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

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Traditional Owner Acknowledgement

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

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ACRONYMS AND ABBREVIATIONS

CAS	Coral Area Saved
CBA	Cost-Benefit Analysis
CCCM	COTS Control Cost Model
CCIP	Crown-of-thorns starfish Control Innovation Program
CCP	COTS Control Program
CDR	COTS Density Reduced
CEA	Cost-Effectiveness Analysis
COTS	Crown-of-thorns starfish
CREAM	Coral Reef Economic Assessment Model
CRIM	Coral Reef Index Model
CRM	Coral Reef Managed
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CV	Coefficient of Variation
DEA	Data Envelopment Analysis
GBR	Great Barrier Reef
GBRF	Great Barrier Reef Foundation
ORA	Outbreaking Reefs Avoided
PPF	Production Possibility Frontier
QCD	Quartile Coefficient of Dispersion
RCI	Reef Condition Index
Reef Authority	Great Barrier Reef Marine Park Authority
RRAP	Reef Restoration and Adaptation Program
RRRC	Reef and Rainforest Research Centre
UQ	University of Queensland

GLOSSARY OF TERMS

Allocative efficiency: An allocation of limited resources that maximises net benefit, usually assessed within a cost-benefit analysis (e.g. Frank 2014).

Benefit transfer: The method of retrieving an economic value estimated in monetary terms from an original source studies and applying it to a new policy context (Johnston et al. 2015).

Consumer surplus: A monetary measure of the benefits consumers enjoy from participating in a transaction (e.g. Frank 2014).

Cost-effectiveness: Minimising cost to achieve a desired level of output or maximising output given a fixed budget (e.g. Frank 2014).

Equivalent annual value: An even spread of a present value across each year of a specified time horizon, adjusted for the time value of money (e.g. Boardman et al. 2018). The value can be a benefit, a cost or a net benefit resulting in an *Equivalent Annual Benefit*, *Equivalent Annual Cost* and *Equivalent Annual Net Benefit*.

Marginal excess tax burden: The decrease in economic efficiency (a decrease in the present value of net benefit) generated by raising an additional monetary unit (e.g., dollar) of tax revenue (e.g. Boardman et al. 2018).

Net benefit: Benefit less cost (e.g. Frank 2014).

Present value: The current aggregated value of a value stream that will be received in the future, discounted at a specific interest rate to account for the time value of money (e.g. Boardman et al. 2018). The value can be a benefit, a cost or a net benefit resulting in a *Present Value of Benefit*, *Present Value of Cost* and *Present Value of Net Benefit*.

Producer surplus: A monetary measure of the benefits a firm enjoys by producing output (e.g. Frank 2014).

Productive efficiency: An allocation of resources that produces as much (joint) output as possible without wasting limited resources (e.g. Coelli et al. 2005).

Profit rate: Percentage of revenue that turns into profit.

Shadow pricing: Adjustment of prices such that costs and benefits reflect their value to society as a whole (e.g. Boardman et al. 2018).

Social Surplus: The sum of consumer and producer surplus (e.g. Boardman et al. 2018).

Standing: Perspective from which costs and benefits are to be included or excluded in a cost-benefit analysis (e.g. Australian residents) (e.g. Dobes et al. 2016).

Sunk Cost: Cost that incurred in the past and cannot be recovered (e.g. Frank 2014).

EXECUTIVE SUMMARY

Crown-of-thorns starfish (COTS) outbreaks contribute significantly to the loss of hard coral on Australia’s Great Barrier Reef (GBR). Loss of hard coral reduces the use value (e.g. tourism and fishing profits, enjoyment of recreational fishers) and non-use value (e.g. the knowledge that the GBR continues to exist in a healthy condition) enjoyed by the Australian people.

The GBR system is spread over a huge area with a large number of reefs. Given that resources are limited, controlling COTS presents a significant challenge. Managers have almost infinite options of how to strategically deploy control effort across the GBR. They need to know which strategies generate value-for-money and are a worthwhile public investment that makes the Australian people better off. Managers also need to understand the trade-offs with using alternative strategies that distribute effort across reefs while considering factors like region or management zone.

In this study, we used a modelling and analysis pipeline to assess the costs and benefits of eighteen scenarios for deployment of COTS Control Program effort across the GBR. Our assessment used outputs from a collaborative COTS Control Innovation Program (CCIP) project focused on GBR-scale ecological modelling (CCIP-R-04 Regional Modelling). Ecological metrics from that study were used to assess the ecological benefits of each scenario in achieving four management objectives. The four corresponding ecological metrics were: (1) the number of COTS culled, (2) the amount of coral area saved, (3) the number of reefs where outbreaks were prevented, and (4) the amount of healthy coral habitat maintained. While detailed GBR-scale ecological modelling can tell us how effectively different control scenarios reduce COTS and protect coral, an economic assessment is required to ensure that, given the limited resources available in the COTS Control Program, public investments in COTS control maximise value-for-money and make the Australian people better off.

Incorporating the economic value of costs and benefits (estimated in monetary terms) helps us to examine which of the assessed scenarios minimise the cost per unit of ecological benefits and maximise the net benefit people derive from the impacts of COTS control. The estimated ecological benefits were used as inputs to estimate the economic value of benefits. The economic value of cost was derived based on data from the current COTS Control Program. Net benefit (benefit less cost) is reported as ‘present value’, which involves discounting. Discounting ensures that the time value of money is taken into account: the idea that a dollar (expressing a benefit or cost) today is worth more to people today than the same dollar in the future. The present value then represents the current aggregated value of a value stream over a specified time horizon (2022-2040) that will be received in the future, discounted at a specific interest rate.

Both the ecological metrics and economic metrics provide the basis for assessing alternative control strategies and any trade-offs between them. We find significant differences in value-for-money (cost-effectiveness assessed against the four ecological metrics) and Present Value of Net Benefit to the Australian people across alternative manual COTS control scenarios.

Of the eighteen COTS control scenarios assessed, three of them ranked highest in terms of cost-effectiveness in maximising the area of coral saved given the fixed budget. One of these top performing scenarios spreads control effort GBR-wide, similar to the current Control Program strategy. Our modelling estimated that this costs, on average, $3,146 per hectare of coral area saved each year. In comparison, the least cost-effective scenario cost $25,670 per hectare each year. If the objective is to minimise the number of outbreaking reefs, then strategies that focus control program effort in the Far Northern and Southern regions rank highest in terms of cost-effectiveness. However, this result should be interpreted carefully because it does not account for the size of the reefs where outbreaks are avoided. Indeed, the strategies that minimise the number of outbreaking reefs across just a set of reefs prioritised within the COTS Control Program are very different. Under this constraint, the most cost-effective scenarios are those that focus effort in the Central and Southern regions, along with the two scenarios that avoid reefs that are effort sinks with high COTS, and the GBR-wide scenario. If management aims to achieve cost-effectiveness jointly by saving coral area and avoiding reefs from outbreaking, then the GBR-wide strategy and two effort sink scenarios perform best. The most promising scenarios to minimise the cost per hectare of healthy coral habitat maintained are those that focus effort on reefs that are not protected from fishing or avoiding reefs that are effort sinks with high COTS and a coral cover of less than 20%. A somewhat lower cost-effectiveness is achieved by scenarios that focus effort in the Far Northern and Northern regions and by avoiding effort sinks irrespective of coral cover.

Seventeen out of eighteen scenarios assessed in a Cost-Benefit Analysis generate an increase in the Present Value of Net Benefit. This strongly suggests that targeted and continuous COTS control is a worthwhile public investment that makes the Australian people better off. We estimated that the GBR-wide strategy for deploying control effort generates a Present Value of Net Benefit of approximately $1.19B, which represents the net benefit discounted and aggregated over a 2022-2040 time horizon. The corresponding Benefit-Cost Ratio (calculated by dividing the Present Value of Benefit by the Present Value of Cost) indicates that for every $1 spent the GBR-wide strategy is expected to return about $6.50 in benefits. The findings of this study suggest further that implementing scenarios that refine this GBR-wide strategy by focusing effort on reefs that are not protected from fishing or avoiding reefs that are effort sinks with high COTS and a coral cover less than 20% could offer an opportunity to almost double the Present Value of Net Benefit delivered by the COTS Control Program. A significant increase in the Present Value of Net Benefit could also be achieved by focusing effort in the Northern and Far Northern regions. However, the Present Value of Net Benefit generated by the control scenario is strongly driven by non-use value (the value to people knowing that a healthy coral reef continues to exist), which derives from an increase in healthy coral habitat maintained and makes up more than 90% of the overall benefits estimated for each strategy.

The results of this study also show how different strategies distribute the Present Value of Benefit across different beneficiaries such as the tourism and fishing industry or recreational fishers. The scenarios that maximise tourism Present Value of Benefits are the GBR-wide strategy and strategies focusing effort in the Central and Northern regions, which are GBR tourism hubs. The scenarios that maximise Present Value of Benefit for commercial and recreational fishing are the GBR-wide strategy and the two scenarios that avoid reefs that are effort sinks with high COTS.

A key insight from these diverse results is that different objectives are best served by different management scenarios. As such, it is vital to both clearly specify the objectives of a program to identify the most effective strategy, and then also to review which secondary objectives are being traded off when the primary objective is maximised. The primary objective of the COTS Control Program and the COTS Control Innovation Program is to protect coral cover across the GBR. In this analysis, the GBR-wide COTS control scenario, the scenario that most closely resembles the current COTS Control Program, was one of the top performers in saving coral area. Other strategies were better at reducing the number of reefs experiencing COTS outbreaks across the whole GBR, but when considering the priority reefs, the GBR-wide strategy was again one of the top performers. Similarly, the GBR-wide strategy was one of the top strategies for protecting tourism and fisheries values. The one metric where the GBR-wide COTS Control strategy provided significant benefit but was not a top performer was in maintaining healthy coral habitat, and as a result, non-use value across the GBR. Additional work will be needed to better understand how protecting healthy coral habitat relates to maintaining protection of coral and avoiding outbreaks.

The results of this research demonstrate that the strategy currently being used to guide the COTS Control Program on the GBR is likely 1) to generate a net benefit to the Australian people relative to the investment required to support them; 2) to be among the most cost-effective of the strategies investigated for the protection of coral; and 3) to be a reasonable strategy in terms of avoiding outbreaks at reefs prioritised by the COTS Control Program and protecting tourism and fisheries values. At the same time, future refinements to the strategy could potentially increase the ability to avoid outbreaks at reefs more broadly and increase non-use value. The modelling framework developed in this project will allow decision makers to assess future strategies to make informed decisions to manage trade-offs between these objectives.

1. INTRODUCTION

1.1 Background

Crown-of-thorns starfish (COTS; *Acanthaster* spp.) outbreaks contribute significantly to the loss of hard coral on the Great Barrier Reef (GBR) (Pratchett et al. 2014). In response, the COTS Control Program (hereafter referred to as Control Program) was established in 2012 (Great Barrier Reef Marine Park Authority 2025). The Control Program is a large-scale, ongoing initiative aimed at reducing the impact of COTS outbreaks on the GBR. The Program is a highly collaborative initiative delivered by the Great Barrier Reef Marine Park Authority (hereafter referred to as the Reef Authority) in partnership with the Great Barrier Reef Foundation (GBRF) and the Reef and Rainforest Research Centre (RRRC), and with support from government agencies, industry partners, and contractors. The program's core objective is to protect GBR resilience through effective management of COTS outbreaks. The program deploys a coordinated fleet of control vessels that operate year-round. Given the vast scale of the GBR and the finite resources available, these vessels are strategically assigned to high-value, priority reef areas that are selected based on ecological value, tourism importance, and connectivity to other reefs. The Control Program uses a targeted effort approach, where data-driven decisions guide where and when to deploy manual culling teams to maximise impact. This ensures that cull effort (the number of COTS removed over time) is concentrated where it can most effectively reduce COTS outbreaks and save coral cover. Controlling COTS through manual culling takes significant resources but in return generates benefits in terms of reduction in COTS, protection of coral cover, reduction in outbreaks, and overall reef resilience (Matthews et al. 2024; Skinner et al. 2025b). When, where, and how COTS are culled changes the distribution of these ecological benefits, and how those benefits accrue to GBR-dependent industries, Traditional Owners, communities that live and work across the GBR, and to the Australian people as a whole. While GBR-scale ecological modelling (Skinner et al. 2025a; Skinner et al. 2025b) enables a comparison of the direct ecological benefits (i.e. reduction of COTS, protection of coral cover, reduction in outbreaks) derived by different Control Program strategies, they do not account for the economic value of the costs associated with delivering the Control Program, nor do they estimate the economic value of the benefits that may be generated through the investment in COTS control.

The term economic value is often narrowly understood as the market value of benefits, which are generated by the buying and selling of goods and services in markets (e.g. tourism profits from diving/snorkelling tours or profits earned by the commercial fishing industry). However, market value only represents one component of total economic value (Cesar 2000). Economic value is generated by the full range of benefits enjoyed by people. The total economic value of benefits includes both market and non-market value, which, in principle, accounts for any benefits associated with commercial, environmental and social impacts of COTS control.

Non-market value can include use value, such as the enjoyment people derive from recreational fishing, as well as non-use value, like the benefit people derive from simply knowing that a healthy coral reef continues to exist even though they never visit it. The latter is referred to as existence value. If benefit is lost (e.g. through a coral bleaching event that reduces existence value and/ or tourism profits), this loss is interpreted as a cost to society. The cost of delivering the Control Program can be interpreted in the same way: public funds invested in the Control Program are a cost as they cannot be used in another public project.

In the economic literature, the economic value of benefits and costs is typically measured in monetary terms. This enables the calculation of the economic value of net benefits – the difference between benefits and cost. Understanding costs and benefits in monetary terms is required to ensure that public investments in COTS control maximise value for money, consider implicit trade-offs, and ensure that the Australian people are made better off by generating a net benefit.

Studies have demonstrated that minimising the impact of COTS outbreaks through COTS control supports coral reef health (Skinner et al. 2025b; Skinner et al. 2025a), which underpins the generation of market value (e.g. economic value in terms of commercial profits earned by the tourism industry though selling snorkelling and diving trips depends on attractive dive sites) as well as non-market value (e.g. economic value generated through existence benefits depends on the continued presence of healthy coral reef habitat) (Scheufele et al. 2022a). While it has been hypothesised that COTS control is a value-for-money investment that makes the Australian people as a whole better off by generating a net benefit, no comprehensive economic assessment of alternative manual COTS control strategies had been performed. This project developed and applied a modelling and analysis pipeline that enabled the first estimation of the economic value of benefits and costs of alternative COTS control scenarios to support decision making for the Control Program - a multimillion-dollar Australian government investment. It supports the Control Program in making strategic decisions about how to best deploy Control Program effort given the large scale of the challenge (there are more reefs than the program can manage).

1.2 Expected benefits and project aims

This project provides the first-ever assessment of the economic value generated by Australia's COTS Control Program. By performing a comprehensive economic assessment, this project provides guidance beyond how to cull the most COTS or protect the most coral cover. The results of this project will provide support to decision makers to decide where, when, and how to cull COTS across the GBR to maximise value for money with the limited resources available to them in the Control Program. The economic assessment was conducted against the following economic evaluation criteria:

- Cost-effectiveness
- Productive efficiency and trade-offs
- Allocative efficiency

<u>Cost-effectiveness</u> of alternative COTS control scenarios values the cost of inputs (e.g. vessels, people, material) in monetary terms. Cost-effectiveness refers to either achieving a desired output at a lower cost or achieving more outcome at a specified fixed cost. Here, it is used to identify the COTS control scenarios that maximise ecological benefits given a fixed budget and therefore deliver value for money. Comparing the alternative scenarios generates

information on if and how benefits could be increased at a fixed budget. Increased cost-effectiveness, given a fixed budget, allows both individual reefs to be controlled faster, saving or maintaining more coral cover, and more reefs to be managed across the GBR. Additionally, it provides information on the cost savings of implementing one scenario over another. Cost-effectiveness is mainly driven by the cull methods' effectiveness in producing ecological benefits under different management scenarios, combined with the extent and timing of effort costs estimated in monetary terms ($).

Productive efficiency of alternative COTS control scenarios provides insights into which scenario produces the most ecological benefits for a fixed control effort budget while also optimising against multiple ecological benefit metrics (e.g. minimising outbreaking reefs and maximising coral area). Quantifying the implicit trade-offs with respect to different metrics (e.g. choosing scenario A over B implies trading off a reduction of x hectares of coral area protected to gain an additional reduction of y number of outbreaking reefs) provides guidance in choosing between alternative control scenarios that are equally productively efficient.

Allocative efficiency takes that a step further and additionally values the benefits in monetary terms ($). It is therefore driven by not just the economic value of cost but also by the extent, timing and spatial distribution of ecological benefits and the economic value they generate to people. Information on allocative efficiency enables managers to compare alternative scenarios by the extent and distribution of net benefit generated by COTS control, with both benefits and costs assessed in monetary terms (a common numeraire that enables aggregation across different benefit types).

This project provides guidance on where and how to invest Control Program effort to maximise one or multiple ecological benefit metrics and/or to generate the largest net benefit, given a set of identified control scenarios, ecological data on coral benefits, as well as costs and benefits estimated in monetary terms. Besides the economic assessment of manual COTS control scenarios, the project also provides a template for future analyses beyond the COTS Control Innovation Program (CCIP) for the assessment of novel COTS control methods and technologies (e.g. automated COTS monitoring, semio-chemical approaches) once details and data about their implementation become available.

The project aims to:

- assess cost-effectiveness of alternative manual COTS control scenarios to provide guidance on where, when, and how to deploy manual COTS control effort to maximise ecological benefits given a fixed budget (value for money),
- assess productive efficiency to make transparent implicit trade-offs across alternative manual COTS control scenarios with respect to different ecological benefit metrics,
- assess allocative efficiency to (i) provide evidence on whether the public investment in manual COTS control generates a net benefit ($) enjoyed by the Australian people, and (ii) offer guidance on when, where, and how to deploy manual COTS control effort to maximise net benefit ($) given the set of assessed scenarios, and
- provide a template for a future assessment of the benefits and costs of novel COTS control methods and technologies that are being investigated/under development.

1.3 CCIP program logic

Within the CCIP program logic (**Figure 1**), this project CCIP-R-06 is part of the Response Subprogram. The project contributes to the development of enhanced modelling capability (output), which facilitates a more efficient and effective operational response (outcome). This is expected to contribute to the prevention and suppression of outbreaks; protection of coral cover across the GBR; and the generation of benefits to industries and communities (impact).

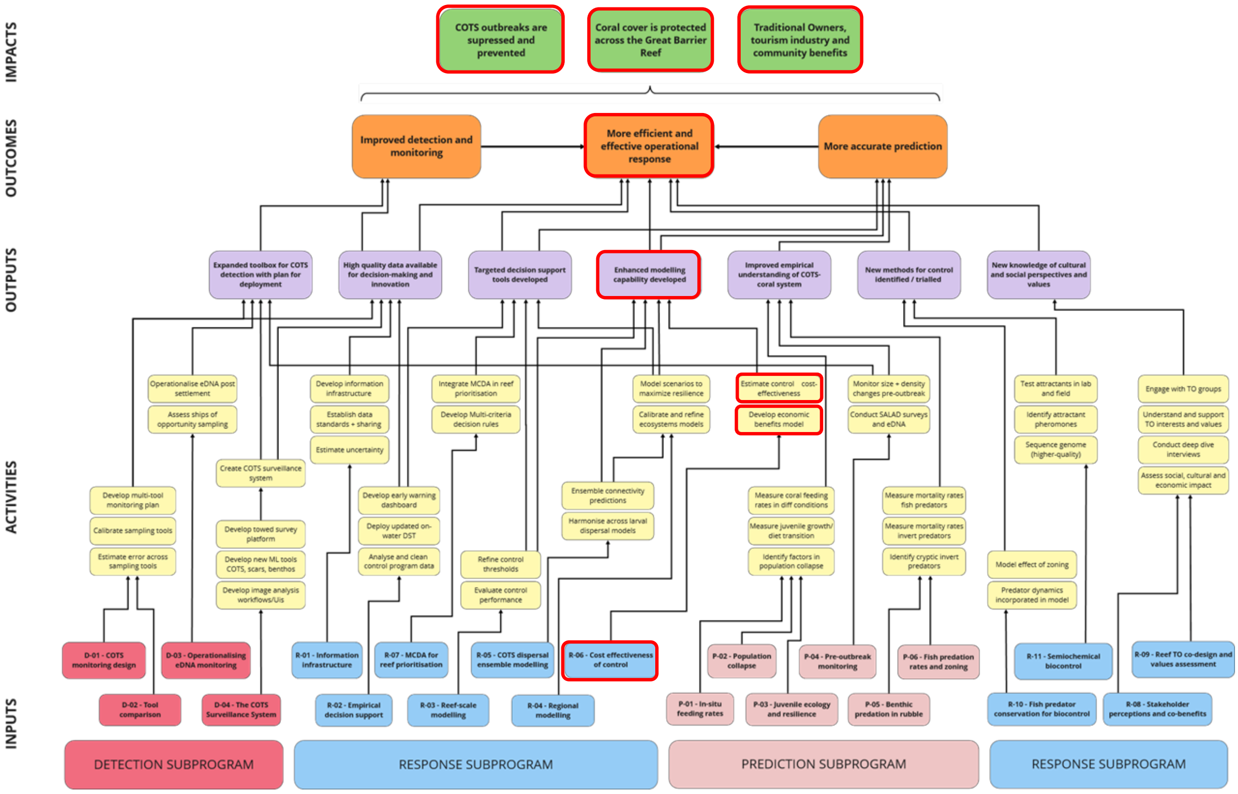

Figure 1. Project CCIP-R-06 within the CCIP program logic. The project and its impact pathway are highlighted in red.

METHODS

The economic assessment performed in this project applied the Economic Assessment Framework developed under the Reef Restoration and Adaptation Program (RRAP) (Scheufele et al. 2022b). The framework sets out the steps and principles to assess (i) cost-effectiveness through a Cost-Effectiveness Analysis (ii) productive efficiency through a Data Envelopment Analysis, (iii) and allocative efficiency through a Cost-Benefit Analysis in the context of the GBR.

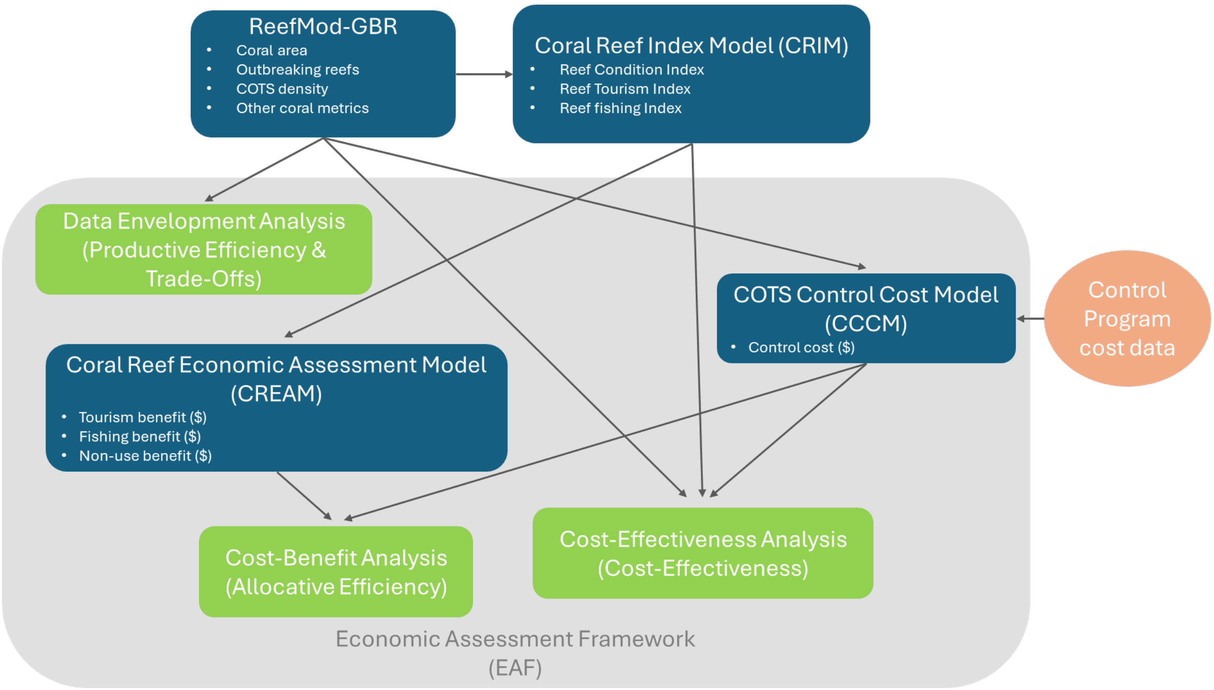

Figure 2. Modelling and analysis pipeline.

Data used in the economic assessment are generated by means of a pipeline of linked models and analyses, underpinned by an Economic Assessment Framework (Scheufele et al. 2022b). In the modelling and analysis pipeline (**Figure 2**), the output of one model becomes the input into another model (blue) or analysis (green): A collaborative CCIP project CCIP-R-04 Regional Modelling (Skinner et al. 2025a) used a GBR-scale ecological model (ReefMod-GBR) (Bozec and Mumby 2019) to simulate the extent of ecological benefits under alternative COTS control scenarios. Some of the simulated coral metrics were used as inputs in the Coral Reef Index Model (CRIM) (Scheufele et al. 2022a; Heneghan et al. 2025) developed under the RRAP to simulate the extent of indices required for the economic assessment. The cost of cull effort in the current Control Program (orange) was elicited through engagement with the GBR Marine Park Authority (Reef Authority). The economic value of cost associated with cull effort modelled in the GBR-scale ecological model (ReefMod-GBR) was estimated by developing and applying the COTS Control Cost Model (CCCM) using the elicited cost data of the current Control Program. Cost-effectiveness was assessed using data on economic cost ($) and ecological benefits (*Coral Area Saved*, *Outbreaking Reefs Avoided*, *COTS Density Reduced*, *Healthy Coral Habitat Maintained*).

Definitions of these ecological benefit metrics are provided subsequently (see section 2.1). Some of the outputs from the GBR-scale ecological model (ReefMod-GBR) were also used to identify and assess the productive efficiency of alternative manual COTS control scenarios. This was complemented by an assessment of the implicit trade-offs across different ecological benefit metrics (*Coral Area Saved* traded-off against *Outbreaking Reefs Avoided*). The economic value of benefits ($) was estimated by customising and employing the economic valuation component of the Coral Reef Economic Assessment Model (CREAM) (Scheufele et al. 2022a) developed under RRAP and interpreting these data in the COTS control context. Inputs into CREAM were the Reef Condition Index, Reef Tourism Index and Reef Fishing Index simulated by the Coral Reef Index Model (CRIM) based on coral metrics simulated by ReefMod-GBR. Data on the economic value of benefits and costs were leveraged to identify and assess allocative efficiency (larger economic value of net benefits generated through manual COTS control) of alternative COTS control strategies.

R (R Core Team 2024) accessed through R studio was used to estimate the models and perform the assessments.

The details of the metrics and methods used in each of these assessments is provided in the following sections.

1.4 Modelling of manual COTS control scenarios

The economic assessment was based on estimates of ecological benefits for alternative COTS control scenarios relative to a counterfactual - a base case with no control, simulated by employing a spatially explicit ecosystem model of the GBR. Hence, the benefits reported represent the difference between estimates with and without COTS control.

The manual COTS control scenarios and the counterfactual considered in the economic assessment were modelled within a collaborative CCIP project (Skinner et al. 2025a) using ReefMod-GBR (Bozec and Mumby 2019). The outputs of the ecological model were used as inputs in the modelling and analyses pipeline (**Figure 2**).

ReefMod-GBR is a spatially explicit ecosystem model simulating coral and COTS population dynamics across the GBR in six-month timesteps. For the economic assessment, these six-month timesteps were aggregated to twelve-month timesteps. ReefMod-GBR uses 20 x 20 m grids to represent 3,806 reefs, considering individual coral colonies from six different morphological groups and COTS. COTS outbreak dynamics are modelled with age-specific mortality rates, adjusted based on reef protection status (Kroon et al. 2021). Environmental stressors such as heat stress, cyclones, and water quality are included, using historical data for hindcasting and climate model predictions for future scenarios. Reef-level coral cover and COTS density are initialised based on established monitoring programs and metacommunity models, with COTS observational data overriding model predictions where available.

COTS control is implemented in the model to reflect the current Control Program as realistically as possible. COTS are culled across the entire GBR by five vessels (with an assumed effort of 3,840 hours per vessel per year). For each vessel, only 90% of total effort is allocated to culling, as 10% is spent on other on-water activities (e.g. manta tow surveys)

(Reef Authority), unpublished data). This results in 3,456 hours of culling effort per vessel per year that is available to be deployed in the model, which generates ecological benefits.

The Reef Authority identifies 500 Priority Reefs for control selected based on ecological value, tourism importance, and connectivity to other reefs, as well as a subset of dynamic Target Reefs which is generated from the Priority Reef list each year to guide and prioritise control activities. To simulate this in the model, a fixed Target Reef list was created (n = 224) by selecting all Priority Reefs that were controlled at least twice over a three-year period (21/22, 22/23, and 23/24; Reef Authority, unpublished data). Unless otherwise stated, at each timestep, control starts first at Target Reefs, then Priority Reefs, then Non-Priority Reefs until all effort has been used. The goal of control actions at each reef the Control Program controls is to reduce COTS densities below the Ecological Threshold, which is where the rate of coral growth is higher than the rate of COTS consumption (Babcock et al. 2014). Each reef is split into 10-hectare cull sites (500 x 200 m), and control is implemented at this level when COTS densities are above the Ecological Threshold.

COTS control scenarios were developed through discussions with key stakeholders (Reef Authority; GBRF) and collaborators (researchers at the University of Queensland (UQ) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO)). A total of eighteen scenarios were identified to address specific management objectives that might be realistically achieved through the current Control Program. The final list of scenarios (**Table 1**) is separated into three major groups: 1) Spatial (n = 13): these scenarios involve assigning vessels to specific regions, management zones, or the outbreak front. 2) Effort Sink (n = 2): certain reefs have exceptionally high COTS densities, requiring substantial control effort to get COTS densities below the Ecological Threshold. These scenarios do not implement control measures at these reefs. 3) Connectivity (n = 3): these scenarios dynamically consider the coral cover and risk of COTS larvae spreading for each reef. Note that the Connectivity scenarios assume an unrealistic perfect knowledge of coral cover and the risk of COTS larval spread for each reef, so real-world results are likely to be more conservative than those presented here. For this reason, the economic assessment first considers the Spatial and Effort Sink scenarios (primary) and then expands the perspective by including the Connectivity scenarios (secondary) in the analysis.

All scenarios simulated by ReefMod-GBR use the same climate model (General Circulation Model CNRM-ESM2-1) and future climate scenario (Shared Socio-economic Pathway 2.6, SSP2.6), with a timeframe starting in summer 2008 and ending in winter 2040. Each scenario is repeated for 20 runs, to account for stochasticity in the system. The counterfactual scenario has no COTS control, while for control scenarios, control begins at the start of 2019.

Three ecological benefit metrics estimated by ReefMod-GBR were chosen to assess the performance of different COTS control scenarios compared to the counterfactual:

- *Coral Area Saved*: the difference in coral area saved (hectares) between the scenario and the counterfactual.
  The coral area for each reef was calculated by summing the percentage of coral cover across all six coral morphological groups, converting this sum to a proportion, and then multiplying it by the total available coral habitat area (km^2) for that reef, then

converting the result to hectares by multiplying by 100. Consequently, the extent of *Coral Area Saved* depends on both coral cover and the size of coral habitat area.

- *Outbreaking Reefs Avoided*: the difference in the number of reefs that have a COTS outbreak or not (irrespective of their size) between the scenario and the counterfactual.
- *COTS Density Reduced*: the total density of COTS culled through control (#/400 m^2).

Table 1. Full list and description of all 18 scenarios implemented in the ecosystem model (ReefMod-GBR). The R_GBR scenario most closely resembles the current Control Program. The model applies a 6-month timestep over the simulated time horizon.

Scenario Group	Scenario	Scenario Code	Brief description
Counterfactual	SP2.6	CF_SP2.6	No CCP; climate scenario SSP2.6.
Spatial	Regional - GBR	R_GBR	CCP across the whole GBR.
Spatial	Regional - Far North	R_FN	CCP across FN regions.
Spatial	Regional - Far North, North	R_FNN	CCP across FN and N regions.
Spatial	Regional - North	R_N	CCP across N regions.
Spatial	Regional - North, Central	R_NC	CCP across N and C regions.
Spatial	Regional - Central	R_C	CCP across C region.
Spatial	Regional - Central, South	R_CS	CCP across C and S regions.
Spatial	Regional - South	R_S	CCP across S regions.
Spatial	Protection Status - Unprotected	PS_UNP	CCP across whole GBR but only reefs that are unprotected (i.e. fishing allowed).
Spatial	Protection Status - Protected	PS_P	CCP across whole GBR but only protected reefs (i.e. no fishing).
Spatial	Outbreak Front - Latitude	OF_LAT	CCP across whole GBR, but control at Target Reef first, then all Priority and non-Priority Reefs with outbreaks within +/-0.5-degree latitude of the Target Reef.
Spatial	Outbreak Front - All Reefs	OF_AR	At each timestep (*ts*), control sector with highest density of COTS across all reefs. Control all reefs in that sector. Then remaining sectors. New order each *ts*.
Spatial	Outbreak Front - Priority Reefs	OF_PR	At each *ts*, control sector with highest density of COTS across Priority Reefs. Control Priority Reefs in sector. Then remaining sectors. New order each *ts*.
Effort sink	High COTS - No Coral Exception	ES_HC	CCP across whole GBR but remove reef from list when COTS density > 3 per manta tow.
Effort sink	High COTS - Coral Exception	ES_HC_CC	As in ES_HC, but a reef is still controlled when COTS density > 3 per manta tow if coral cover > 20%.
Connectivity	COTS Larvae and Coral Cover	C_COTS_CC*	At each *ts*, rank Priority Reefs by COTS larval output and coral cover. Then do same for non-Priority Reefs.
Connectivity	COTS Larvae, Coral Cover, Protected Reefs	C_COTS_CC_P	As in C_COTS_CC, but when reef rankings are similar, protected reefs (i.e. no fishing) are prioritised.

Connectivity	COTS Larvae, Coral Cover, Unprotected Reefs	C_COTS_CC_UNP	As in C_COTS_CC, but when reef rankings are similar, unprotected reefs (i.e. fishing) are prioritised.

A fourth ecological benefit metric was generated by using output of ReefMod-GBR as input into the Coral Reef Index Model (CRIM) that translates coral metrics into condition indices that capture ecosystem services:

- *Healthy Coral Habitat Maintained*: the difference in coral habit in good and very good condition (hectares) between the scenario and the counterfactual. The calculation of coral habitat is based on the Reef Condition Index. The Reef Condition Index integrates coral cover with four additional ecological attributes that underpin reef condition either positively (shelter volume, abundance of coral recruits), or negatively (rubble cover and the abundance of COTS). This metric summed the total 3D area of coral habitat within all reefs estimated to be in *good* or *very good* condition for both the control scenario and the counterfactual and calculated the difference.

The differences and comparability of the two different 'coral metrics' (*Coral Area Saved* and *Healthy Coral Habitat Maintained*) are as follows:

- While *Coral Area Saved* depends on coral cover only, the estimation of *Healthy Coral Habitat Maintained* integrates coral cover within a broader set of five ecological attributes that underpin reef health either positively (coral cover, shelter volume, abundance of coral recruits), or negatively (rubble cover and the abundance of COTS).

- While *Coral Area Saved* is derived by multiplying coral cover by the size of the 3D coral habitat area, *Healthy Coral Habitat Maintained* assigns the full extent of the 3D coral habitat area to reefs that are estimated to be in good or very good condition. Hence the former does not differentiate reef habitat quality independent of habitat size (e.g. a coral reef habitat with an average coral cover of 10% or 20% and extent of 100 hectares or 50 hectares, respectively, are assigned the same *Coral Area Saved* of 10 hectares).

Hence, *Coral Area Saved* and *Healthy Coral Habitat Maintained* are different metrics and, while related and both estimated in hectares, they are not directly comparable.

The metrics *Coral Area Saved*, *Outbreaking Reefs Avoided* and *COTS Densities Reduced* were calculated across two different subsets of GBR reefs: 1) all 3,806 reefs on the GBR to investigate GBR-wide effects; and 2) the 500 Priority Reefs inclusive of the subset of Target Reefs, to investigate effects at the reefs that have been identified as high priorities for COTS control. *Healthy Coral Habitat Maintained* was estimated across all reefs on the GBR.

The ReefMod-GBR output contained 20 runs for each metric, year and reef over the specified modelling time horizon, which was used as an input into the economic assessment. This ensured that variation through time was incorporated.

Comprehensive information on the GBR-scale ecological modelling based on ReefMod-GBR and underlying assumptions, as well as a more detailed description of the modelled COTS control scenarios and the counterfactual can be found in Skinner et al. (2025a).

1.5 Cost-effectiveness analysis

The assessment of cost-effectiveness was guided by the Economic Assessment Framework (Scheufele et al. 2022b). In a Cost-Effectiveness Analysis (CEA) (e.g. Boardman et al. 2018), the costs of inputs (e.g. control effort) are estimated in monetary terms, while the benefits (effect) are estimated by a physical metric (e.g. ecological benefits). A CEA is used to rank the alternative COTS control scenarios, identify which one is the most cost-effective, and estimate their differences in cost-effectiveness. Cost-effectiveness was expressed in terms of ratios: ‘cost per unit of benefit’ and as ‘unit of benefit per dollar’. The former represents the average cost of generating a unit of average benefit (e.g. $ per hectare), while the latter exhibits the average benefit per dollar spent (e.g. hectares per $).

Both cost (estimated in a monetary unit) and benefit (estimated in a non-monetary unit) were discounted and converted into present values. Discounting ensures that the time value of money is taken into account: the idea that a dollar (expressing a benefit or cost) today is worth more to people today than the same dollar in the future. We note that benefits estimated in a non-monetary unit are sometimes left undiscounted in environmental and health economics (Smith and Gravelle 2001). Leaving benefits undiscounted while discounting costs would lead to distortions, since it implicitly values future benefits as if they occur now, while devaluing costs in the future. The present value applied in this study represents the current aggregated value of a value stream over a specified time horizon (2019-2040) that will be received in the future, discounted at a specific interest rate.

Applying discounting, cost-effectiveness ratios were derived by dividing the Present Value of Cost by the Present Value of Benefit (and vice versa). Consequently, the ratios represent a ‘cost per unit of benefit’ and ‘unit of benefit per dollar’ per year, averaged over the specified time horizon. We note that the specified time horizon implicitly assumes that the alternative COTS control scenarios were implemented from 2019 onwards.

All benefits and costs were discounted over the specified time horizon (2019–2040) to the chosen base year (2019) using a 7% real annual discount rate, which is recommended for the base case by the Cost-Benefit Analysis (CBA) guidance note of the Office of Best Practice Regulations (2020).

It is important to note that since the benefits are estimated in physical and not monetary terms, a CEA does not provide insights into whether COTS control scenarios generate a gain in net benefit. Rather, it generates information on which scenarios maximise a specified ecological benefit metric given a fixed investment budget. The following ecological benefit metrics were used in the CEA: *Coral Area Saved*, *Outbreaking Reefs Avoided*, *COTS Density Reduced*, and *Healthy Coral Habitat Maintained*.

The alternative COTS control scenarios (see Section 2.1) were treated as mutually exclusive, i.e. each analysis considered only one control scenario, not combinations of scenarios or a switch of scenarios over time. The scope of the CEA was all 3,806 reefs across the GBR

Marine Park (even though a Priority Reefs focused assessment was also conducted), with the overall goal to enhance coral reef resilience to the benefit of the Australian people.

The investment budget is assumed to be fixed and constant across the alternative COTS control scenarios assessed in this project. That is, each scenario deploys the same amount of control effort. Furthermore, due to data availability limitations, simplifying assumptions regarding the costs under each scenario were necessary (Appendix A). As a result, the cost per unit of effort is assumed to be the same across all scenarios. Hence, cost-effectiveness is driven by the scenarios' respective input-effectiveness (i.e. how effective the control effort is in producing ecological benefits under each scenario).

The costs are estimated based on modelled effort (Appendix B) and effort cost of the Control Program FY21/22 (Reef Authority, unpublished). Costs are expressed in 2022 real values (Australian Dollars)[1]. The total costs are comprised of the following components: costs of on-water days, cost of activity days, dive hour cost, cost of program management, and cost of other COTS monitoring and surveillance (Appendix A). Total costs were divided into variable cost (the first three cost components) and fixed cost (the last two cost components).

The risk and uncertainty associated with the benefits are captured to some degree by using the 20 model runs for each scenario simulated within ReefMod-GBR (Bozec and Mumby 2019)[2]. All cost-effectiveness estimates were expressed in terms of means across these 20 runs to be consistent with the results reported for project CCIP-R-04 (Skinner et al. 2024). Due to availability data limitations, risk and uncertainty surrounding the costs were not captured and no sensitivity analysis was performed. However, given that the cost estimates were based on real COTS control data this approach was deemed acceptable.

1.6 Data envelopment analysis

Data Envelopment Analysis (DEA) (e.g. Coelli et al. 2005; Bogetoft and Otto 2011) with a 7% discount rate was used to identify productive efficiency[3] gains of alternative COTS control scenarios. DEA is a mathematical programming method usually employed in a productivity analysis within an industry. It is more broadly used to estimate productive efficiency of individual companies but can also be applied to assessing outputs under management alternatives such as COTS control scenarios. Productive efficiency in this context is the extent to which a set of outputs (e.g. ecological benefit metrics) are being maximised given a set of inputs (e.g. control effort). That is, DEA enables maximising against more than one benefit metric generated across alternative control scenarios.

The productive efficiency measure indicates how well a particular scenario performs relative to others across multiple ecological benefit metrics: for example, *Coral Area Saved* and *Outbreaking Reefs Avoided* given control effort. A key advantage of DEA is that the individual outputs do not need to be measured in a common unit. That is, output measures of *Coral Area Saved* in hectares, for example, can be combined with number of *Outbreaking Reefs Avoided*, without the need for a common unit or index to be derived. The DEA

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[1] Values were adjusted for inflation using the Reserve Bank of Australia's inflation calculator (https://www.rba.gov.au/calculator/).

[2] No sensitivity analysis was undertaken in the ecological modelling performed in ReefMod-GBR.

[3] Productive efficiency depends on technical, scale, and cost efficiency. Since scale and costs are constant, productive efficiency refers to technical efficiency only.

specification applied in this project is a radial model assuming constant returns to scale. A radial model assumes that a contraction or expansion of inputs and outputs occurs proportionally. The concept of constant returns to scale means that an increase in input results in an equivalent increase in output. Examples of applications of DEA in an environmental context are discussed in Scheufele et al. (2022b).

The productive efficiency assessment was complemented by an assessment of implicit trade-offs across alternative COTS control scenarios with respect to different ecological benefits. The trade-off analysis was performed based on two-dimensional Production Possibility Frontiers. A production possibility frontier illustrates all possible output bundles generated by two goods (e.g. *Coral Area Saved* and *Outbreaking Reefs Avoided*) that can be produced with the available resources (e.g. control effort) and technology (e.g. manual culling under each scenario). All scenarios that produce output bundles that lie on the Production Possibility Frontiers are productively efficient. Even though any two scenarios that are located on the Production Possibility Frontiers are productively efficient, choosing one or the other implies a trade-off between any two ecological benefit metrics. These trade-offs were quantified in terms of opportunity costs at a 7% discount rate: for example, choosing scenario A over B implies an opportunity cost of x fewer hectares of *Coral Area Saved* for an additional y number of *Outbreaking Reefs Avoided*.

1.7 Cost-benefit analysis

The loss of hard coral on the GBR caused by COTS outbreaks generates costs (lost benefits), which implies that a prevention of hard coral loss through COTS control (e.g. *Coral Area Saved*) would represent a benefit. COTS control uses resources (e.g. labour, capital), which represents a cost. Hence, an allocation of resources that ensures an increase in net benefit requires an assessment of benefits and costs. Such an assessment of allocative efficiency is typically performed by a Cost-Benefit Analysis (CBA).

A social CBA provides a rigorous framework to identify, quantify, and compare the social benefits and social costs of a public investment projected over the time horizon of the assessment (e.g. Hanley and Barbier 2009, Campbell and Brown 2016, Boardman et al. 2018). ‘Social’ means that both private and public benefits and costs are included in the assessment (e.g. private benefits to tourism operators and public benefits to the Australian people more generally in knowing the GBR continues to exist in a healthy condition). For simplification, the term ‘social’ will be suppressed in the remainder of this report. Costs and benefits generated by management alternatives (e.g. COTS control scenarios) were assessed relative to a counterfactual (no COTS control). The generation of a net benefit (benefits less costs) represents a gain in allocative efficiency, which means that the public investment would make the Australian people as a whole better off. In comparison to productive efficiency, allocative efficiency takes people’s preferences (“what people want”) into account by estimating the value people derive from the generated ecological benefits (e.g. Frank 2014).

The CBA performed in this project was guided by the Economic Assessment Framework (Scheufele et al. 2022b) with the aims (i) to assess the extent and distribution of benefits and costs of the considered COTS control scenarios, (ii) to rank their relative performance in terms of allocative efficiency gains compared to the counterfactual, and (iii) to assess which of the considered COTS control scenarios maximises the net benefit given the available alternatives. The results of the CBA also provide information to assess trade-offs between allocative efficiency and other means objectives that underpin investment decisions such as equity across regions.

The alternative COTS control scenarios (see Section 2.1) were treated as mutually exclusive. The scope of the CBA was the Great Barrier Reef Marine Park. Only Australian residents have standing, which defines whose costs and benefits count. This is justified by the fact that the Control Program is funded by the Australian taxpayers. Given the UNESCO World Heritage Status, it is recognised that the condition of the GBR is of international interest. Furthermore, to our knowledge, no studies exist that estimated the economic value of non-use benefits associated with a marginal change in GBR coral condition enjoyed by the global community. Consequently, based on standing and the lack of data, the analysis does not include value estimates of non-use benefits enjoyed by the global community. Hence, it is acknowledged that the estimates are conservative from a global perspective.

All COTS control impacts that are considered desirable by people affected are classed as benefits, whereas all undesirable effects are costs. The impacts are valued in monetary terms to estimate changes in social surplus (surplus to society), which is the sum of consumer and producer surplus. Consumer surplus is the extra benefit consumers get when they buy something for less than they would have been willing to pay; producer surplus is the extra benefit producers get when they sell something for more than they would have been willing to accept (e.g. Frank 2014). A change in allocative efficiency is defined as the sum of changes in social surplus occurring through impacts in input, output, and secondary markets.

Costs of the alternative COTS control scenario options estimated in the project are based on market prices and assumed to reflect the opportunity cost of resource use from a society's perspective. Ideally, costs estimated from market prices are adjusted for any distortions (e.g. taxes and subsidies) so that more accurate shadow prices can be used. Shadow pricing refers to an adjustment of prices such that costs and benefits reflect their value to society as a whole. Using shadow prices was deemed unfeasible given the aggregate nature of the cost data.

Due to a lack of data, it is assumed that there are no adverse ecological impacts of COTS control that may generate costs. Similarly, adverse impacts of resource use (associated with fishing, tourism, and recreation) on coral reef condition are acknowledged but could not be quantified, let alone monetarised, due to a lack of data availability. The resources used in COTS research underpinning this CBA are classified as sunk cost. Sunk costs are costs that were incurred in the past and cannot be recovered (e.g. Frank 2014). Hence, they are irrelevant to any decision made in the present or the future. A justification is provided in the Economic Assessment Framework (Scheufele et al. 2022b).

As recommended by The Australian Government's Handbook of Cost-Benefit Analysis (Department of Finance and Administration 2006), the CBA presents Marginal Excess Tax Burden adjusted value estimates within the sensitivity analysis. The Marginal Excess Tax Burden refers to the cost of reduced surplus ('wasted benefit nobody gets') due to additional taxation used to fund interventions. More details on Marginal Excess Tax Burden are provided in the Economic Assessment Framework (Scheufele et al. 2022b).

The benefits were identified, and their economic value estimated, by first using the Coral Reef Index Model (CRIM) (Heneghan et al. 2025) to convert coral metrics estimated by ReefMod-GBR (Bozec and Mumby 2019) into indices (Reef Condition Index, Reef Tourism Index, Reef Fishing Index), which were subsequently used as inputs in the economic valuation component of the Coral Reef Economic Assessment Model (CREAM) (Scheufele et al. 2022a) developed under RRAP. The economic valuation component is based on benefit transfer, which was used to develop a predictive model of benefits associated with changes in condition of coral ecosystems in the GBR. Benefit transfer refers to the method of retrieving an economic value estimated in monetary terms from an original source study and applying it to a new policy context (e.g. Johnston et al. 2015).

The following benefit types were estimated in monetary terms using the economic valuation component of CREAM:

- Tourism benefits:
  Tourism benefits are generated by scuba-diving, snorkelling, and coral viewing trips offered by commercial tour operators (a subset of the tourism industry) on coral reefs of the GBR and enjoyed by visitors and locals.

- Commercial fishing benefits:
  Commercial fishing benefits are generated by fish catch bought and sold in domestic and export markets. Given the focus on coral reef ecosystems, only coral reef dependent catch was included in the valuation.

- Recreational fishing benefits:
  Recreational fishing benefits are generated by recreational fishing trips. Given the focus on coral reef ecosystems, only recreational fishing trips targeting coral reef dependent species are included in the valuation.

- Charter fishing benefits:
  Charter fishing benefits are generated by charter fishing trips. Given the focus on coral reef ecosystems, only charter fishing trips targeting coral reef dependent species are included in the valuation.

- Non-use benefits:
  Non-use benefits are generated by *Healthy Coral Reef Habitat* which people seek to preserve for themselves or others in the future (generating option benefits), for future generations for whatever reason (generating bequest and altruistic benefits), or for their non-use qualities (generating existence benefits).

The following benefit types were identified and/or specified but not quantified nor estimated in monetary terms due to data limitations and methodological challenges: benefits to Aboriginal and Torres Strait Islanders, cultural benefits, education and training benefits, and benefits generated within non-coral habitats (e.g. seagrass, mangroves).

All benefits and costs were discounted over the specified time horizon (2022–2040) to a chosen base year (2022) using real annual discount rates (7% for base case, 3% and 10% for sensitivity analysis) as recommended by the CBA guidance note of the Office of Best Practice Regulations (2020). Present Value of Net Benefit is calculated by subtracting

Present Value of Costs from the Present Value of Benefits. Additionally, Equivalent Annual Net Benefit estimates are reported. They are derived by spreading the Present Value of Net Benefit evenly across each year of the simulated time horizon. Furthermore, we report a Benefit-Cost Ratio, which indicates the return of investment: for every $1 spent, the investment is expected to return $x in benefits.

We note that the specified time horizon implicitly assumes that the alternative COTS control scenarios were implemented from 2019 onwards. However, due to the specification requirements of the Coral Reef Economic Assessment Model (CREAM), benefits could only be estimated in monetary terms from 2022 onwards.

Costs and benefits are expressed in 2022 real values (Australian Dollars) and expressed in terms of medians to capture potential effects of skewed distributions.

A Monte Carlo Simulation was used in the CBA to account for uncertainty in the value of input variables (e.g. tourism industry profit rates, population projections, non-use value) that underpin the estimation of benefit. Instead of using single-point value estimates (e.g. one fixed profit rate), it runs thousands of simulations using a range of possible values for these input variables — generating a probabilistic distribution of possible outcomes. Input variables used to estimate cost were kept fixed. This study used 2,000 simulations to produce a probability distribution of the Present Value of Net Benefits for each scenario. This captures some of the uncertainty associated with the ecological model ReefMod-GBR, the Coral Reef Index Model (CRIM), and the Coral Reef Economic Assessment Model (CREAM) estimates. The risk of a COTS control generating a negative Present Value of Net Benefit (a loss to the Australian people) is then captured as the product of probability and impact (here Present Value of Net Benefit) to provide the risk profiles of the alternative investments (here scenarios). The risk profile shows the probability of a loss (negative Present Value of Net Benefit) and the extent of the expected loss in monetary terms ($). We acknowledge that the assumed probability distributions and impacts are surrounded themselves by a high level of uncertainty.

Despite best efforts, it was not possible to capture the full range of risk and uncertainty given severe data limitations. Some of the uncaptured sources of risk and uncertainty might have a substantial impact on the results. This high level of risk and uncertainty should be taken into account when making investment decisions. All assumptions underpinning the benefit valuation using CREAM are listed in Scheufele et al. (2022a). A sensitivity analysis was performed that assessed the change in the Present Value of Net Benefit due to a change in the magnitude of variables that were surrounded by a high level of uncertainty and have a substantial impact on the Present Value of Net Benefit. The sensitivity analysis focused on profit rates earned by operators underpinning tourism benefits and the inclusion/exclusion of Marginal Excess Tax Burden in the cost estimations.

Whether or not scenarios differ in terms of the ecological metrics (*Coral Area Saved*, *Outbreaking Reefs Avoided*, *COTS Density Reduced*, *Healthy Coral Habitat Maintained*) and Present Value of Net Benefit was tested using the Games-Howell test of pairwise comparisons of differences in means. The term ‘different’ refers to ‘statistically significantly different at the 5% significance level’ throughout the report.

1.8 Stakeholder engagement

The COTS control scenarios were developed in collaboration with key stakeholders (Reef Authority, GBRF) through the circulation of an input document and several workshops, as well as informal discussions and conversations during other meetings to ensure they were targeted at stakeholders needs. These engagements provided valuable information on stakeholders' priorities, concerns, and sensitivities as well as invaluable technical insights, which have been used in the implementation of the control scenarios into ReefMod-GBR.

Several meetings with the Reef Authority and the Director of CCIP were held to discuss the input cost data from on-water operators. The development of the cost models included discussing, socialising, and recording the limitations and required assumptions with the Reef Authority.

These conversations and discussions also allowed us to socialise our methods and build capability in end-users to understand the methods and approaches that are used to assess cost-effectiveness, productive efficiency and trade-offs, and allocative efficiency. This understanding will be vital to support the uptake and adoption of the research outcomes into management decisions.

The presentation of preliminary results of scenario assessments, as well as discussions during the annual CCIP Workshop in Townsville in November 2023, an online workshop in January 2024, and the Reef Resilience Symposium in Cairns in March 2024, generated feedback and ideas that were incorporated into the economic assessment.

1.9 Ethics approvals

Ethics approval was obtained from CSIRO Human Research Ethics for the project "Platform for identifying effectiveness, cost-effectiveness, and efficiency gains of manual Crown-of-Thorns Starfish (COTS) control" (054/23).

2. RESULTS

2.1 Overview of ecological benefits

Table 2 provides an overview of the four ecological benefits estimated under each scenario for all reefs (i.e. Target, Priority, and Non-Priority), expressed in terms of undiscounted annual means aggregated over the modelling time horizon (2019 to 2040)[4]. The aggregated *Coral Area Saved* and *Healthy Coral Habitat Maintained* for the GBR-wide scenario (R_GBR) converts to an average annual gain of about 0.5% and 1% of the total coral habitat area of the 1,384,244 hectares modelled in ReefMod-GBR, respectively.

The results suggest that the scenarios which perform best differ depending on the benefit metric of interest. When considering the fifteen primary scenarios, the three that perform best

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[4] Note that *Coral Area Saved*, *Outbreaking Reefs Avoided*, and *COTS Density Reduced* were estimated for 2019–2040, whereas *Healthy Coral Habitat Maintained* was estimated from 2022–2040 due to CREAM specification requirements. However, given the small extent of benefits estimated from 2019–2021, ignoring this discrepancy is unlikely to result in changes of relevance in practical terms.

to maximise *Coral Area Saved* are the GBR-wide (R_GBR) and the two Effort Sink (ES_HC and ES_HC_CC) scenarios. Maximising *Outbreaking Reefs Avoided* is achieved by the Regional Far North (R_FN) scenario, while Outbreak Front All Reefs (OF_AR) outperforms any other scenario in maximising *COTS Density Reduced*. We note that the scenarios aiming to maximise *Coral Area Saved* generate the least benefits with respect to *COTS Density Reduced*, and vice versa. The best performing scenarios to maximise the *Healthy Coral Habitat Maintained* are the Protection Status Unprotected (P_UNP) and one of the Effort Sink scenarios (ES_HC_CC), followed by Regional Far North/North (R_FNN) and the other Effort Sink scenario (ES_HC). The three connectivity scenarios, if added to the consideration set, are also promising scenarios if maximising *Coral Area Saved* or *Healthy Coral Habitat Maintained* is the main objective. They perform poorly, though, if *Outbreaking Reefs Avoided* or *COTS Density Reduced* are the focus of COTS management.

More detailed information on these results and their interpretation is available in Skinner et al. (2024) and not repeated here given the economic assessment focus of this report.

Table 2. Benefits of alternative COTS control scenarios estimated in terms of undiscounted annual means aggregated over the modelling time horizon (2019 to 2040).

Green figures represent the best performing scenarios. The R_GBR scenario most closely resembles the current Control Program.

Scenario Group	Scenario	Coral Area Saved (ha)	Outbreaking Reefs Avoided (#)	COTS Density Reduced (#/400 m^2)	Healthy Coral Habitat Maintained (ha)
Effort Sink	ES_HC	**147,604**	535	209	1,493,071
	ES_HC_CC	**148,242**	535	212	**1,755,827**
Outbreak Front	OF_AR	14,880	252	**1,333**	125,611
	OF_LAT	97,733	336	235	818,594
	OF_PR	120,796	481	556	673,584
Protection Status	PS_P	50,677	439	437	258,840
	PS_UNP	107,420	459	225	**1,778,103**
Regional	R_C	47,930	671	454	311,904
	R_CS	68,694	766	399	731,074
	R_FN	53,682	**1,052**	331	1,153,230
	R_FNN	93,631	315	213	1,494,471
	R_GBR	**144,860**	544	218	864,927
	R_N	91,002	170	259	922,174
	R_NC	94,300	200	222	995,239
	R_S	51,567	822	520	425,561
Connectivity	C_COTS_CC	142,514	659	295	1,661,922
	C_COTS_CC_P	132,470	677	314	1,561,161
	C_COTS_CC_UNP	135,972	707	308	1,441,124

2.2 Cost-effectiveness

To make intervention options comparable, costs and benefits in this study have been discounted to account for the timing of the benefit generation. To illustrate the rationale behind discounting, **Figure 3** shows results of undiscounted cost-effectiveness for *Coral Area Saved* plotted against time across a range of scenarios selected for demonstrative purposes (ribbons represent 95% confidence intervals). The following example illustrates the need to discount costs and benefits in the Cost-Effectiveness Analysis. The cost-effectiveness is low (little benefit for a lot of money) in the first few years but increases at an increasing rate until the scenarios exhibit more erratic behaviour. That is, the value-for-money first improves and then varies with COTS control effort over time. While most scenarios show a similar pattern, some scenarios generate benefits earlier than others (e.g. C_COTS_CC compared to OF_PR). Applying discounting ensures that the timing of the benefit generation is taken into account. It captures the fact that most people value benefits more highly when received in the present than the future ('people prefer to get things now rather than in the future').

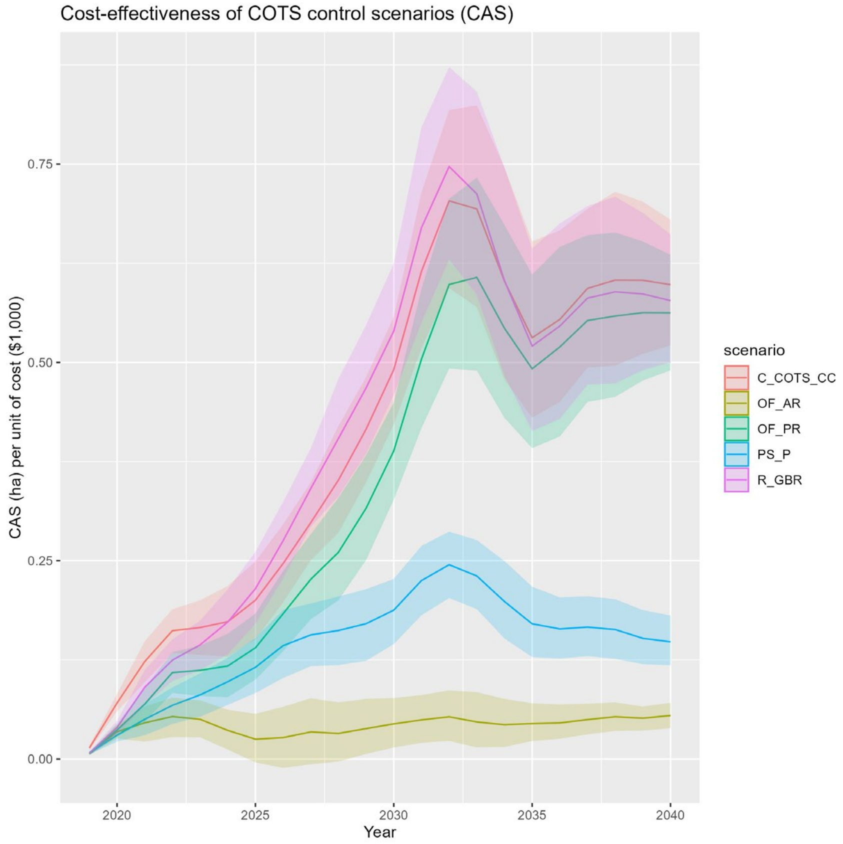

Figure 3. Selected undiscounted cost-effectiveness of *Coral Area Saved* plotted against time.

2.2.1 Primary scenarios

The fifteen primary scenarios are grouped into Regional, Effort Sink, Protection Status and Outbreak Front.

The mean relative cost-effectiveness scores for the ecological benefit metrics *Coral Area Saved*, *Outbreaking Reefs Avoided*, and *COTS Density Reduced* across the fifteen primary scenarios are presented in **Figure 4**[5]. Cost-effectiveness scores closer to one indicate greater value for money (e.g. lower cost relative to benefit achieved). These scores provide an indication of the value for money achieved by each scenario, with larger scores indicating greater benefit per $ spent. The data suggests, for example, that the scenario focusing COTS control effort in the Central and South regions (R_CS) would only achieve about half of the cost-effectiveness when considering the metric *Coral Area Saved* (i.e. coral area saved per $ spent) compared to one of the best performing scenarios that invests COTS control effort across the whole GBR (R_GBR) and most closely resembles the current Control Program. Looking at *Outbreaking Reefs Avoided*, the best performing scenario focuses control effort on the Far North (R_FN), which is twice as cost-effective than the GBR-wide control scenario (R_GBR). The cost-effectiveness of the *COTS Density Reduced* metric is maximised under a scenario that follows the Outbreak Front across All Reefs (OF_AR), although this strategy performs poorly for other metrics. The performance ranking does not change which scenarios perform best for *Coral Area Saved* and *COTS Density Reduced* if the considered benefits are restricted to Priority Reefs. Yet, the ranking does change for the cost-effectiveness of *Outbreaking Reefs Avoided*. Assessing only Priority Reefs, the best performing scenarios to maximise *Outbreaking Reefs Avoided* per $ spent are the Central South (R_CS) followed by the two Effort Sink scenarios (ES_HC_CC and ES_HC) (Appendix C). When focusing on the metric of *Healthy Coral Habitat Maintained* (**Figure 5**), the data suggest that the GBR-wide control scenario (R_GBR) is only half as cost-effective compared to the best performing scenarios, which have control effort focused on unprotected reefs where fishing is allowed (PS_UNP) or a strategy where effort sink reefs are avoided unless they have more than 20% coral cover (ES_HC_CC).

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[5] The interpretation of the results did not change when using undiscounted benefits and costs. This is not surprising given the costs are kept constant across time and strategies and the benefits follow a similar temporal trajectory under all strategies.

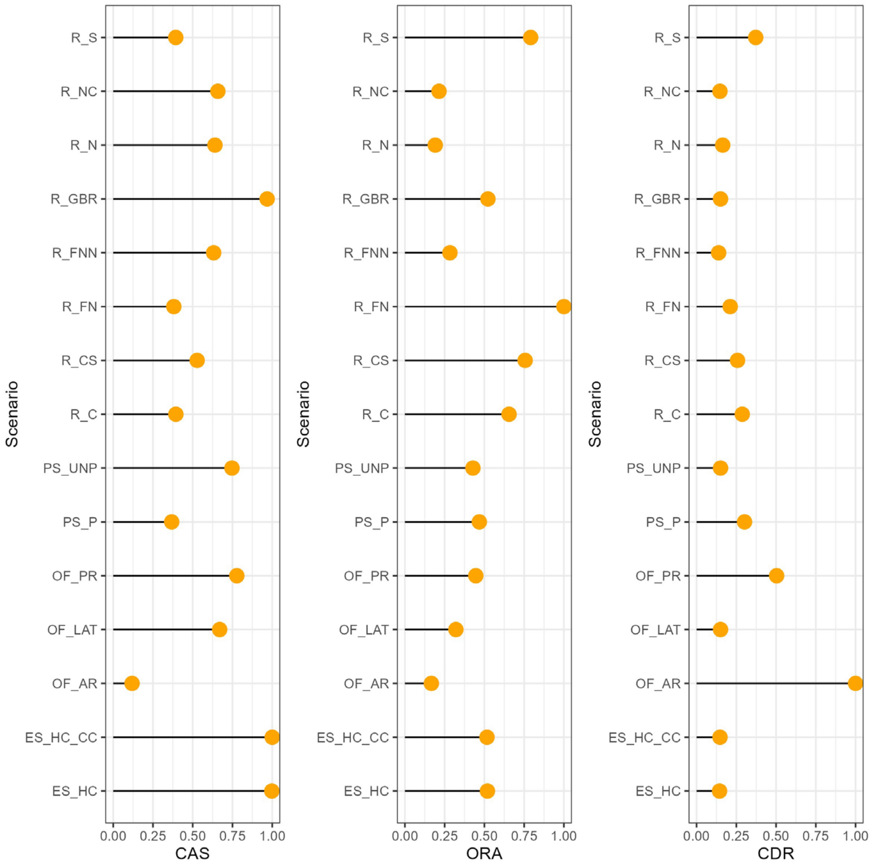

Figure 4. Mean relative cost-effectiveness scores across *Coral Area Saved* (CAS), *Outbreaking Reef Avoided* (ORA), and *COTS Density Reduced* (CDR).

Cost-effectiveness scores closer to 1 indicate greater value for money (e.g. lower cost relative to benefit achieved). The R_GBR scenario most closely resembles the current Control Program.

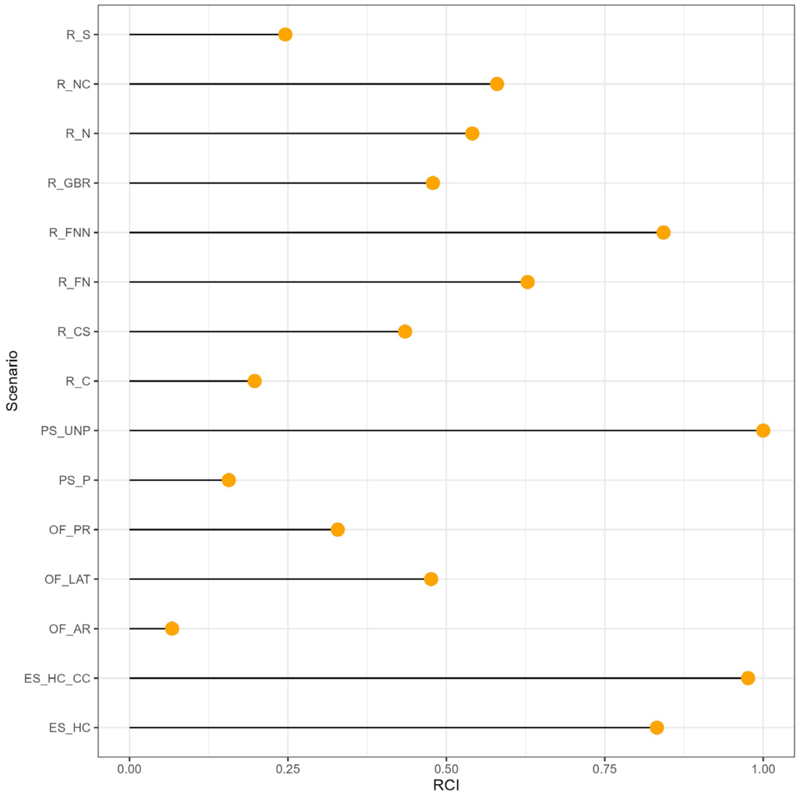

Figure 5. Mean relative cost-effectiveness of the *Healthy Coral Habitat Maintained* (RCI) metric.

Cost-effectiveness scores closer to 1 indicate greater value for money (e.g. lower cost relative to benefit achieved). The R_GBR scenario most closely resembles the current Control Program.

The mean cost-effectiveness ($/ha and ha/$1,000) for *Coral Area Saved* for scenarios that consider all reefs across the GBR are shown in **Table 3**. The results for scenarios when restricted to Priority Reefs only are presented in Appendix C. The annual cost per hectare ranges from Effort Sink High COTS and Coral Cover (ES_HC_CC) costing $3,046/ha ($2,813/ha–$3,321/ha)[6] to Outbreak Front All Reefs (OF_AR) costing $25,670/ha ($17,004/ha–$52,340/ha). The cost per hectare under the GBR-wide scenario (R_GBR), the third best performing scenario, is $3,146 ($2,904/ha–$3,432/ha)[7]. If it is assumed that a linear increase in effort under the scenario following the Outbreak Front All Reefs (OF_AR) could achieve a linear increase in gains, additional spending of about $71M per year (on average) would be required to achieve the same amount of *Coral Area Saved* as generated under R_GBR. However, using the means alone to draw conclusions about scenario performance may be misleading given large differences in variability in their cost-effectiveness. This variability is indicated by the Coefficient of Variation (CV) based on the 20 simulation runs provided by ReefMod-GBR. A low variability indicates a lower level of uncertainty (given the true distribution of cost-effectiveness is unknown): the probability of a scenario achieving a cost-effectiveness that deviates from the estimated mean is lower compared to scenarios with a higher variability.

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[6] 95% confidence interval in brackets.

[7] The undiscounted mean cost-effectiveness is estimated at $2,457 ha^{-1} year^{-1}.

The variability ranges from ES_HC_CC (0.18) to OF_AR (1.09). The data suggests that the scenarios with the lowest variability (CV = 0.18) are the scenarios that generated the most *Coral Area Saved*: both Effort Sink scenarios and GBR-wide control scenario (R_GBR). **Figure 6** shows the distributions of cost-effectiveness. While the cost-effectiveness estimates of these top three scenarios are not different from each other (Games-Howell: p-value > 0.05), they are different from all other scenarios (p-value ≤ 0.05)[8]. This indicates that these three scenarios are the most and equally cost-effective with the lowest variability.

Looking at Outbreaking Reef Avoided, the most cost-effective are the scenarios where COTS control is focused in the Far North (R_FN) and South (R_S) (Appendix C). The variability of cost-effectiveness is lower for R_S (CV = 0.18) than that of R_FN (CV = 0.26). If any of these two scenarios were implemented, the estimated annual mean costs would range between $392,718 (R_FN) and $496,412 (R_S) per *Outbreaking Reef Avoided*. In comparison, maximising *Outbreaking Reefs Avoided* under the GBR-wide scenario (R_GBR) was estimated to be almost two times as costly ($752,062 per *Outbreaking Reef Avoided*).

If minimising the cost of reducing COTS densities is the management goal, then following the outbreak front (OF_AR) is the single most cost-effective scenario (Appendix C), but this scenario is the most costly in maximising *Outbreaking Reefs Avoided* and *Coral Area Saved*.

The mean cost-effectiveness estimates (ha/$1,000 or $/ha) using the *Healthy Coral Habitat Maintained* metric, when considering all reefs across the GBR are shown in **Table 4**. The annual cost per hectare of *Healthy Coral Habitat Maintained* range from $171/ha ($168–$175) for the scenario where COTS control is undertaken only on unprotected reefs where fishing takes place (PS_UNP) to $2,548/ha ($2,432–$2,676)[9] for the scenario where COTS control follows the outbreak front (OF_AR). The annual cost per hectare of *Healthy Coral Habitat Maintained* under the GBR-wide scenario (R_GBR, rank 8) is $357/ha ($351–$365). The variability of the cost-effectiveness estimates is indicated by the Coefficient of Variation, based on the 2,000 simulations generated by the Coral Reef Index Model (CRIM). The variability ranges from 0.4 for the scenario that avoids effort sinks unless they have more than 20% coral cover (ES_HC) to 1.09 for the Outbreak Front All Reefs scenario (OF_AR). The Coefficient of Variation suggests that the scenario that exhibits the lowest variability (0.40) is ES_HC. The GBR-wide scenario (R_GBR) has a Coefficient of Variation of 0.45. The distributions of the cost-effectiveness estimates are illustrated in **Figure 7**. The scenarios where COTS control is undertaken on unprotected reefs (PS_UNP) or avoided on effort sink reefs unless they have high coral cover (ES_HC_CC) generate the largest area *Healthy Coral Habitat Maintained* per $1,000 and while not different from each other (Games-Howell: p-value > 0.05), they differ from any other scenario (Games-Howell: p-values ≤ 0.05). Hence, they are the most and equally cost-effective scenarios when it comes to maximising this metric at the given budget.

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[8] We note that R_GBR and ES_HC are also not different from OF_PR (p-value > 0.05). However, the variability of OF_PR is larger (0.26) than that of R_GBR and ES_HC (0.18).

[9] 95% confidence interval in brackets.

Table 3. Cost-effectiveness: *Coral Area Saved*.

Cost-effectiveness is reported as annual $ per hectare and hectares per $1,000. Green and red figures represent the best and worst performing scenarios, respectively. The R_GBR scenario most closely resembles the current Control Program.

Rank	Scenario	$/ha each year	ha/$1,000 each year	Coefficient of Variation
1	ES_HC_CC	**3,046**	**0.33**	**0.18**
2	ES_HC	**3,053**	**0.33**	**0.18**
3	R_GBR	**3,146**	**0.32**	**0.18**
4	OF_PR	3,919	0.26	0.26
5	PS_UNP	4,078	0.25	0.20
6	OF_LAT	4,549	0.22	0.29
7	R_NC	4,628	0.22	0.25
8	R_N	4,759	0.21	0.24
9	R_FNN	4,821	0.21	0.29
10	R_CS	5,771	0.17	0.31
11	R_C	7,731	0.13	0.31
12	R_S	7,744	0.13	0.49
13	R_FN	7,993	0.13	0.50
14	PS_P	8,283	0.12	0.37
15	OF_AR	**25,670**	**0.04**	**1.09**
	C_COTS_CC	3,186	0.31	0.19
	C_COTS_CC_UNP	3,423	0.29	0.21
	C_COTS_CC_P	3,545	0.28	0.22

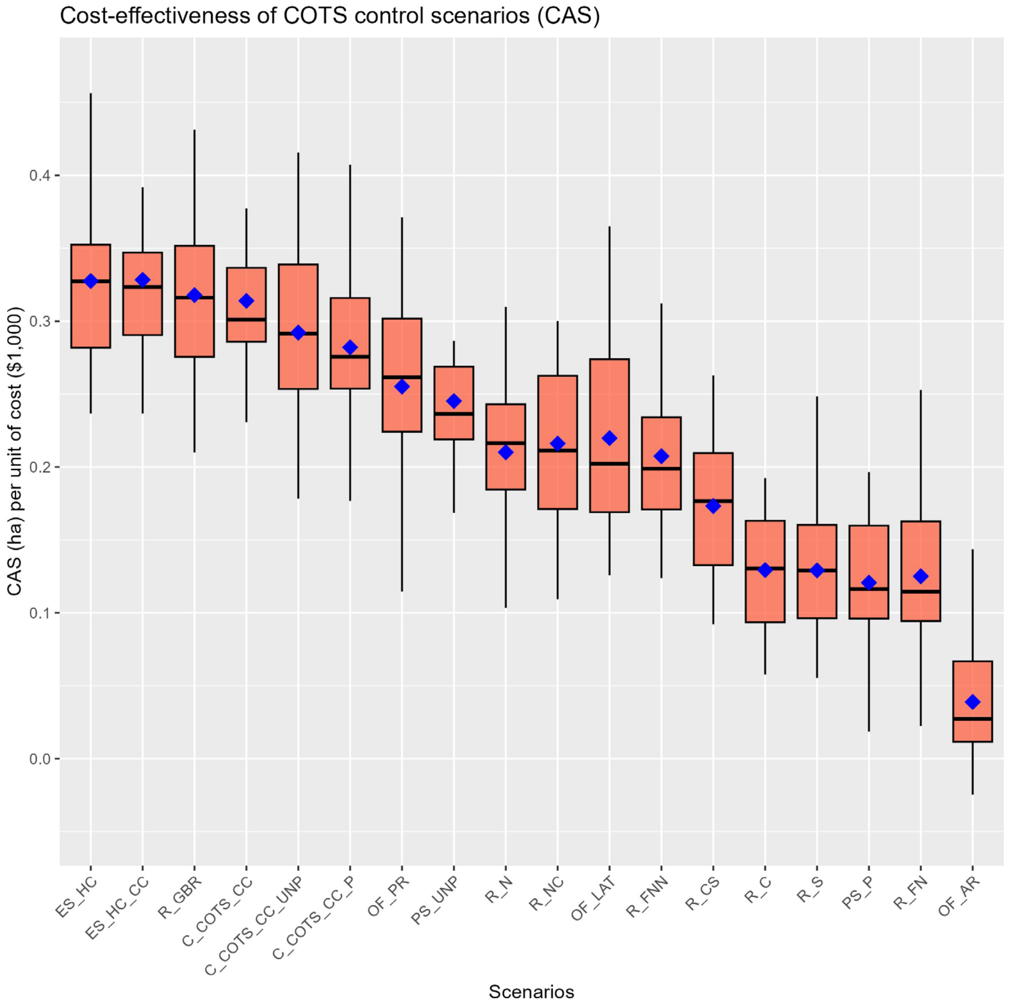

Figure 6. Boxplot of distributions of cost-effectiveness estimates: *Coral Area Saved* (CAS).

Mean values are indicated by the blue diamonds in each box. The R_GBR scenario most closely resembles the current Control Program.

Table 4. Cost-effectiveness: *Healthy Coral Habitat Maintained* (based on the Reef Condition Index).

Cost-effectiveness is reported as annual $ per hectare and hectares per $1,000. Green and red figures represent the best and worst performing scenarios, respectively. The R_GBR scenario most closely resembles the current Control Program.

Rank	Scenario	$/ha	ha/$1,000	Coefficient of Variation
1	PS_UNP	**171**	**5.84**	0.44
2	ES_HC_CC	**175**	**5.70**	0.42
3	R_FNN	203	4.92	0.46
4	ES_HC	206	4.86	**0.40**
5	R_FN	272	3.67	0.48
6	R_NC	295	3.39	0.44
7	R_N	316	3.16	0.45
8	R_GBR	357	2.80	0.45
9	OF_LAT	360	2.78	0.46
10	R_CS	394	2.54	0.42
11	OF_PR	521	1.92	0.46
12	R_S	696	1.44	0.49
13	R_C	867	1.15	0.58
14	PS_P	1,092	0.92	0.67
15	OF_AR	**2,548**	**0.39**	**1.09**
	C_COTS_CC	190	5.27	0.38
	C_COTS_CC_P	201	4.99	0.37
	C_COTS_CC_UNP	216	4.62	0.36

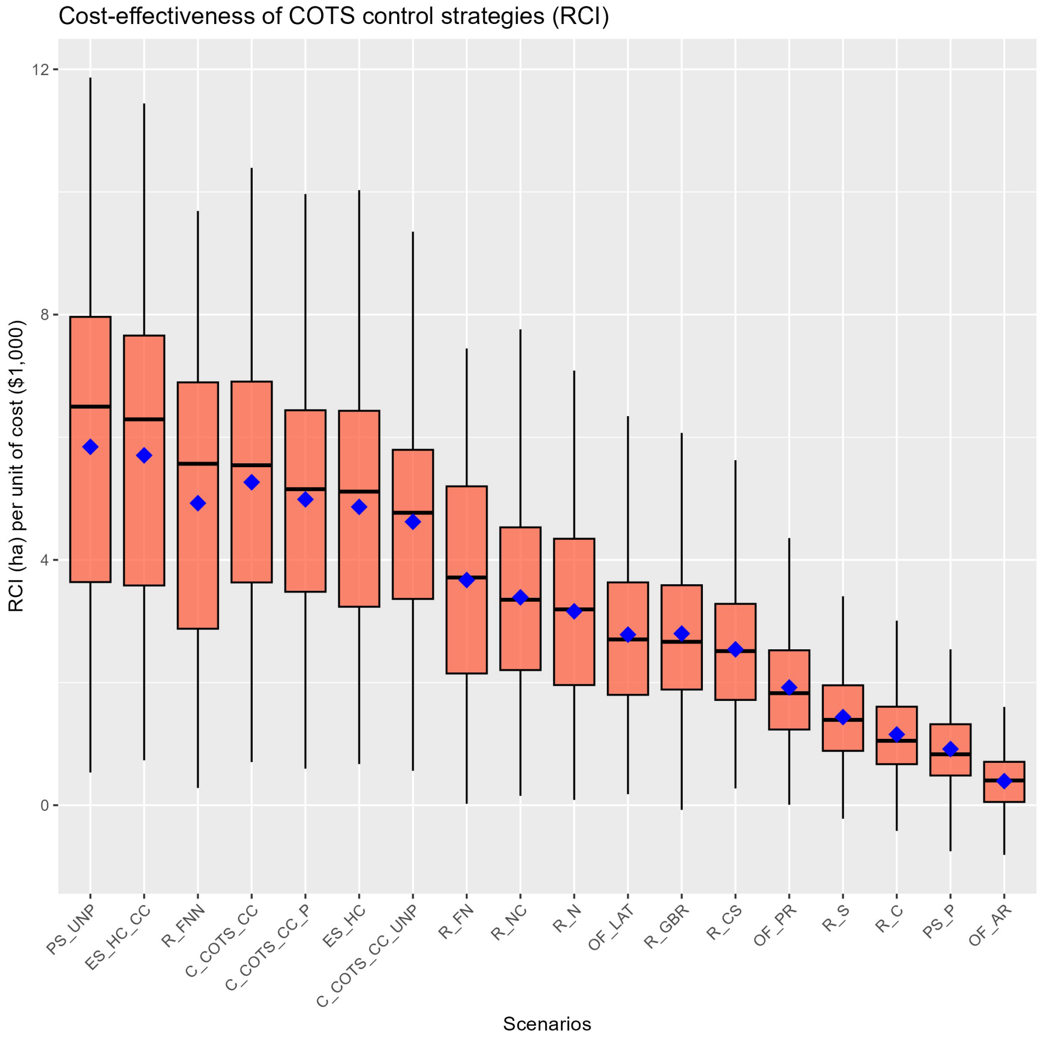

Figure 7. Boxplot of distributions of cost-effectiveness estimates: *Healthy Coral Habitat Maintained* (RCI). Mean values are indicated by the blue diamonds in each box. The R_GBR scenario most closely resembles the current Control Program.

2.2.2 Secondary scenarios

The three secondary scenarios belong to the Connectivity scenario group.

Overall, the three connectivity scenarios performed well in terms of maximising *Coral Area Saved* per unit cost (**Table 3, Figure 6**). The top performing connectivity scenario focusing COTS control on reefs with high COTS larval output (C_COTS_CC) achieved a cost of $3,186/ha ($2,939/ha–$3,447/ha)[10]. This scenario was equally as cost-effective as the best performing scenarios for this metric (e.g. the two effort sink scenarios and the GBR-wide scenario) (Games-Howell: p-values ≤ 0.05). Scenarios that also considered a reef's protection status (C_COTS_CC_P or C_COTS_CC_UNP) were less cost-effective in comparison (Games-Howell: p-values > 0.05). All three Connectivity scenarios are poor performers relative to scenarios identified as best performers to maximise *Outbreaking Reefs Avoided* and *COTS Density Reduced* per unit cost (Appendix C). Looking at maximising

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[10] 95% confidence interval in brackets.

Healthy Coral Habitat Maintained per unit of cost, none of the three Connectivity scenarios outperform the best primary scenarios (**Table 4**, **Figure 7**).

2.3 Productive efficiency and trade-offs

2.3.1 Primary scenarios

The fifteen primary scenarios are grouped into Regional, Effort Sink, Protection Status and Outbreak Front.

The Production Possibility Frontier for all fifteen primary scenarios, with respect to mean values of *Coral Area Saved* and *Outbreaking Reefs Avoided* is presented in **Figure 8**. The red points indicate the relative position of each scenario relative to the Production Possibility Frontier (dashed red line). Only the scenarios that are directly on or close to the Production Possibility Frontier as well as the least productively efficient scenario are labelled. The scenarios that are productively efficient at their means are located directly on the Production Possibility Frontier; these are the scenarios that avoid Effort Sinks No Coral Exception (ES_HC) and focus control effort on the Far North (R_FN). Close to the Production Possibility Frontier are also the GBR-wide control scenario (R_GBR) and the scenario that avoids effort sinks unless they have more than 20% coral cover (ES_HC_CC). All other scenarios are inefficient in jointly producing *Coral Area Saved* and *Outbreaking Reefs Avoided*. The worst performing scenario is the one that follows the Outbreak Front All Reefs (OF_AR), which is the furthest away from the Production Possibility Frontier. If the analysis is restricted to Priority Reefs, while ES_HC remain productively efficient, the Far North scenario (R_FN) is replaced by one that focuses control in the Central and Southern GBR (R_CS).

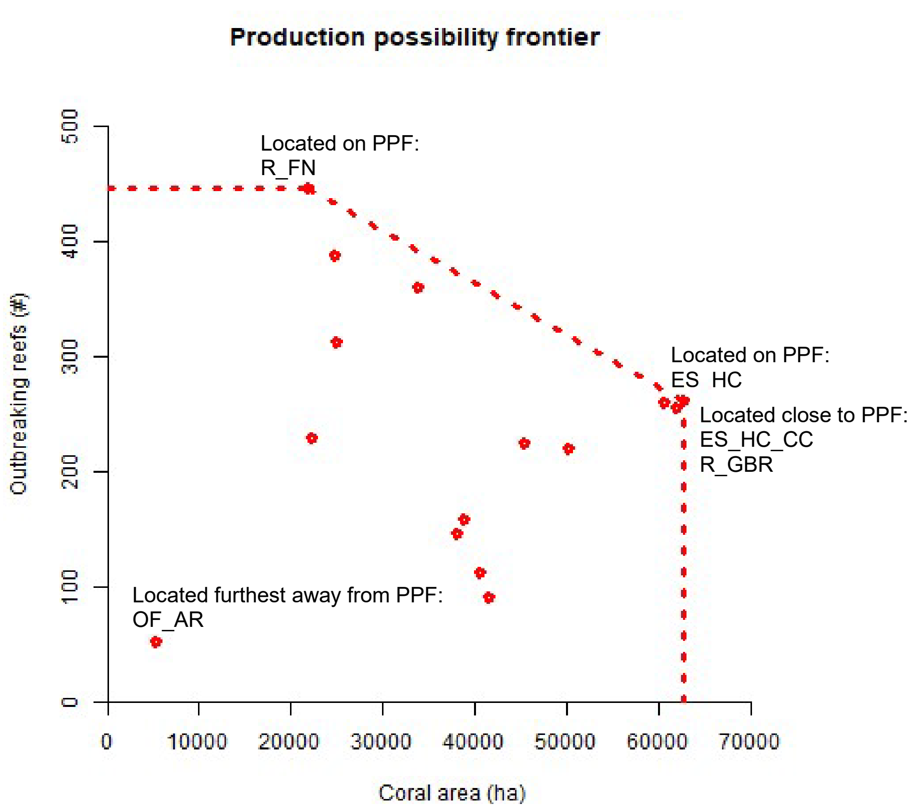

Figure 8. Production Possibility Frontier (PPF) of *Coral Area Saved* against *Outbreaking Reefs Avoided*.

The red points indicate the relative position of each scenario relative to the PPF (dashed line). The further they are away from the PPF, the less productively efficient they are.

Data Envelopment Analysis was used to estimate productive efficiency scores when maximising against more than one benefit metric. The distribution of these scores with the goal of maximising *Coral Area Saved* and *Outbreaking Reefs Avoided* jointly when considering all reefs across the GBR is shown in **Figure 9**.

There are five scenarios that have the highest productive efficiency scores – the two Effort Sink scenarios, the GBR-wide scenario (R_GBR), following the Outbreak Front on Priority Reefs (OF_PR), and focusing control effort on the Far North (R_FN). These scenarios are not different from each other (Games-Howell: p-values > 0.05) but the two Effort Sink scenarios are different from all other eleven scenarios (Games-Howell: p-value ≤ 0.05). This suggests that the two Effort Sink scenarios perform the best overall in terms of maximising jointly *Coral Area Saved* and *Outbreaking Reefs Avoided* at the given control budget, and these two scenarios along with the GBR-wide scenario exhibit lower variabilities than the other two in the top performing group. However, the implicit trade-offs are different across some of these five scenarios.

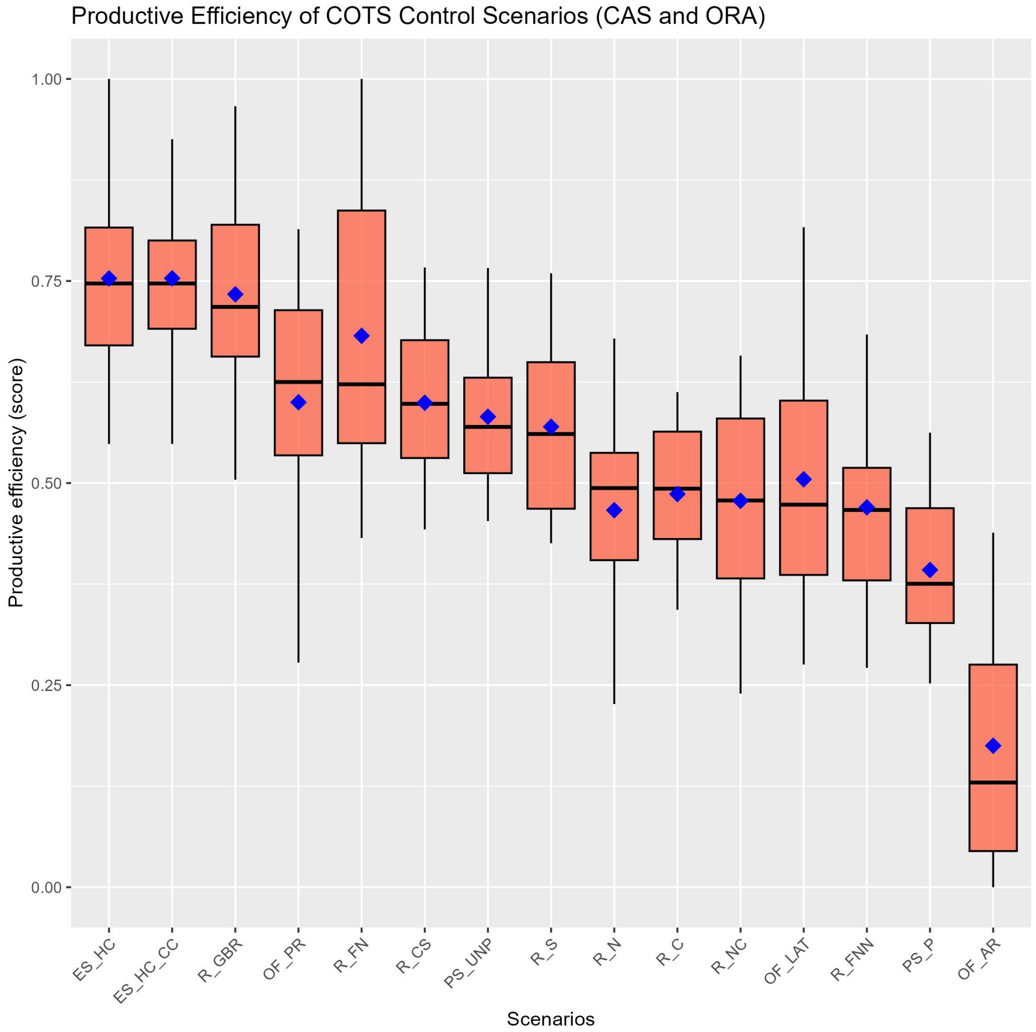

Figure 9. Boxplot of distributions of productive efficiency scores of *Coral Area Saved* (CAS) and *Outbreaking Reefs Avoided* (ORA)**.**

Mean values are indicated by the blue diamonds in each box. The R_GBR scenario most closely resembles the current Control Program.

The opportunity costs associated with these trade-offs are shown in **Table 5** for two of the top performing scenarios, which also exhibit the largest trade-offs (GBR-wide and Far North). Given the other top performers (the two Effort Sink scenarios) and the GBR-wide scenario are not different from each other (Games-Howell: p-value ≤ 0.05), presenting trade-offs between them may be misleading. Implementing focused control effort in the Far North (R_FN) instead of a GBR-wide strategy (R_GBR) would result in 36,908 hectares less *Coral Area Saved* and would cost an additional $4,847 per hectare compared to implementing R_GBR. Vice versa, implementing a GBR-wide strategy (R_GBR) instead of a focused effort in the Far North (R_FN) would result in 233 less *Outbreaking Reefs Avoided* and would cost an additional $359,345 per reef compared to implementing R_FN. The opportunity cost in terms of trading off one biological benefit against the other would be 158 hectares of *Coral Area Saved* per *Outbreaking Reef Avoided*.

Table 5. Opportunity cost of trade-offs between scenarios for *Coral Area Saved* and *Outbreaking Reefs Avoided*.

Scenario	Coral Area Saved (ha)	Outbreaking Reef Avoided (#)	Cost ($) per ha	Cost ($) per reef	Ha per reef
Far North vs GBR-wide (15 scenarios)	-36,908	233	4,847	-359,345	158
Far North vs COTS Larval Connectivity (18 scenarios)	-38,914	236	4,947	-367,928	165

2.3.2 Secondary scenarios

The three secondary scenarios belong to the Connectivity scenario group.

Including the Connectivity scenarios in the assessment (looking at all eighteen scenarios) changed their relative productive efficiency and inherent trade-offs. Keeping in mind the uncertainty inherent in real-world implementation of the three Connectivity scenarios, the analysis suggests that the three Connectivity scenarios are not different from the most productive and equally productive primary scenarios (Games-Howell: p-values > 0.05). If the analysis is restricted to Priority Reefs, the Far North scenario (R_FN) is no longer productively efficient as was the case in the primary scenario assessment that excluded the Connectivity scenarios. The opportunity costs between the two top performers with the largest trade-offs (Far North and COTS Larval Connectivity) when all eighteen scenarios are assessed are shown in **Table 5**. Implementing focused control effort in the Far North (R_FN) instead of a scenario where COTS control is focused on reefs with predicted high COTS Larval Connectivity (C_COTS_CC), would result in 38,914 hectares less *Coral Area Saved* and would cost an additional $4,974 per hectare compared to implementing C_COTS_CC. Vice versa, implementing C_COTS_CC instead of a focused effort in the Far North (R_FN) would result in 236 less *Outbreaking Reefs Avoided* and would cost an additional $367,928 per reef compared to implementing R_FN.

2.4 Allocative efficiency

2.4.1 Primary scenarios

The fifteen primary scenarios are grouped into Regional, Effort Sink, Protection Status and Outbreak Front.

The Present Value of Net Benefit (annual net benefit discounted and aggregated over the time horizon 2022-2024) is presented in terms of medians rather than means, given the skewed distributions of the modelled estimated Present Value of Net Benefit. This is illustrated for the GBR-wide scenario (R_GBR) as an example in **Figure 10**. It shows the probability distributions of 2,000 Monte Carlo simulations of the Present Value of Net Benefit for the GBR-wide scenario and reports its median and mean. This probability distribution illustrates the uncertainty surrounding median and mean of the Present Value of Net Benefit. Blue and red bars indicate positive and negative values, respectively. Given that the number of bars in the illustration does not capture all 2,000 simulations individually, the bar around zero is blue-red stacked. Even though the GBR-wide scenario shows a widespread distribution (indicating a high level of uncertainty), about 98% percent of the simulations generated a positive Present Value of Benefit. Consequently, only about 2% resulted in a negative Present Value of Net Benefit (a loss) of about $1.05M. This means the results suggest that implementing the GBR-wide scenario carries a low risk to the Australian people.

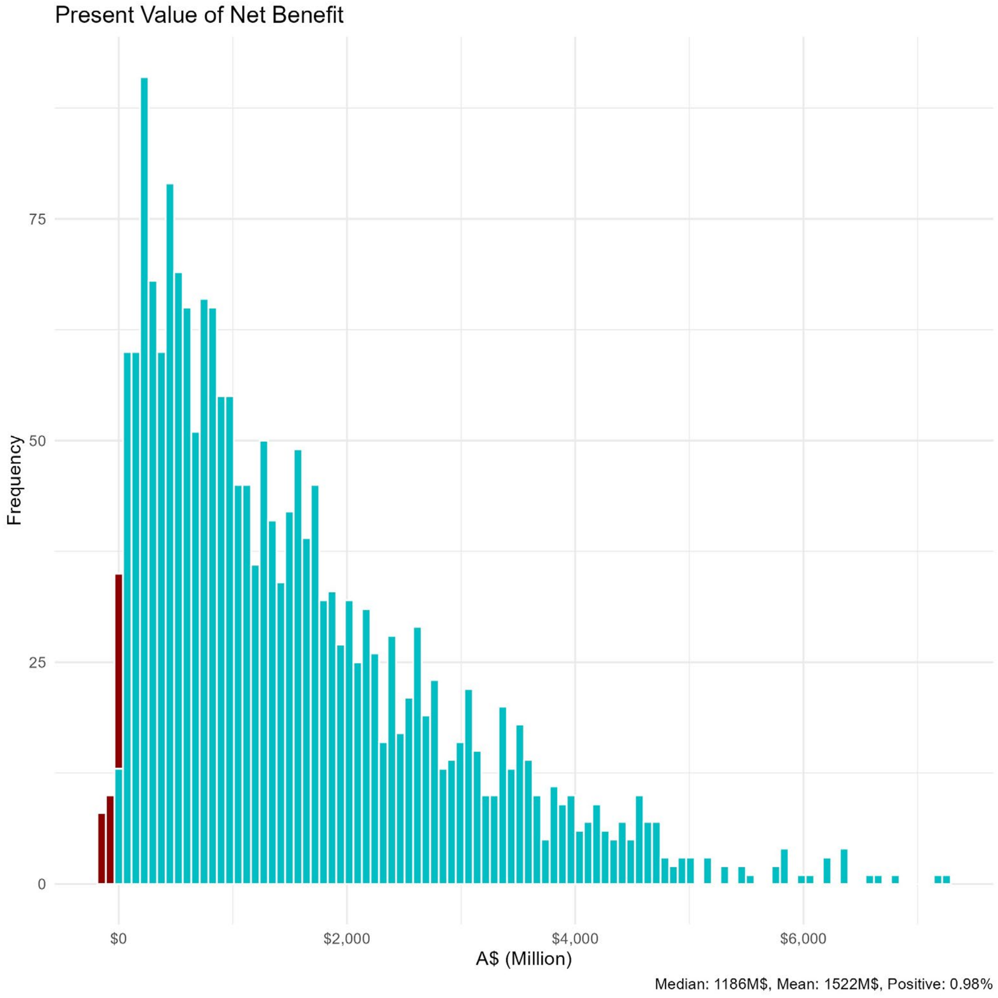

Figure 10. Histogram of the distribution of Present Value of Net Benefit ($) for the GBR-wide scenario.

Distribution was estimated over 2,000 Monte Carlo simulations. This illustrates the uncertainty surrounding median and mean of the Present Value of Net Benefit.

The results of the assessment of allocative efficiency through a Cost-Benefit Analysis across the scenarios when all reefs are considered is provided in **Table 6** and **Figure 11**.

Table 6 shows a ranked list of the median Present Value of Net Benefit at a 7% discount rate. The secondary scenarios remain unranked as they are discussed separately (see section 3.4.2). The table also displays the median Present Value of Benefit and the median Present Value of Cost. Given that the latter was estimated based on single data points rather than a distribution, the Present Value of Cost is constant across all scenarios. The results for means as well as for medians of the Present Value of Net Benefit at 3% and 10% discount rates are provided in Appendix D.

Table 6. Median Present Value of Net Benefit ($) of assessed COTS control scenarios estimated using a Cost-Benefit Analysis at a 7% discount rate. The Present Value of Net Benefit represents the net benefit discounted and aggregated over a 2022-2040 time horizon.

Green and red figures represent the best and worst performing scenarios, respectively. The R_GBR scenario most closely resembles the current Control Program.

Rank	Scenario	Median Present Value of Net Benefit ($)	Median Present Value of Benefit ($)	Present Value of Cost ($)	Quartile Coefficient of Dispersion
1	PS_UNP	**2,335,980,473**	2,517,251,162	181,270,690	0.64
2	ES_HC_CC	**2,314,332,482**	2,495,603,171	181,270,690	0.63
3	ES_HC	2,074,430,498	2,255,701,188	181,270,690	**0.61**
4	R_FNN	1,934,766,595	2,116,037,285	181,270,690	0.65
5	R_NC	1,427,924,635	1,609,195,325	181,270,690	0.63
6	R_N	1,315,982,392	1,497,253,081	181,270,690	**0.62**
7	R_FN	1,310,152,922	1,491,423,611	181,270,690	0.69
8	R_GBR	1,186,252,866	1,367,523,555	181,270,690	**0.62**
9	OF_LAT	1,137,013,966	1,318,284,656	181,270,690	0.63
10	R_CS	999,041,410	1,180,312,099	181,270,690	0.67
11	OF_PR	720,205,157	901,475,846	181,270,690	0.68
12	R_S	439,369,206	620,639,895	181,270,690	0.80
13	R_C	357,858,121	539,128,810	181,270,690	0.80
14	PS_P	234,187,307	415,457,997	181,270,690	0.94
15	OF_AR	**-45,736,133**	135,534,557	181,270,690	**21.49**
	C_COTS_CC	2,186,887,600	2,368,158,290	181,270,690	0.62
	C_COTS_CC_P	2,116,457,409	2,297,728,099	181,270,690	0.61
	C_COTS_CC_UNP	1,994,306,185	2,175,576,875	181,270,690	0.60

The distributions of the Present Value of Net Benefit were estimated for all scenarios and are presented in **Figure 11. Table 6** reports the corresponding Quartile Coefficient of Dispersion, which is a relative measure of statistical dispersion that uses quartiles to describe the spread of a dataset. Larger values indicate a higher dispersion, which in turn indicates a higher level of uncertainty (given the true distribution of Present Value of Net Benefit is unknown): the probability of a scenario generating a Present Value of Net Benefit that deviates from the estimated median is higher compared to scenarios with a lower dispersion.

All but one of the fifteen primary scenarios assessed in this study generate a positive median Present Value of Net Benefit (**Table 6**, **Figure 11**). This also holds if a 10% discount rate is applied. The only scenario that generates a negative median Present Value of Net Benefit (the cost is larger than the benefit) is the one where COTS control follows the outbreak front (OF_AR). This suggests that COTS control improves allocative efficiency regardless of the specific strategy that is used to allocate control effort and resources across the GBR (with the exception of OF_AR). While fourteen out of fifteen primary scenarios consistently delivered a positive Present Value of Net Benefit, their estimated magnitude varied considerably across the scenarios, ranging from a median of $2.36B for the top ranking scenario where COTS control focuses on unprotected reefs that are open to fishing (PS_UNP) to a median net benefit of $234M for a scenario where COTS control focuses on reefs that are protected from fishing (PS_P). This translates into an Equivalent Annual Net Benefit of about $226.01M and $22.66M, respectively. Quartile Coefficient of Dispersion (QCD) suggests that the Outbreak Front All Reefs (OF_AR) scenario (QCD = 21.49) is the most dispersed (highest uncertainty) and the Effort Sink No Coral Exception (ES_HC) scenario (QCD = 0.61) is the least dispersed (lowest uncertainty).

The scenarios focusing control effort on unprotected reefs (PS_UNP) and avoiding control on effort sink reefs unless they have high coral cover (ES_HC_CC) generate the largest Present Value of Net Benefit and differ from any other scenario (Games-Howell: p-values ≤ 0.05). The next best performers are those focusing control effort on the Far North and North (R_FNN) and the Effort Sink No Coral Exception scenario (ES_HC), which are not different from each other (Games-Howell: p-values > 0.05), but are different from all other scenarios (Games-Howell: p-values ≤ 0.05). Among these four scenarios, ES_HC exhibits the lowest dispersion (QCD = 0.61) and hence the lowest uncertainty.

Considering the regional scenario that most closely resembles the current Control Program, the GBR-wide scenario (R_GBR), is ranked 8th in terms of its estimated Present Value of Net Benefit. However, it should be noted that the Present Value of Net Benefit generated by scenarios North Central (R_NC), North (R_N), and Far North (R_FN) (ranked 5 to 7) are not different from R_GBR (Games-Howell: p-values > 0.05). The Present Value of Net Benefit generated by the GBR-wide scenario is about $1.19B, with a Benefit-Cost Ratio of about 6.5. This means that for every $1 spent, the GBR-wide scenario generates $6.50 in benefits. The Present Value of Net Benefit translates into an Equivalent Annual Net Benefit of about $114.77M. The corresponding Equivalent Annual Benefit and Equivalent Annual Cost are about $132.31M and $17.54M, respectively.

The fraction of simulations with negative Present Value of Net Benefit across all scenarios does not exceed 5%, except for the scenarios that focus control effort on the South (R_S) with 14%, Central (R_C) with 16%, Protection Status Protected (PS_P) with 22%, and Outbreak Front All Reefs (OF_AR) with 58%. The expected Present Value of Net Benefit of negative simulations does not exceed losses of about $3.15M, except for the R_S ($10.95M), R_C ($12.26M), PS_P ($23.79M), and OF_AR ($95.06M). This indicates that regardless of the uncertainty in the magnitude of the Present Value of Net Benefit, implementing most strategies carries a low risk of making the Australian people worse off. A complete table of expected Present Value of Net Benefit of negative simulations for all scenarios is provided in Appendix D.

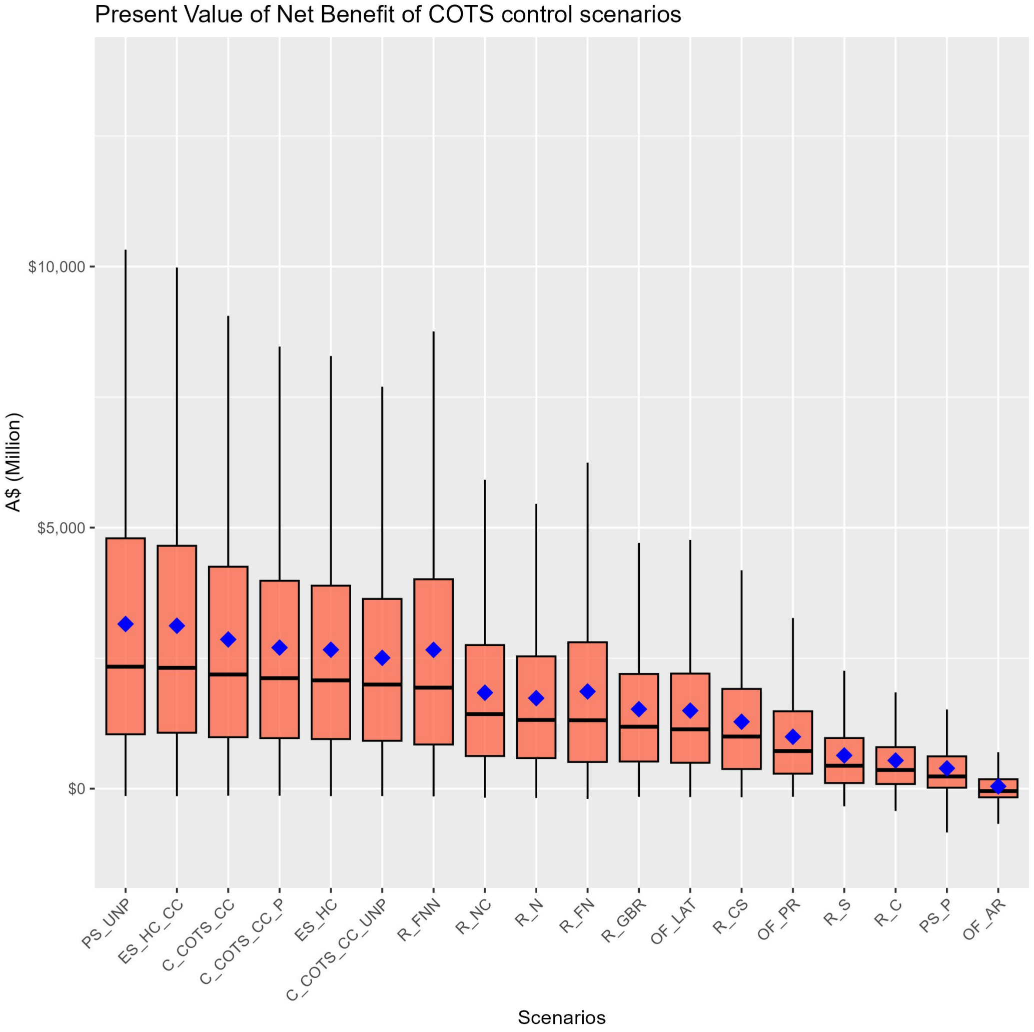

Figure 11. Boxplot of distributions of Present Value of Net Benefit ($).

Mean values are indicated by the blue diamonds in each box. The R_GBR scenario most closely resembles the current Control Program.

The allocation of the median Present Value of Benefit is shown in **Table 7** for each benefit type (use and non-use). This information cannot be included in the previous table that shows the Present Value of Net Benefit (calculated as the Present Value of Benefit less the Present Value of Cost) since the Present Value of Cost cannot be allocated by benefit type.

It is important to note that across all the scenarios, the Present Value of Benefit is primarily comprised of non-use benefits which make up more than 90% of the overall benefits estimated for each scenario (**Table 7**). No single scenario maximises the Present Value of Benefit across all five benefit types. The two Effort Sink scenarios (ES_HC, ES_HC_CC) maximise non-use benefits and fishing-related benefits (commercial, recreational and charter), but not tourism benefits. Tourism benefits are maximised by three regional scenarios (R_GBR, R_N, R_NC) that all include control effort in the North, which is a major tourism hub. The regional scenario that most closely resembles the current COTS Control Program (R_GBR) maximises tourism and fisheries benefits, but not non-use benefits.

Table 7. Median Present Value of Benefit ($) for each benefit type.

Green and red figures represent the best and worst performing scenarios. The R_GBR scenario most closely resembles the current Control Program.

Rank	Scenario	Non-Use ($)	Tourism ($)	Commercial Fishing ($)	Charter Fishing ($)	Recreational Fishing ($)
1	PS_UNP	**2,447,014,196**	58,806,132	**2,014,252**	55,241	308,103
2	ES_HC_CC	**2,406,917,467**	100,179,454	**2,171,617**	**61,297**	**361,767**
3	ES_HC	**2,137,173,525**	112,763,573	**2,206,092**	**60,621**	**358,858**
4	R_FNN	**2,037,373,587**	84,281,890	1,638,654	32,294	170,492
5	R_NC	1,477,691,966	**121,210,986**	1,808,464	45,431	256,398
6	R_N	1,344,672,669	**142,730,369**	1,673,827	45,893	246,047
7	R_FN[11]	1,505,949,451	-8,256,426	487,480	8,776	41,314
8	R_GBR	1,235,286,852	**133,153,574**	**2,136,098**	**63,735**	**380,061**
9	OF_LAT	1,200,918,587	111,627,877	1,755,511	51,271	245,738
10	R_CS	1,137,873,867	30,650,765	800,875	40,857	277,580
11	OF_PR	801,950,182	88,535,661	950,936	57,107	175,118
12	R_S	610,500,284	9,176,342	160,172	34,995	160,963
13	R_C	473,968,118	67,206,115	1,004,194	28,169	222,136
14	PS_P	363,982,124	58,774,931	124,627	5,396	28,872
15	OF_AR	**131,855,318**	**316,919**	**63,392**	**7,724**	**8,380**
	C_COTS_CC	2,296,036,572	77,436,096	1,523,193	59,989	304,589
	C_COTS_CC_P	2,212,480,012	78,365,243	1,242,747	56,872	283,345
	C_COTS_CC_UNP	2,092,704,536	87,875,052	1,356,449	58,984	291,823

Given that the Present Value of Benefit aggregated over all types is largely driven by non-use benefits, it is important to note that estimation of the non-use benefit is surrounded by a high level of uncertainty (see Section 2.4 and 4.3). A threshold analysis was performed to determine the extent of overestimation that would result in the second worst performing scenario (PS_P) to generate a zero Present Value of Net Benefit. The results suggest that this would require an overestimation of non-use benefit of about two-thirds. This indicates that if the economic benefit of non-use is at least one-third of the estimated value, the conclusions remain valid.

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[11] The negative Present Value of Net Benefit of tourism is caused by the ecological benefit metrics generated by ReefMod-GBR that underpin the economic models. The occurrence of negative values is likely caused by two processes: (1) model stochasticity causing fluctuations that should be viewed as random noise and not interpreted in relation to ecological gains or losses relative to the counterfactual; and (2) ecological feedback consecutive to the application of COTS control (see Appendix E for more details) (Based on personal communication with Yves-Marie Bozac, May 2024). The negative values are magnified by large numbers of visitation numbers in GBRMPA Cairns/Cooktown Management Area (North) and Townsville/Whitsunday Management Area (Central), which more than offset the positive values generated by relatively low visitation in the Far Northern Management Area where the COTS control is focused on in this Far North scenario (R_FN).

A sensitivity analysis was performed by including/excluding the Marginal Excess Tax Burden and over a specified profit rate range of tourism operators, given their impact on the estimates of tourism benefits and the high level of uncertainty due to severe data availability limitations. The sensitivity analysis is based on the GBR-wide scenario (R_GBR):

- Tourism profit rates: In the base case, the profit rates are assumed to follow a uniform distribution, ranging from 0% to 16%. This range is based on the best available but anecdotal evidence (Binney 2009)[12] and data published by the Australian Bureau of Statistics (https://www.abs.gov.au/)[13]. Fixing the profit rates over a range of 2% to 8% results in a Present Value of Benefit change of about $2.70M per percentage point.

- Marginal Excess Tax Burden*:* The inclusion of a 25% Marginal Excess Tax Burden ($45,317,672) into the Present Value of Cost would not result in a negative Present Value of Net Benefit at any discount rate.

2.4.2 Secondary Scenarios

The three secondary scenarios belong to the Connectivity scenario group.

The set of best performers to maximise Present Value of Net Benefit is expanded if Connectivity scenarios are included in the assessment (**Table 6**). The distributions of the Present Value of Net Benefit simulations of these scenarios are provided in **Figure 11**. Scenarios where COTS control is focused on all reefs with predicted high COTS larval connectivity (C_COTS_CC) or restricted to protected reefs (C_COTS_CC_P) are not different from each other or the best performers of the primary scenarios (Games-Howell p-values > 0.05) but are different from all other scenarios (Games-Howell p-values ≤ 0.05). Hence, the most and equally allocatively efficient scenarios now include C_COTS_CC (about $2.30B) and C_COTS_CC_P (about $2.21B) in addition to the scenarios Effort Sink No Coral Exceptions (ES_HC_CC) and Protection Status Unprotected (PS_UNP). This aligns with the results of the cost-effectiveness analysis against *Healthy Coral Habitat Maintained*. This is not surprising given that non-use is the largest benefit type, which is underpinned by the metric *Healthy Coral Habitat Maintained*.

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[12] Profit rates are hardly above 5%, some operators make losses.

[13] Australian Bureau of Statistics average gross operating profit-to-sales ratio for recreational services over the last 20 years – 16% (mean of codes 9139 and 5010).

3. DISCUSSION AND OUTPUTS

3.1 Interpretation of results

This study has developed a novel modelling and analysis pipeline for estimating benefits and cost of eighteen alternative manual COTS control strategies and conducted the first ever comprehensive economic assessment of Australia's COTS Control Program. The results of the economic assessment suggest that identifying the optimal COTS control scenario depends on the management objectives. The three impact objectives identified by the CCIP's program logic model (**Figure 1**) are: 1) that coral cover is protected across the GBR; which is enabled by ensuring that 2) COTS outbreaks are suppressed and prevented; so that 3) Traditional Owners, the tourism industry, and communities realise benefits. The economic value of the benefits to people have never been estimated in monetary terms until now. The extent of these economic benefits generated by use (tourism, commercial fishing, recreational fishing, charter fishing) and non-use value (existence, bequest, option, altruistic) ultimately stem from the protection of coral, but this is supported by avoiding outbreaks and maximising the cost-effectiveness and allocative efficiency of COTS control given a specified set of alternative COTS control strategies.

3.1.1 Cost effectiveness and trade-offs

The Cost-Effectiveness Analysis assessed eighteen COTS control scenarios across four alternative benefit metrics: *Coral Area Saved*, *Outbreaking Reefs Avoided*, *COTS Density Reduced*, and *Healthy Coral Habitat Maintained*.

The metric directly capturing the ability of a control strategy to protect coral was the *Coral Area Saved* metric. The most promising scenarios to minimise the cost per hectare of *Coral Area Saved* considering all reefs across the GBR were the two Effort Sink scenarios and the GBR-wide scenario (R_GBR). The commonality between these three scenarios is not surprising, given that the Effort Sink scenarios are based on the R_GBR scenario, modified slightly to omit the reefs requiring the most effort to complete control. As well as being the most cost-effective scenarios, they also exhibited the lowest level of variability. A low variability indicates that the probability of a scenario achieving a cost-effectiveness that deviates from the estimated mean is lower compared to scenarios with a higher variability. If any of these scenarios were implemented, the estimated annual mean cost per hectare of *Coral Area Saved* would range from $3,046 per hectare to $3,146 per hectare. The results do not change if only Priority Reefs are included in the analysis. These results suggest that the scenario that most closely resembles the current COTS Control Program forms part of the best performing scenario bundle if the management objective was to maximise the hectares of *Coral Area Saved* given the fixed budget.

The metric related to suppressing or preventing outbreaks was *Outbreaking Reefs Avoided*. The most cost-effective scenarios to minimise the number of outbreaking reefs considering all GBR reefs were the scenarios that focused control effort in the Far North (R_FN) and South (R_S). This result should be interpreted carefully because it does not factor in variation in the size (i.e. coral area) of reefs where outbreaks are suppressed. Regional scenarios focus Control Program efforts within a region, where, after they have protected the highest priority reefs, they move on to protecting lower priority reefs, which are often smaller and quicker to control. The Far North and South regions include many small reefs, which take relatively less effort to “complete” control at, so control effort modelled in these regions ends up suppressing outbreaks across a higher number/proportion of the reefs in the region. More geographically dispersed scenarios, such as the GBR-wide scenario (R_GBR), have a larger pool of high priority reefs to control, which may take more time but ultimately suppress outbreaks across larger areas of reef (but not necessarily a higher number of reefs).

The variability of the cost-effectiveness under the Far North (R_FN) and South (R_S) scenarios are comparatively low. A low variability indicates that the probability of a strategy achieving a cost-effectiveness that deviates from the mean is lower compared to scenarios with a higher variability. If any of these two scenarios were implemented, the estimated annual mean costs would range between $392,718 (R_FN) and $496,412 (R_S) per *Outbreaking Reef Avoided*. In comparison, maximising *Outbreaking Reefs Avoided* under the GBR-wide scenario (R_GBR) was estimated to be almost two times as costly ($752,062 per *Outbreaking Reef Avoided*). The higher cost per *Outbreaking Reef Avoided* for the GBR-wide scenario relative to the regionally focused scenarios is due to controlling a smaller number of reefs (see above). Interestingly, if the focus of the analysis is narrowed to control effort on Priority Reefs, the four best performing scenarios were the Central South (R_CS), the two Effort Sink scenarios, and GBR-wide scenario (R_GBR). This highlights that many of the reefs protected when the assessment includes all reefs on the GBR are outside the COTS Control Program Priority Reef list.

The most productively efficient scenarios that maximise *Coral Area Saved* and *Outbreaking Reefs Avoided* jointly were the two effort sink scenarios, the regional scenario that focuses effort on the Far North (R_FN), the GBR-wide scenario (R_GBR), and scenario following the Outbreak Front on Priority Reefs (OF_PR). However, while they are equally productively efficient, choosing one over another involves trade-offs. These trade-offs were estimated in terms of opportunity costs, which should be considered when selecting a scenario. Implementing the Far North scenario (R_FN) over any of the other scenarios would result in an increase in the number of *Outbreaking Reefs Avoided*, (although many of these may be small Non-Priority Reefs) at the cost of reduced *Coral Area Saved*. Implementing the other scenarios would lead to an increase in the amount of *Coral Area Saved*, at the expense of fewer total number of reefs where outbreaks are avoided.

The metric *Healthy Coral Habitat Maintained* measures the amount of coral area in good and very good condition in hectares estimated based on the Reef Condition Index, which was estimated using the Coral Reef Index Model (CRIM). It integrates coral cover with ecological attributes that underpin reef condition positively (shelter volume, abundance of coral recruits), or negatively (rubble cover and the abundance of COTS). It is not directly related to a management or research program objective but provides a complementary measure of program performance. The most promising scenarios to minimise the cost per hectare of *Healthy Coral Habitat Maintained* when the analysis considers all reefs across the GBR were Protection Status – Unprotected reefs (PS_UNP) and Effort Sinks with High COTS and Coral Cover (ES_HC_CC), followed by Regional – Far North & North (R_FNN) and Effort Sink with high COTS No Coral Exception (ES_HC). It is hard to identify a single physical mechanism driving these results, but many of the scenarios that performed well attempt to modify a baseline GBR-wide strategy by taking into account ecological characteristics of the reefs being protected, such as whether they are protected from fishing or particularly high dispersal sources for COTS and coral. If scenarios such as focusing control effort on unprotected reefs (PS_UNP) or avoiding reefs that are effort sinks (ES_HC_CC) were implemented, the estimated annual mean cost would range between $171 and $175 per hectare of *Healthy Coral Habitat*. In contrast, maximising *Healthy Coral Habitat Maintained* under the R_GBR scenario was estimated to be almost twice as costly ($357/ha). Hence, while the data suggests that the scenario that most closely resembles the current Control Program performs reasonably well in maximising *Healthy Coral Habitat Maintained* per $ spent, there are still opportunities to increase cost-effectiveness. If the management objective was focused on *Healthy Coral Habitat Maintained* – protecting coral habitat in good and very good condition (as compared to coral habitat in any condition as measured by Coral Area Saved), the possibility to focus more effort on unprotected reefs and avoid effort sink reefs with a coral cover lower than 20% should be explored. However, before these insights were actioned, additional investigation of the underlying drivers of these trends in *Healthy Coral Habitat Maintained* should be completed, and any additional costs that may result from vessel repositioning should be considered.

The secondary Connectivity scenarios do not generate a significant increase in *COTS density Reduced*, *Coral Area Saved*, *Outbreaking Reefs Avoided* and *Healthy Coral Habitat Maintained* relative to the primary scenarios discussed above. This suggests that strategies that take a more flexible approach to the distribution of management effort by leveraging connectivity information have only limited potential to improve cost-effectiveness beyond those identified as the best performing primary scenarios.

3.1.2 Economic benefit of COTS control

Seventeen out of the 18 COTS control scenarios tested generated a positive Present Value of Net Benefits (benefits are larger than costs) when considering the broader economic benefits (e.g. tourism, fishing, non-use) and control cost of this management activity. This indicates that COTS control effort on the GBR using any scenario (other than the Outbreak Front – All Reefs (OF_AR) scenario) is a worthwhile investment that makes the Australian people better off. This holds for all discount rates and whether Marginal Excess Tax Burden is included in the cost, indicating result robustness.

The estimated median Present Value of Net Benefit (discounted benefits less discounted costs aggregated over a 2022-2040 time horizon) generated ranged from $234M up to $2.34B, depending on the COTS control scenario tested. The GBR-wide control scenario (R_GBR) that most closely resembles the current COTS Control Program was estimated to generate a median Present Value of Net Benefit of $1.19B. The findings of this study suggests that implementing scenarios that refine this GBR-wide strategy by focusing effort on reefs that are not protected from fishing (PS_UNP) or avoiding reefs that are effort sinks with high COTS and a coral cover less than 20% (ES_HC_CC) could offer an opportunity to almost double the Present Value of Net Benefit delivered by the COTS Control Program. When interpreting these findings, it is important to note that by far the biggest component (>90%) of Present Value of Net Benefit relates to non-use value, which derives from improvements in the *Healthy Coral Habitat Maintained*. As noted above, the mechanisms that drive the biggest gains in *Healthy Coral Habitat Maintained* across scenarios are unclear, but it is no surprise that the management scenarios that maximise this metric (PS_UNP, ES_HC_CC) provide the largest Present Value of Net Benefit. Again, any strategy that sought to maximise Present Value of Net Benefit should look in more detail at the processes driving *Healthy Coral Habitat Maintained* at reefs under different scenarios and assess any additional costs due to vessel repositioning.

The outstanding performance of the Effort Sink scenario (ES_HC_CC) is likely because the control strategy effectively avoids investing resources in the very small number of reefs that require the largest effort to completely control. However, the practicality of implementing an Effort Sink scenario would incur additional complexity and require additional resources (e.g. logistics). Moreover, the implementation of the Effort Sink scenarios in ReefMod-GBR assume an unrealistic perfect level of foreknowledge about the amount of effort required to control a reef. If Effort Sink scenarios were to be implemented, a sensitivity analysis to less-than-perfect knowledge, as well as any additional cost due to complexity should be carefully considered given this assessment assumes constant costs across scenarios. Understanding these factors will be important to understand potential allocative efficiency losses if conditions do not match the assumptions of the analysis.

This study has also provided novel insight into which assessed scenarios are most likely to maximise economic benefits for the tourism and fishing industries. The best scenarios to maximise tourism Present Value of Benefit are two of the regional scenarios and the GBR-wide scenario (R_N, R_GBR, R_NC). This makes sense given these scenarios focus effort on regions with a high density of ‘tourism reefs’. The most efficient scenario to maximise the Present Value of Benefit for commercial, recreational and charter fishing are the two Effort Sink and the R_GBR scenarios. This might be explained by the fact that fishing effort and catch is spread across the GBR. We note, however, that recreational and charter fishing contribute only marginally to the Present Value of Benefit. This is not surprising given that the value of these activities is not exclusively related to fish catch, and that the marginal value of fish catch decreases with an increase in catch (e.g. Parsons 2017).

Risk of making the Australian people worse-off is captured as the product of probability and impact (Present Value of Net Benefit) based on Monte Carlo Simulations. The probability of a negative outcome does not exceed 5% and expected losses (negative Present Value of Net Benefit) are moderate for all scenarios except for the scenarios focusing on the South and Central regions (R_S, R_C) and protected reefs (PS_P), and the scenario that deploys efforts to all reefs by following the Outbreak Front (R_AR). We also note that none of these riskier scenarios are top performers in maximising Present Value of Net Benefit. This underlines that most control strategies are very likely worthwhile public investments that make the Australian people better off.

The secondary Connectivity scenarios do not generate a significant increase in Present Value of Net Benefit relative to the primary scenarios discussed above. This suggests that strategies that take a more flexible approach to the distribution of management effort by leveraging connectivity information have only limited potential to improve allocative efficiency beyond those identified as the best performing primary scenarios. Additionally, the scenarios modelled assumed an unrealistic level of perfect knowledge regarding larval connectivity. Including imperfect knowledge would reduce actual cost-effectiveness and allocative efficiency. Further analysis of specific implementation models and the impact of imperfect knowledge would be crucial before pursuing implementation. However, the limited potential gains suggest that additional investigation might be an unappealing investment.

3.2 Key insights

A key insight from these diverse results is that different objectives are best served by different management strategies. As such, it is vital to both clearly specify the objectives of a program to identify the most effective strategy, and then also to review which secondary objectives are being traded off when the primary objective is maximised.

The primary objective of the COTS Control Program and the COTS Control Innovation Program is to protect coral cover across the GBR. In this analysis, the GBR-wide COTS control strategy, the strategy that most closely resembles the current COTS Control Program, was one of the equal-top performers in total area of coral saved per $ spent. Other strategies were more cost-effective at reducing the number of reefs experiencing COTS outbreaks across the whole GBR. However, when considering which strategies could reduce most outbreaks when considering Priority Reefs only, yet another set of strategies performed best, including the GBR-wide strategy.

Very different strategies maximised the coral habitat in good and very good condition measured by the *Healthy Coral Habitat Maintained*, and as a result, the Present Value of Net Benefits, of which more than 90% is derived from non-use benefits. For use benefits, such as benefits to tourism and commercial and recreational fisheries, a different set of strategies produced the greatest efficiency gains, including the GBR-wide strategy.

The Benefit-Cost Ratio of about 6.5 estimated for the GBR-wide strategy indicates that for every $1 spent the expected return is $6.50 in benefits. The highest Benefit-Cost Ratio of about 12.9 was achieved by the scenario that focused effort on reefs unprotected from fishing (PS_UNP). To our best knowledge, no Cost-Benefit Analysis was conducted for COTS control anywhere in the world to compare our results. Yet, the Benefit-Cost Ratio of the GBR-wide scenario estimated in our study falls within the range of those reported for coral reef restoration investments. Abrina and Bennett (2021) estimated a Benefit-Cost Ratio based on non-use benefit for an investment in coral gardening and mass larval enhancement at the national level in the Philippines of about 11.5 and 21.0, respectively. A meta-analysis of global coral reef restoration investments reported a Benefit-Cost ratio of about 4 (Stewart-Sinclair et al. 2021).

Additional work will be needed to better understand how to design COTS Control Program strategies that can protect broad benefits, including non-use benefits, while maintaining protection of coral and avoiding outbreaks. Trade-offs between strategies in terms of opportunity costs should be considered. Care should be taken when interpreting these results to ensure that any additional costs of changing strategies not captured in this analysis are considered. These could include explicit costs, such as the costs of relocating vessels to different regions in the GBR with more responsive strategies, and implicit costs, such as sub-optimal decisions made due to imperfect data availability.

3.3 Key assumptions, limitations and future considerations

The key assumptions underpinning the ReefMod-GBR outputs used in this assessment are reported in the CCIP-R-04 Regional Modelling report (Skinner et al. 2025a).

All assumptions underpinning the benefit valuation using the Coral Reef Economic Assessment Model (CREAM) are listed in Scheufele et al. (2022b). The benefit valuation required many assumptions due to limitations of the data (quality and age) that were available and used in the benefit transfer that underpins the benefit valuation component of CREAM.

Due to data availability limitations, simplifying assumptions regarding the costs under each scenario had to be made (Appendix A). As a result, the cost per unit of effort is assumed to be constant across all scenarios.

We acknowledge that the Present Value Benefit does not include the economic value of benefits that were identified as relevant but could not be quantified and monetarised (benefits to Aboriginal and Torres Strait Islanders, cultural benefits, education and training benefits, and benefits generated within non-coral habitats) nor the non-use benefits of protecting the GBR enjoyed by the global community.

We note that the assumed probability distributions and estimated impacts used to assess risk are themselves surrounded by uncertainty. Despite best efforts, it was not possible to capture the full range of risk and uncertainty given data availability limitations, especially data on economic benefits estimated in monetary terms. Some of the uncaptured sources of risk and uncertainty might have a substantial impact on the results. It cannot be stressed enough that this risk and uncertainty should be considered when making investment decisions.

The results of the Cost-Benefit Analysis can be used to assess the trade-offs when other means objectives external to the modelling effort (e.g. non-monetarised benefits, logistics, spatial equity, contractual arrangements, politics) are considered in deciding the preferred scenario. These trade-offs, generated in the case that a less allocatively efficient scenario is chosen, can be estimated in terms of a loss in Present Value Net Benefit.

A potential increase in Present Value of Net Benefit through effort cost reductions might be generated if novel technology (e.g. automation of COTS monitoring, semio-chemical approaches) was integrated into the current Control Program. Automated monitoring would provide ‘more’ and ‘better’ data, which would improve the accuracy of model estimations, and thus provide ‘better’ information to make strategic, potentially more cost-effective, and allocatively efficient COTS control management decisions. Once this technology has been developed, scenarios that assess their impact should be analysed using the economic assessment platform developed in this project (CCIP-R-06).

3.4 Final project outputs

- Modelling framework and models to estimate costs and benefits of COTS control scenarios.
- Tools for assessing effectiveness, cost-effectiveness, efficiency of COTS control.
- Dataset on input and output metrics used in economic modelling and assessment.
- R-script of economic models and tools.
- Economic assessment results of strategic control scenarios co-developed with the Control Program (tables, plots).

4. RESEARCH SYNERGIES AND NEXT STEPS

The following research synergies have been identified (see **Figure 1**):

- CCIP-R-01: Information Infrastructure to Underpin and Accelerate Innovation in COTS Control
  Outputs of this research (CCIP-R-06) will be incorporated into the CCIP Information System implemented as part of project CCIP-R-01.

- CCIP-R-04: Design and optimisation of regional models and decision support scenarios for COTS control and ecosystem resilience.
  This research depended on the development of input-output modelling (effort-benefit relationships based on data-based dynamic GBR-scale models using ReefMod-GBR) of alternative scenarios (including a counterfactual). Additionally, model outputs from ReefMod-GBR were harmonised to be used for economic assessments, not just within CCIP but also RRAP. This will facilitate economic assessments of model outputs generated from a potential future integrated RRAP-CCIP model based on ReefMod-GBR.

- CCIP-R-07: Multi-criteria decision-making framework for balancing management priorities under resource constraints.
  There is potential for using the results of this research in the multi-criteria decision-making framework, as flagged in the Final Technical Report for that project. Exploring such potential would need further discussions.

- CCIP-R-08: Stakeholder perceptions of COTS management, socio-economic risks, opportunities, and co-benefits.
  There is potential to investigate if a synthesis of the results of this research and CCIP-R-08 could support the overall picture of socio-economic COTS control impacts. Exploring such potential would need further discussions.

- CCIP-R-09: Reef Traditional Owner co-design, values, and governance assessment.
  There is potential to collaborate in designing COTS control scenarios that involve Traditional Owners led COTS surveillance and control. Exploring such potential would need further discussions.

- RRAP - Modelling & Decision Support
  The Coral Reef Economic Assessment model (CREAM) and the Coral reef Index Model (CRIM), both developed under RRAP, were used to estimate benefits in non-monetary and monetary terms.

The following top priority areas for further R&D that have emerged through this project include[14]:

- Economic assessment of refined and additional scenarios:

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[14] The order does not imply a ranking by priority.

  - Scenario switching over the modelling time horizon to further increase realism and capture potential cost-effectiveness and efficiency gains.
  - Inclusion of Traditional Owner vessels in their specific Sea Country.
  - Scenarios that deploy automated monitoring technology and/or other novel COTS control methods.
- Strengthening knowledge integration:
  - Investigation of potential to incorporate outputs of this research in the multi-criteria decision-making framework.

5. MANAGEMENT IMPLICATIONS AND IMPACT

This research finds significant differences in cost-effectiveness as well as productive and allocative efficiency of alternative manual COTS control scenarios.

Cost-effectiveness, productive efficiency, and trade-offs. The most and equally cost-effective scenarios to maximise the hectares of *Coral Area Saved* per $ spent are the regional GBR-wide strategy (the scenario that most closely resembles the current Control Program) and the two effort sink scenarios. The latter two scenarios do not seem to generate additional benefit at the same cost compared to the regional GBR-wide scenario when considering *Coral Area Saved*. The regional GBR-wide scenario also forms part of the best performing scenario bundle if the management objective is the simultaneous maximisation of both *Coral Area Saved* and *Outbreaking Reefs Avoided*. In contrast, the best performers to maximise *Outbreaking Reefs Avoided* per $ spent are the scenarios that focus effort within the Far North and South regional scenarios. However, this result is likely driven by avoiding outbreaks at a large number of small non-Priority Reefs. When focusing on Priority Reefs only, the best scenarios are the regional Central South scenario, the two effort sink scenarios, and regional GBR-wide scenario. The most promising scenarios to minimise the cost per hectare of *Healthy Coral Habitat Maintained* are scenarios that focus effort on unprotected reefs and avoid reefs that are effort sinks if the coral cover is smaller than 20%, followed by the regional scenario Far North/North and the scenario that avoids reefs that are effort sinks irrespective of coral cover.

Allocative efficiency. All scenarios (other than the scenario that follows the outbreak front on all reefs) under all discount rates generated a positive Present Value of Net Benefit (aggregated discounted benefit less aggregated discounted cost). This strongly suggests that targeted and continuous COTS control is a worthwhile public investment since it makes the Australian people better off. However, this result is strongly driven by non-use benefits, which are estimated based on the ecological benefit metric *Healthy Coral Habitat Maintained*, rather than *Coral Area Saved* or *COTS Outbreaks Avoided*.

The metric *Healthy Coral Habitat Maintained* captures exclusively coral reef habitat in a very good and good condition. In contrast, *Coral Area Saved* does not differentiate coral reef habitat quality independent of habitat size. For example, a 100 hectares coral reef habitat with an average coral cover of 10% and one spanning 50 hectares with 20% coral cover both result in a *Coral Area Saved* of 10 ha. Hence, *Coral Area Saved* and *Healthy Coral Habitat Maintained* are different metrics and, while related and both estimated in hectares, they are not directly comparable.

The regional GBR-wide scenario, which most closely resembles the current Control Program, does produce significant Present Value of Net Benefit of $1.19B, which represents the net benefit discounted and aggregated over the time horizon 2022-2040. The findings of this study suggest that implementing scenarios that refine this GBR-wide strategy by focusing effort on reefs that are not protected from fishing or avoiding reefs that are effort sinks with high COTS and a coral cover smaller than 20% could offer an opportunity to almost double the Present Value of Net Benefit delivered by the COTS Control Program.

Strategies that take a more flexible approach to the distribution of management effort by leveraging connectivity information have only limited potential to capture further cost-effectiveness and allocative efficiency gains. Furthermore, the scenarios modelled assumed an unrealistic level of perfect knowledge regarding larval connectivity, so further analysis of the impact of imperfect knowledge would be crucial before pursuing implementation of the connectivity scenarios examined here.

A key insight from these diverse results is that different objectives are best served by different management scenarios. Despite this complexity, however, the results of this research demonstrate that the regional GBR-wide strategy currently being used to guide the COTS Control Program on the GBR: 1) is very likely to generate a net benefit to Australian people given the investment required to support them; 2) is likely to be among the most effective of the strategies investigated for protection of coral; and 3) is likely to be a reasonable strategy in terms of avoiding outbreaks at Priority Reefs and protecting tourism and fisheries values. At the same time, future refinements to the strategy could potentially increase the ability to avoid outbreaks at reefs more broadly and further protect non-use value.

The findings of this assessment and the final outputs have several implications for COTS management. The following entry points have been identified:

1. **Governance, Engagement and Communications**: Sharing the findings of this research with key stakeholders, managers, and decision-makers will enhance governance and engagement. Communicating the value-for-money proposition of COTS management supports future investment propositions.

2. **COTS Strategic Management Framework**: The research results provide the opportunity to improve strategic decision-making to further increase cost-effectiveness and allocative efficiency of COTS control strategies. Future opportunities regarding the prospects of technological innovations could be tested using the platform developed to capture any additional cost-effectiveness gains through more effective COTS control and/or effort cost reductions.

3. **Annual Reef Prioritisation Process**: The findings of this research will be valuable to complementing the existing limited economic data used in the Annual Reef Prioritisation Process.

This research contributes to the development of enhanced modelling capability that enabled an assessment of productive efficiency, cost-effectiveness, and allocative efficiency of alternative COTS control scenarios (output), which facilitates a more efficient and effective operational response (outcome). The methods developed in this report will allow decision makers to assess future strategies to make informed decisions to manage trade-offs between these objectives. This is expected to contribute to the prevention and suppression of outbreaks, protection of coral cover across the GBR, and the generation of benefits to the industries and communities (impact).

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7. DATA ACCESSIBILITY

The data are incorporated into the ‘Information Infrastructure to Underpin and Accelerate Innovation in COTS Control’ developed within CCIP-R-01. Some of these data cannot be made publicly available due to commercial-in-confidence concerns and protection under the human ethics permits.

Output data underpinning this report are available in the CSIRO Data Access Portal (https://data.csiro.au/categories).

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APPENDIX A – COST DATA AND MODEL

The cost data used in the model is based on the Reef Authority work orders for the Control Program for financial year 2021/22 (Reef Authority, unpublished). The discrepancy between the actual total cost of the Control Program FY21/22 and the total cost modelled in this research are due to the number of vessels deployed. During the FY 21/22 the Control Program had two additional vessels for part of the year to provide surge capacity, which are not included in the model which assumes five vessels.

Work orders are based on quotes from suppliers that specify the planned number of on-water days per year, planned number of diver hours per year, and administration/reporting. The contract length is typically between 12 and 24 months and the payments are spread throughout each financial year and follow delivery and reporting milestones.

The costs of the Control Program are comprised of the following components:

1. Cost of On-water Days:
    - Based on total work order value divided by the planned number of on-water days
    - Days when vessel is at sea (i.e. not in port for provisioning, maintenance etc.)
    - Includes salary of all marine and dive crew on board, plus project/fleet management
2. Cost of Activity Days:
    - Based on total work order value divided by the planned number of activity days
    - Activity days are a subset of on-water days that involve in-water dive/snorkel operations (e.g. manta tow, culling, RHIS), but excludes steaming to/from port or among reefs
    - Includes salary of all marine and dive crew on board, plus project/fleet management
3. Cost of program management:
    - 7 full-time FTEs (Reef Authority staff)
    - Travel (meetings, workshops, joining voyages for training QA etc.)
    - Purchase of equipment (tablet computers for data entry)
4. Cost of Other COTS surveillance:
    - 60 on-water days used for manta-tows and RHIS (Reef Joint Field Management Program)
    - Provides ‘scouting’ and ‘early warning system’ for on-water Control Program

The cost of potential repositioning (defined as switching ports for a defined period within a work order) under alternative COTS control scenarios modelled in the economic assessment has not been included due to data limitations. Repositioning cost consists of the cost of add-on water days and hidden costs. The following hidden costs were identified:

- staff relocation (flights/buses) or substitution
- additional cost of sourcing new suppliers for maintenance, food catering, logistical cost

- potential additional marina fees (depends on whether operators own wharf and also use for other purposes)
- differences in marina fees across different ports (supply shortages of marina space?)
- potential vessel shortage in ports
- cost of divers who are not used during repositioning but need to be relocated via flights/buses.

Not including repositioning costs likely biased the cost estimates associated with the spatial-focused scenarios. The impact of this bias on the results is assumed to be negligible for the following reasons (supported by some simplifying assumptions):

- Recontracting of on-water operators every 12–24 months.
- Modelling time frame about 35 years.
- Plausible assumption that contracts awarded to spatial needs rather than assuming additional on-water days to steam additional days from ports further away.
- Likely increased costs of contracts that require relocation of vessels assumed to be negligible (with respect to outcomes) relative to total program cost.
- Assumption that potential vessels supply shortage and mooring capacity constraints are manageable and have zero cost.
- Assumption that vessel allocation not constrained by social equity concerns.
- Assumption that base vessel capacity across GBR for general monitoring and enforcement operations if deployed for COTS control does not add to cost.

APPENDIX B – INPUTS IN COST MODELS

Table B.1 shows the model inputs used in the cost models, chosen to approximate as close as possible the current Control Program.

Table B.1. Inputs in cost models.

	Input	Quantity
1	Number of vessels	5.0
2	Voyages per year	18.0
3	Number of days per voyage	12.0
4	Number of activity days per voyage	10.0
5	Number of non-activity days per voyage	2.0
6	Dives per activity day	4.0
7	Divers per vessel	8.0
8	Length of dive (min)	40.0
9	Cull proportion of all dives	0.9
10	Cull dive budget (hrs) per year	17,280
13	Manta dive budget (hrs) per year	1,920

APPENDIX C – RESULTS COST-EFFECTIVENESS ANALYSIS

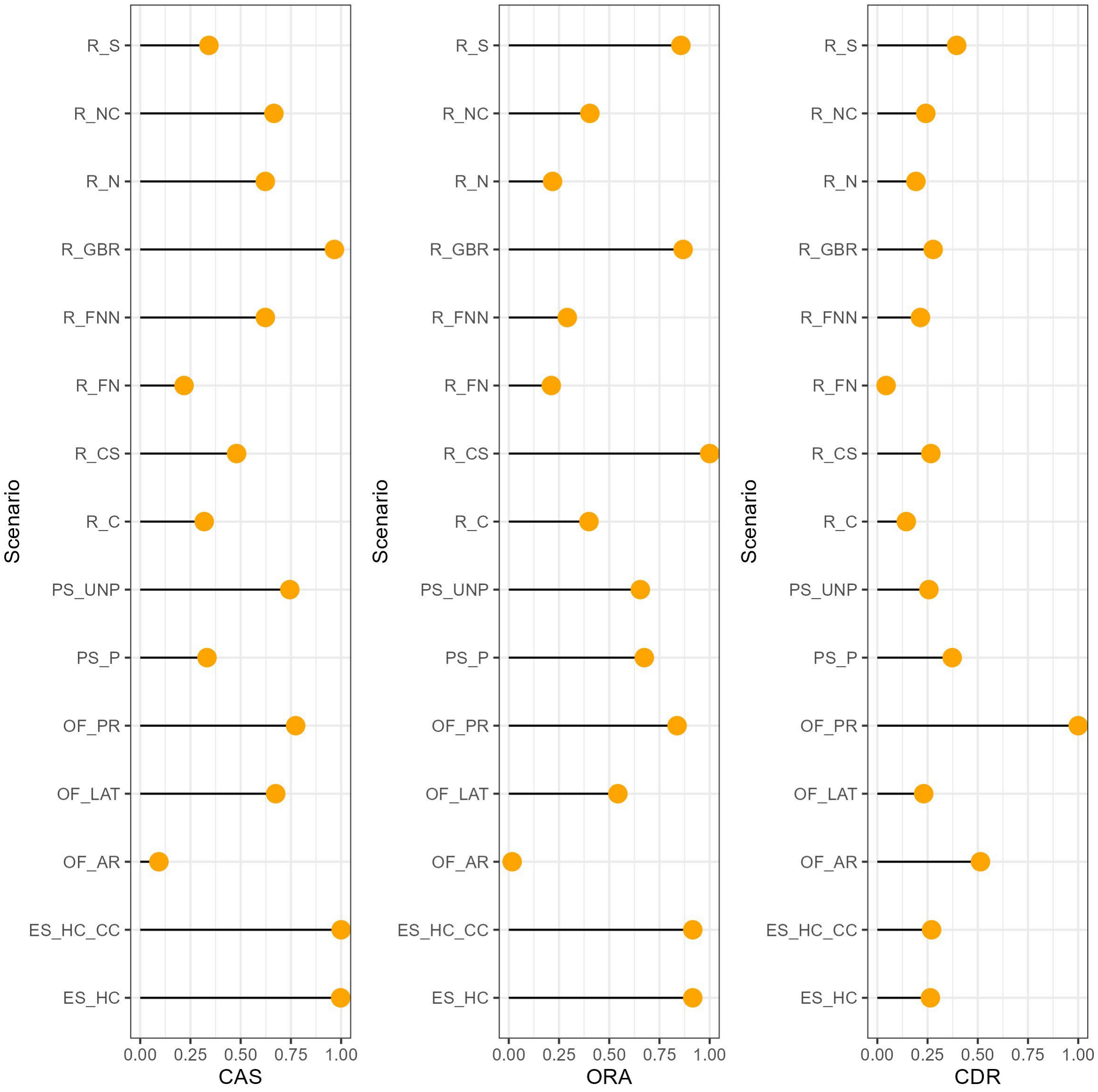

Figure C.1. Relative cost-effectiveness across *Coral Area Saved* (CAS), *Outbreaking Reefs Avoided* (ORA) and *COTS Density Reduced* (CDR) considering Priority Reefs only.

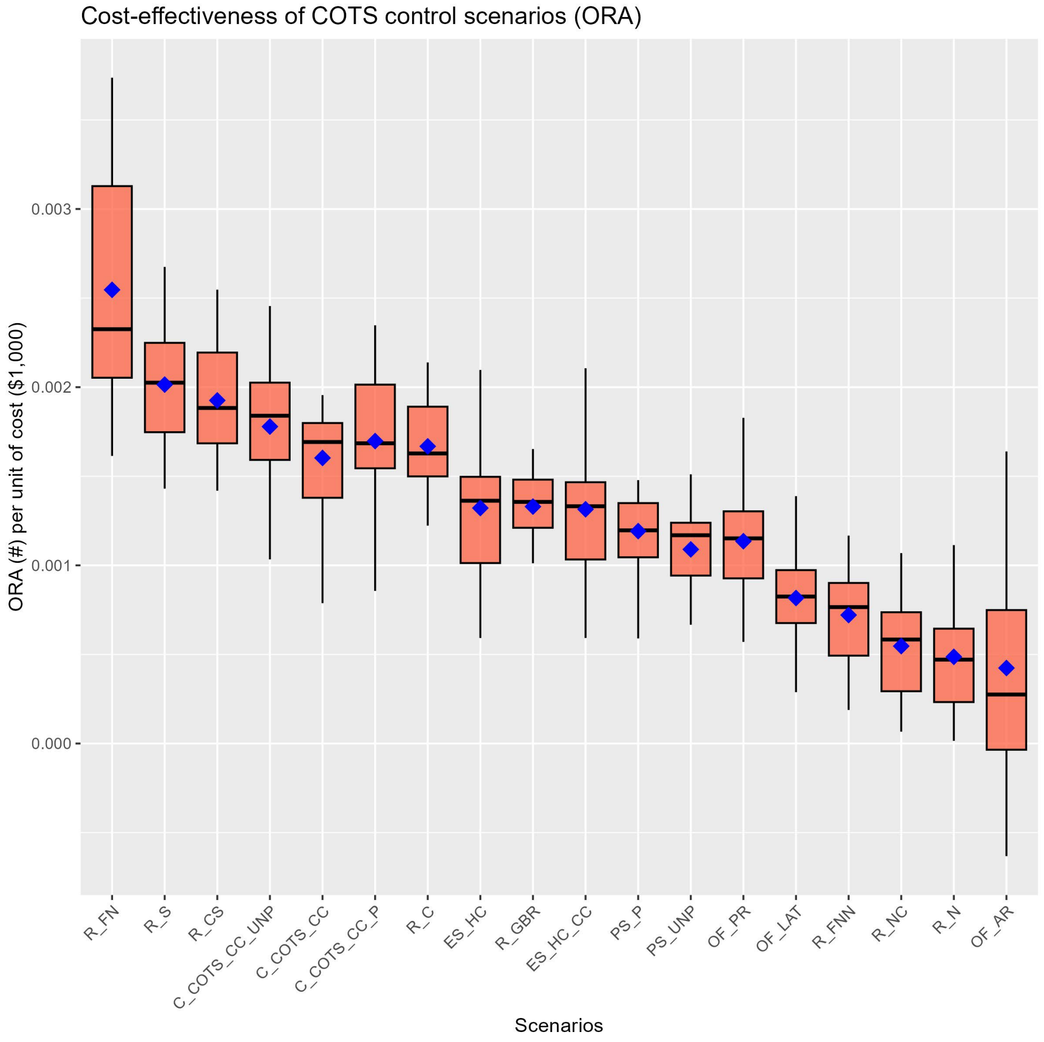

Figure C.2. Boxplot of distributions of cost-effectiveness of *Outbreaking Reef Avoided* (ORA) considering all reefs.

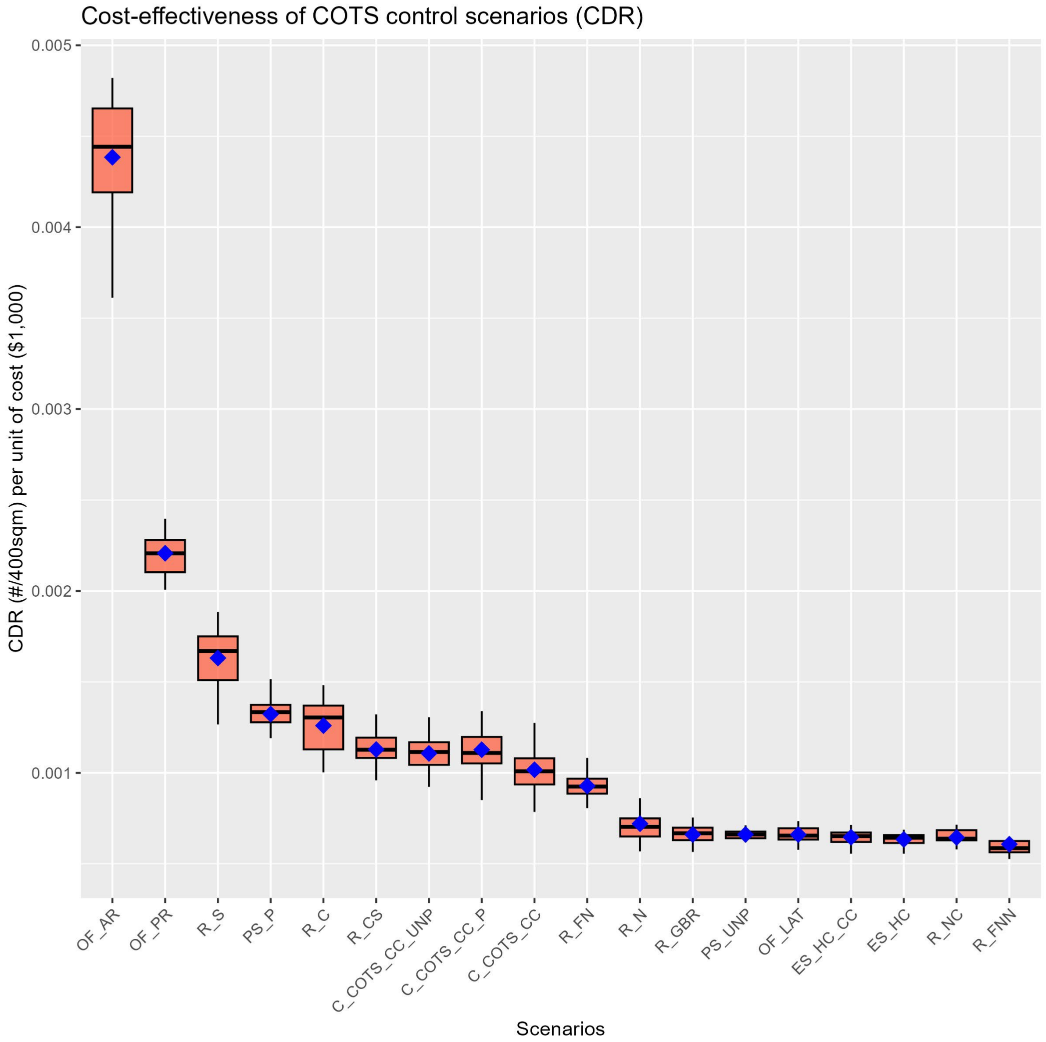

Figure C.3. Boxplot of distributions of cost-effectiveness of *COTS Density Reduced* (CDR) considering all reefs.

APPENDIX D – RESULTS COST-BENEFIT ANALYSIS

Table D.1. Mean of the Present Value of Net Benefit (AUS$) at a 7% discount rate.

Rank	Scenario	Mean Present Value of Net Benefit ($)	Mean Present Value of Benefit ($)	Mean Present Value of Cost ($)	Coefficient of Variation
1	PS_UNP	3,153,792,925	3,335,063,615	181,270,690	0.84
2	ES_HC_CC	3,119,718,667	3,300,989,357	181,270,690	0.82
3	ES_HC	2,661,210,386	2,842,481,076	181,270,690	0.80
4	R_FNN	2,658,803,972	2,840,074,661	181,270,690	0.85
5	R_FN	1,861,627,085	2,042,897,775	181,270,690	0.93
6	R_NC	1,838,257,086	2,019,527,776	181,270,690	0.83
7	R_N	1,733,832,536	1,915,103,226	181,270,690	0.84
8	R_GBR	1,522,471,326	1,703,742,015	181,270,690	0.84
9	OF_LAT	1,495,192,391	1,676,463,081	181,270,690	0.87
10	R_CS	1,281,789,546	1,463,060,236	181,270,690	0.89
11	OF_PR	993,489,482	1,174,760,172	181,270,690	0.92
12	R_S	637,092,484	818,363,174	181,270,690	1.09
13	R_C	539,912,894	721,183,584	181,270,690	1.15
14	PS_P	389,822,221	571,092,910	181,270,690	1.34
15	OF_AR	44,120,168	225,390,857	181,270,690	7.36
	C_COTS_CC	2,857,933,124	3,039,203,813.52	181,270,690	0.80
	C_COTS_CC_P	2,701,889,216	2,883,159,905.60	181,270,690	0.79
	C_COTS_CC_UNP	2,505,294,542	2,686,565,231.13	181,270,690	0.78

Table D.2. Median of Present Value of Net Benefit (AUS$) at 3%, 7%, and 10% discount rates.

Scenario	Median Present Value of Net Benefit (3%)	Median Present Value of Net Benefit (7%)	Median Present Value of Net Benefit (10%)
PS_UNP	3,101,531,394	2,335,980,473	1,948,478,638
ES_HC_CC	3,118,178,139	2,314,332,482	1,926,382,422
C_COTS_CC	2,956,851,134	2,186,887,600	1,800,752,512
C_COTS_CC_P	2,834,956,817	2,116,457,409	1,742,611,443
ES_HC	2,735,601,513	2,074,430,498	1,720,124,262
C_COTS_CC_UNP	2,697,746,183	1,994,306,185	1,648,893,159
R_FNN	2,538,821,462	1,934,766,595	1,613,437,994
R_NC	1,823,944,144	1,427,924,635	1,212,464,088
R_N	1,697,128,269	1,315,982,392	1,121,407,367
R_FN	1,780,444,396	1,310,152,922	1,068,778,852
R_GBR	1,596,627,986	1,186,252,866	973,798,120
OF_LAT	1,491,828,493	1,137,013,966	963,494,875
R_CS	1,246,952,568	999,041,410	855,352,483
OF_PR	1,074,398,126	720,205,157	540,580,174
R_S	576,393,824	439,369,206	365,158,423
R_C	431,849,771	357,858,121	314,050,858
PS_P	285,162,917	234,187,307	202,146,142
OF_AR	-57,983,618	-45,736,133	-40,462,964
C_COTS_CC	2,956,851,134	2,186,887,600	1,800,752,512
C_COTS_CC_P	2,834,956,817	2,116,457,409	1,742,611,443
C_COTS_CC_UNP	2,697,746,183	1,994,306,185	1,648,893,159

Table D.3. Risk assessment of alternative COTS control scenarios (7% discount rate).

Scenario	Fraction - positive trials	Present Value of Net Benefit – positive trials ($)	Present Value of Net Benefit - negative trials ($)
ES_HC	0.99	2,661,550,239	-339,853
ES_HC_CC	0.99	3,120,013,455	-294,787
OF_AR	0.42	139,182,850	-95,062,682
OF_LAT	0.98	1,496,398,405	-1,206,014
OF_PR	0.95	996,276,651	-2,787,167
PS_P	0.78	413,608,559	-23,786,338
PS_UNP	0.99	3,154,260,091	-467,166
R_C	0.84	552,176,758	-12,263,864
R_CS	0.96	1,284,137,571	-2,348,024
R_FN	0.95	1,864,777,095	-3,150,010
R_FNN	0.99	2,659,436,807	-632,835
R_GBR	0.98	1,523,515,912	-1,044,586
R_N	0.98	1,734,837,022	-1,004,486
R_NC	0.98	1,839,166,462	-909,376
R_S	0.86	648,046,890	-10,954,405
C_COTS_CC	0.99	2,858,197,202	-264,078
C_COTS_CC_P	0.99	2,702,177,224	-288,008
C_COTS_CC_UNP	0.99	2,505,595,341	-300,799

APPENDIX E – NEGATIVE VALUES OF ECOLOGICAL MODEL BENEFITS[15]

In ReefMod-GBR, most ecological processes are stochastic (background mortality, coral settlement, mortality by predation from COTS), and their occurrence and magnitude are determined by random drawing. For a given run of the model, a specific seed is assigned to the algorithm controlling the generation of (pseudo) random numbers to reproduce the timing and magnitude of stochastic events within two model scenarios (i.e. Counterfactual/COTS control). Yet, the exact same suite and magnitude of random events cannot be reproduced because the application of COTS control modifies the sequence of random number generation. This creates delta differences (i.e. COTS control – Counterfactual) for the selected outputs (e.g. percent coral cover, area of live coral) that can be either positive or negative at the reef level and at different points in time. These fluctuations should be viewed as random noise and not interpreted in relation to ecological gains or losses relative to the counterfactual. They typically tend to fade away when averaged across a fair number of stochastic runs (i.e. at least 20). Conversely, negative delta differences that persist across multiple stochastic runs likely indicate ecological feedback consecutive to the application of COTS control. This typically occurs when a population of COTS is culled after drastic reductions of coral cover: in the Counterfactual scenario, a low level of coral cover would eventually lead the COTS population to collapse due to starvation, whereas in the Control scenario, culling only resets COTS density to non-harmful levels, allowing the population to quickly recover and damage corals again (unless repeated culling is implemented).

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[15] Based on personal communication with Yves-Marie Bozec (May 2024).

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