are compared against accepted outbreak thresholds (De’ath, 2003; Miller et al., 2009) to deliver assessments of the current state of CoTS and coral cover across the Marine Park (Figure 4a). Providing the historical and current context of the severity and extent of CoTS outbreaks and coral trends gives spatial and temporal bounds to the ecological problem to help set and refine objectives and reporting metrics. Moreover, the early detection components help visualise and assess the build-up of CoTS populations at finer scale resolution to provide forward guidance around imminent populations irruptions in key regions of the Marine Park.

Design – Prioritisation for resilience based intervention

Once strategic and tactical objectives are specified and available resources are known, the CoTS Control Program sets specific target reefs each year. The long-term strategic objective is to protect a network of coral reefs that will optimise for protecting live coral cover, suppressing CoTS density and outbreak propagation and boosting overall resilience of the GBR. The Prioritisation Dashboard (Figure 4b) offers an interactive a multi-criteria decision analysis (MCDA) interface that integrates ecological value (i.e. coral health, resilience metrics, connectivity, outbreak severity), tourism value and logistical feasibility into a dynamic ranking of reefs for control via swing-weighting and Weighted Linear Combination (Fletcher et al., 2024, Matthews et al., 2025). Importantly, the MCDA process runs within the data model, so any change in the system or user defined changes to weightings can update the draft prioritisation list. The results of this initial process are presented at stakeholder workshops using the Prioritisation Dashboard to refine the target reef list for the annual work plan. Managers and stakeholders can adjust the weightings of these criteria, and the MCDA algorithm updates the ranking of reefs enabling the exploration of different management scenarios in a workshop setting. The MCDA process aims to identify reefs that represent the best compromise solutions across multiple objectives and under deep uncertainty (Matthews et al. 2025). This process proposes which reefs are to be actioned for culling operations under the established and structured Integrated Pest Management framework (Fletcher et al., 2020) and are refined during annual planning workshops (Fletcher et al., 2024). The Prioritisation Dashboard equips managers with a rigorous yet flexible decision-support system for designing conservation actions, bridging the gap between knowing where problems exist and deciding where to act for optimal impact.

Figure 4 CoTS Dashboard modules mapped to each phase of the adaptive management cycle, supported by foundational elements of stakeholder engagement and quality assurance.

Implement – On-water operations

Effective implementation of the CoTS Control Program's Integrated Pest Management framework requires precise coordination and oversight across a large, spatially distributed fleet. The Operations Dashboard (Figure 4c) supports this by serving as a central interface to track progress toward tactical objectives, guide field teams, and ensure adherence to the defined Integrated Pest Management sequence: initial surveillance, targeted culling, and post-intervention verification. Managers and QA officers can select any reef to view its current status, whether manta tow surveys have been completed, which sites are open for culling, CoTS removal counts, and follow-up survey outcomes. Visual indicators and maps display site-level metrics such as CPUE and effort, providing a near real-time overview of operational progress. For contractors, the dashboard highlights outstanding tasks and trends in CoTS densities, facilitating daily decision-making and allowing efficient prioritisation of resurveys or additional effort. The interface also streamlines reporting by aggregating operational data, reducing administrative overhead and error. This system tightens the feedback loop between on-water operators, program managers and researchers to ensure on-water operations are continuously being fine-tuned and effectively implemented.

Monitor – Tracking progress

The CoTS Dashboard consolidates multiple data streams from various monitoring programs to provide a unified view of CoTS and coral dynamics and culling interventions. Decision makers, operational managers and cull-vessel operators can interrogate time series data, aggregated by voyage, month, quarter, or year, to monitor the trends of CoTS densities, coral cover and culling effort at varying spatial scales (individual sites, whole reefs, or across regions) (Figure 4d). Outcome monitoring is strengthened by the integration of manta-tow surveys collected by the Control Program, the AIMS Long-Term Monitoring Program, and the Reef Joint Field Management Program, together with Reef Health and Impact Surveys (RHIS), allowing concurrent evaluation of coral-cover trajectories pre and post CoTS control, on controlled and non-controlled reefs. Crucially, there are an increasing suite of additional survey methods, including eDNA (Uthicke et al., 2024) , fine scale SALAD Surveys (Chandler et al., 2023; Pratchett et al., 2022), ReefScan (AI) surveys (Bainbridge et al., 2025), and additional manta-tow data currently being integrated in the CoTS Dashboards. Importantly these new methods are being incorporated into a bespoke monitoring program designed to yield statistically robust, spatially explicit assessments of both CoTS suppression and coral protection (Lawrence et al., 2025)

Evaluate – Automated reporting and analysis

The Reporting and Evaluation Dashboard enables evaluation of observed outcomes against the objectives and reporting metrics defined during the Assess phase. Automated visualisations track catch-per-unit-effort (CPUE) over time at site, reef, and regional scales, benchmarked against ecological thresholds to determine whether control targets are being achieved (Figure 4e). Reefs with unexpected CPUE trends are flagged for further investigation, facilitating targeted diagnosis of drivers such as post-cull recruitment, habitat complexity, or gaps in control effort. These summaries also incorporate coral-cover trajectories based on all available monitoring data, supporting ongoing evaluation of the program's impact on coral protection. As the monitoring program matures, these evaluations will expand to include more statistically robust, spatially explicit assessments which are currently limited without a spatially balanced monitoring program.

The Reporting and Evaluation dashboard serves multiple audiences, including the overarching governance bodies (CoTS Partnership Group, GBRMP board), and the public, through tailored reporting products to enhance transparency and accountability (GBRMPA, 2025). Critically, the dashboard also tracks delivery performance, enabling routine analysis of cost-effectiveness (e.g., cost per hectare treated or per diver hour). By integrating outcome and performance data within the same interface, the system ensures that efficacy and efficiency are reviewed regularly, during 6-monthly program workshops, 6-weekly operations meetings and via ongoing QA oversight allowing timely and evidence-based adjustments to the control strategy and integration with the broader suite of interventions that are being deployed to protect the Reef and enable climate adaptation under the Reef 2050 long-term sustainability plan.

Adjust – Institutional Learning and refinement

Institutional learning is consolidated through two program-wide workshops that translate evaluation findings into strategic and operational adjustments. The Annual Prioritisation Workshop integrates newly delivered scenario model outputs, updated trends in CoTS density and coral cover, and operational performance indicators such as the number of reefs/sites successfully closed and total diver hours expended. These insights inform reef rankings and objectives for the upcoming control season. For example, comparing actual effort (e.g., dive hours or visits required to achieve suppression) against initial expectations allows managers to identify "effort sinks" or identify areas where modelled predictions had performed poorly. Mid-season, a Pre-Spawning Workshop enables further adaptation based on interim CPUE trends, and delivery metrics in order to guide the repositioning of fleet resources ahead of spawning (e.g. towards hot spots of CoTS activity or "initiation zones"). The CoTS Dashboards are central to both adjustment cycles, providing the automated analyses that aggregate monitoring and effort data and serving as the shared visual platform through which results are communicated and decisions are negotiated during these workshops (Figure 4g). The tight adaptive management cycle deployed in the Program also enables potential adjustments to reef prioritisation in response to other disturbances including coral bleachng events and tropical cyclones. This climate adaptation opportunity is an increasingly important priority.

Foundational Activities – quality assurance and stakeholder engagement

The CoTS Dashboards also greatly enhance the capacity for QA/QC processing, informed stakeholder engagement and research collaboration, which are foundational activities required throughout the adaptive management cycle. A dedicated quality-assurance interface screens data against Integrated Pest Management rules, flags anomalies, and provides visualisations to monitor error rates and types over time, ensuring that subsequent analyses and decision-making rest on high quality data (Figure 4i). The Dashboards also underpin a wide range of stakeholder engagement activities with operators, traditional owners, managers and tourism industry. For example, the Dashboards are foundational tools for the prioritisation pre-spawning workshops where progress is reviewed, and strategic adjustments are planned and confirmed. The Dashboards are a powerful communication tool which builds the understanding of the ecosystem and data literacy of all partners within the Control Program (Figure 4h). This produces greater stakeholder buy-in and informed involvement in decision making throughout the adaptive management process. Moreover, GBRMPA has developed a public-facing reporting tool, providing stakeholders and the general public an overview of the program's achievements and the current status of CoTS and coral on the GBR. This enhances transparency and keeps the broader community informed about progress of the Program. The Dashboards enable meaningful engagement with stakeholders and strong QA/QC processes, which underpin the delivery of a large scale adaptively managed conservation program. The transparency and clarity of communication provided by the dashboards also serve to reinforce the case for ongoing and potentially enhanced Program capacity.

Recent Management Shifts Enabled by Conservation Intelligence

Beyond supporting the adaptive management cycle conceptually, the CoTS Dashboards have catalysed tangible changes in operational workflows, contract management, and institutional processes within the CoTS Control Program. For instance, visualising contract delivery metrics such as dive hours, on-water days, and effort by reef, highlighted gaps in operational delivery. This prompted updates to contractor work orders, introducing new deliverables such as "number of divers per voyage" and "dive hours per diver per day," which have since improved capacity estimates and enabled more precise workforce planning. The move towards automating QA processes and streamlining reporting also revealed ambiguities in how IPM rules were operationalised. This led to formalisation of decision rules, such as when a reef is considered "closed," when revisits are required, or when surveillance qualifies as reconnaissance thereby improving consistency and reducing subjectivity in management decisions.

Integration of contract and ecological data has also enhanced strategic flexibility. Managers now routinely monitor delivery performance in near real-time, allowing dynamic reallocation of fleet resources to high-priority areas based on evolving outbreak conditions. The growing use of vessel-based satellite internet connectivity has further accelerated this shift. In one recent case, surveillance data collected by a partner program (RJFMP) collected on the outer Far Northern GBR was uploaded while at sea; by the following day, the data was accessed by the local contractor and initiated control at the same reef, minimising delays and improving outbreak suppression. These examples demonstrate that the implementation of Conservation Intelligence has extended beyond simple visualisation, enabling deeper integration between data systems, contractors, and institutional workflows. As a result, the program has matured into a more responsive, transparent, and analytically driven operation, hallmarks of effective RBM. The transparency and clarity of communication provided by the dashboards also serve to reinforce the case for ongoing and potentially enhanced Program capacity.

FUTURE DEVELOPMENT AND LIMITATIONS

The CoTS Dashboards were developed to support the RBM goals of the Reef Authority as an adaptation response to increasing coral losses driven by rapid climate change. The dashboards address the research–implementation gap in conservation, whereby scientific insights often fail to influence on-ground management (Knight et al., 2008). By ingesting emerging research outputs including larval-connectivity matrices, early-warning indicators (eDNA, SALAD, EotR), revised culling thresholds, and simulation model predictions into a unified tool, the dashboards enable emerging research to be operationalised for strategic decision-making. The next phase of development will integrate a shared orchestration and data layer to support co-development with research partners (Figure 3). By leveraging cloud-based notebooks and computing environments, researchers and analysts will be able to collaborate to execute models at scale, generating and updating outputs (e.g., updated CoTS risk layers, predictive effort estimates) that feed directly into the dashboards and drive decision making. This tightened integration of research code, data, and outputs will further enhance reproducibility, reduce latency between research and action, and strengthen the program's adaptive, evidence-based approach to protecting coral habitats from preventable CoTS losses on the Great Barrier Reef.

However, this approach is not without limitations. While powerful and commercially supported, platforms such as Power BI are not open-source and may present cost barriers for conservation programs operating in low-resource settings, despite the availability of a limited free version. Enterprise solutions also are prone to vendor lock in risk, where users are at the mercy of large corporations. Scoping the long-term planning developmental support for any enterprise solution is therefore essential. The platform also imposes constraints on customisation: it lacks the flexibility of bespoke decision-support tools and is not designed to perform advanced statistical modelling, which must instead occur upstream in the data pipeline. Nonetheless, the trade-offs are often justified particularly as many large organisations already have enterprise licensing agreements. Bespoke systems typically require specialised expertise and long-term maintenance budgets that many conservation programs cannot sustain. These tools may be developed in lieu of or as a complement to other bespoke decision support tools allowing bespoke solutions to focus on tasks that cannot be delivered by Conservation Intelligence tools. BI platforms like Power BI offer a pragmatic alternative allowing programs to rapidly operationalise complex data streams and focus limited resources on conservation outcomes rather than software development.

CONCLUSION

The development and implementation of the CoTS Dashboards has significantly advanced adaptive, resilience-based management of crown-of-thorns starfish (CoTS) on the Great Barrier Reef by transforming complex raw field data into actionable insights. These dashboards automate previously manual processes, providing managers with near real-time analytics essential during rapidly evolving outbreaks and/or mass bleaching events. Their modular architecture allows seamless integration of emerging data sources and research findings, ensuring flexibility and responsiveness. By supporting all phases of RBM, from outbreak assessment and early warnings to outcome tracking and stakeholder communication, the dashboards have enhanced transparency and fostered more meaningful engagement. Built upon widely accessible Business Intelligence platforms like Power BI, this cost-effective and easily maintainable system exemplifies how commercial tools can sustainably address common data management challenges faced in conservation. As the Reef 2050 Integrated Monitoring and Reporting Program (RIMReP) progresses, the CoTS Dashboards represent a replicable model for large-scale, integrated, real-time ecological reporting. The CoTS Dashboards demonstrates that Conservation Intelligence may be an important emerging paradigm for conservation management, addressing some of the foremost challenges to adaptive management in complex systems and enabling more nimble, transparent, and informed conservation actions.

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Author Contributions

S.A.M. conceived the study, designed and implemented the Dashboard 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 tool. I.R. and J.W. developed the Dashboard tool, 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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