Assessing alternative control scenarios for crown-of-thorns starfish on the Great Barrier Reef: An ensemble approach

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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.

Cover Photo Credit: Rick Abom, RRRC

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Acronyms and Abbreviations

AIMS	Australian Institute of Marine Science
CCIP	Crown-of-thorns starfish Control Innovation Program
CCP	Crown-of-thorns starfish Control Program
COTS	Crown-Of-Thorns Starfish
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DHW	Degrees Heating Weeks
ET	Ecological Threshold
FMP	Field Management Program
GBR	Great Barrier Reef
GBRF	Great Barrier Reef Foundation
IPM	Integrated Pest Management
LTMP	Long-Term Monitoring Program
NPR	Non-Priority Reefs
PR	Priority Reefs
Reef Authority	Great Barrier Reef Marine Park Authority
RRAP	Reef Restoration and Adaptation Program
SSP	Shared Socioeconomic Pathway
TO	Traditional Owner
TR	Target Reefs
UQ	The University of Queensland

EXECUTIVE SUMMARY

Crown-of-thorns starfish (COTS), a native pest of the Indo-Pacific, are known to devastate coral reefs by consuming large areas of live coral tissue, leading to significant coral mortality. On the Great Barrier Reef (GBR), persistent outbreaks of COTS populations have been a major factor in the substantial decline of coral cover over recent decades. While large-scale disturbances such as climate change and cyclones also contribute to coral loss, they are challenging to manage at a local level. In contrast, COTS populations can be managed through direct local interventions. The COTS Control Program employs teams of trained divers on dedicated vessels to manually cull COTS, thereby mitigating coral loss. However, selecting the most effective locations for targeted culling efforts is challenging as the GBR Marine Park spans over 14 degrees of latitude. Running various control scenarios in ecosystem models offers an opportunity to identify the most effective strategy to reduce COTS populations and slow the spread of their outbreaks. Using two distinct ecosystem models, ReefMod-GBR and CoCoNet, to identify scenarios that are consistently effective across both, we simulated 18 different control scenarios to guide management efforts. The first 15 scenarios were divided into two groups: "Spatial" (13 scenarios), which included distributing vessels across specific management areas (Far North, North, Central, South) or according to reef protection status (fished or unfished), and targeting the outbreak front (i.e. where COTS densities are highest); and "Effort Sink" (2 scenarios), which avoided deploying control on reefs where COTS densities were extremely high and would require a disproportionate culling effort to reduce numbers below management thresholds. A further three "Connectivity" scenarios adopted a dynamic approach, selecting reefs for control based on coral cover, their risk of spreading COTS larvae, and their protection status.

Our findings revealed substantial variations in the benefits of each scenario. Gains in coral area were positive for all control scenarios in ReefMod-GBR and for most scenarios in CoCoNet, emphasising the importance of targeted and continuous COTS control to enhance coral cover and reef resilience. Among the initial regional scenarios, the GBR-wide strategy had the greatest gains in coral area in ReefMod-GBR and performed well in CoCoNet for Priority Reefs (those prioritised for control based on ecological, economic, and cultural values), leading to marked reductions in outbreaking reefs across all reefs in both models. This is the strategy that most closely resembles the current COTS Control Program and demonstrates the effectiveness of broad, consistent control efforts. Both models supported prioritising control on unprotected reefs (Blue Zones), which may have less intact predator populations to naturally regulate COTS populations, and avoiding "effort sink" reefs with very high COTS densities. Excluding these effort sinks yielded modest additional benefits in ReefMod-GBR and major benefits in CoCoNet, improving both outbreak reduction and coral cover. Decisions to control these reefs will likely be context-dependent and should consider additional factors such as costs and logistics.

Dynamic control approaches that continually ranked and prioritised reefs with high coral cover and high COTS larval spread risk had similar gains in coral area as the GBR-wide strategy but had the lowest mean percentage of outbreaking Priority Reefs when compared across all scenarios in ReefMod-GBR, likely as they helped to stem the downstream supply

of COTS larvae, a key factor contributing to persistent outbreaks. However, these scenarios would require additional innovations in monitoring and prediction to implement. These findings highlight the need for a flexible, adaptive management strategy that integrates real-time data on coral cover and COTS populations ensuring that control efforts are dynamically targeted for maximum efficacy.

This study provides retrospective support for the GBR-wide vessel deployment strategy that most closely resembles the current COTS Control Program, but also underscores the necessity of continuous monitoring and refinement of control strategies. By adopting dynamic, data-driven approaches to COTS management, resource allocation can be optimised, achieving better outcomes for coral conservation. The integration of real-time monitoring and adaptive management will be crucial in responding to the ever-changing conditions of the GBR, ultimately enhancing the reef's resilience to COTS outbreaks and other stressors. This comprehensive strategy not only addresses immediate threats but also ensures sustainable management practices that can adapt to future challenges, securing the GBR's ecological health for future generations.

1. INTRODUCTION

Across terrestrial and aquatic ecosystems, pest species pose significant threats to both economic prosperity and ecological stability, contributing to declines in valuable resources (Levins and Wilson 1980; Kogan 1998; Westcott et al. 2016). Indeed, even native, problematic pest species can cause profound losses in biodiversity and productivity (Carey et al. 2012). While the need for effective pest management is evident, it is especially challenging in the aquatic environment, due to inherent difficulties in conducting effective monitoring and implementing adequate control efforts (Goldson et al. 2015; Hubert et al. 2019). One notable example of a marine pest is the corallivorous crown-of-thorns starfish (*Acanthaster* spp.; COTS). While COTS are native to the Indo-Pacific, regular and persistent outbreaks of their populations strip large areas of live coral tissue, causing widespread coral mortality (Yamaguchi 1986; Pratchett et al. 2014). Early detection of COTS outbreaks and an integrated pest management approach (IPM) (Westcott et al. 2016), which combines ecological knowledge with technological advances, is crucial for suppressing their populations and mitigating their impacts (Rogers et al. 2023).

On the Great Barrier Reef (GBR), coral cover is declining from a combination of stressors including rising sea temperatures leading to coral bleaching, tropical cyclones, and outbreaks of COTS (De'ath et al. 2012; Mellin et al. 2019; Bozec et al. 2022). While cyclones and increased water temperatures are hard to manage locally, COTS outbreaks, which account for substantial coral mortality on the GBR (De'ath et al. 2012; Bozec et al. 2022), are responsive to direct management action (Westcott et al. 2016; Fletcher et al. 2020; Castro-Sanguino et al. 2023). The COTS Control Program (CCP), established in 2012 by the Great Barrier Reef Marine Park Authority (Reef Authority), delivers a tactical response to persistent COTS outbreaks by using professionally trained divers on dedicated vessels to manually cull COTS using lethal injections of bile salts or vinegar (Fletcher et al. 2020). The goal of the CCP is not to eradicate all COTS but to reduce their densities below an ecological threshold (ET) where the rate of coral growth exceeds COTS predation (Babcock et al. 2014; Fletcher et al. 2020; Plagányi et al. 2020). Targeted culling in locations with the greatest benefit helps to reduce coral mortality and support future resilience of the GBR (Westcott et al. 2020; Rogers and Plagányi 2022; Rogers et al. 2023; Matthews et al. 2024).

Identifying the best reefs to cull in a marine park system spanning more than 14 degrees of latitude (2,300 km) presents a major challenge. With limited resources (e.g. 5–6 vessels), ensuring that control is implemented in the most effective locations is paramount. For example, focusing vessels in specific management areas (Far North, North, Central, South; **Figure 1**) or attacking the sector where COTS densities are the highest at a given time, rather than spreading resources more widely, could increase effectiveness in suppressing outbreaks and maintaining coral cover. Furthermore, certain reefs may require disproportionate effort to control effectively (known as "effort sinks"; Rogers et al. 2023), particularly if COTS densities are extremely high or because of complex geomorphic structures, e.g. internal bommie fields. In these cases, it may be more beneficial to move control to other reefs and spread resources more widely rather than focusing control resources on these potential effort sinks. Choosing which reefs to control, and how best to spread control effort, are therefore important considerations that may improve the efficacy of the current CCP, ultimately underpinning adaptive strategic management of COTS populations by the Reef Authority (Great Barrier Reef Marine Park Authority 2020).

Figure 1. The four management areas of the Great Barrier Reef Marine Park.

Ecosystem models play a pivotal role in pinpointing where culling may be most effective in reducing COTS densities and slowing down outbreak progression. Running different intervention scenarios can also enhance CCP efficacy by identifying control strategies with the greatest benefits. The literature describes a range of model formulations including ReefMod-GBR (Bozec et al. 2022; Castro-Sanguino et al. 2023), CoCoNet (Condie et al. 2018; Condie et al. 2021), CoTS-Mod (Matthews et al. 2020), and others (Fabricius et al. 2010; Morello et al. 2014; Vanhatalo et al. 2017; Rogers 2022). However, modelling COTS dynamics is complicated by the spatial and temporal variability of their populations at all life stages (Pratchett et al. 2014; Pratchett et al. 2017b). Performing validation of model predictions (including disturbance events) against in situ observations and incorporating and testing updated parameters from empirical studies can help to alleviate some of these complications.

Here, we use two spatially explicit ecosystem models of the GBR that vary in their spatiotemporal resolutions to simulate different control scenarios that the CCP might implement to improve ecological outcomes and long-term benefits. The advantage of using two complementary, but different, ecosystem models is that we can determine which scenarios are consistently effective across both, which will better support any future management decisions. Expected benefits arising from this project include enhanced modelling of COTS populations and outbreaks, a detailed assessment of the management benefits arising from different control scenarios, and recommendations to managers on the optimal strategies to adopt to maintain coral cover and suppress COTS outbreaks.

This project (CCIP-R-04: Regional modelling) sits within the COTS Control Innovation Program's (CCIP) Response Subprogram (**Figure 2**), which broadly aims to enhance modelling capabilities and develop more targeted decision support tools, ultimately contributing to a more efficient and effective operational response. There are key synergies with multiple other projects across the Response Subprogram, for example "CCIP-R-05: COTS dispersal ensemble modelling" (Choukroun et al. 2025) and "CCIP-R-06: Cost-effectiveness of control" (Scheufele et al. 2025) in particular, but also with projects in the Prediction and Detection Subprograms, which provide updated biological parameters to be used in the models, and refined COTS density predictions, respectively. The specific aims of this project were to:

- **AIM 1**: Optimise existing COTS control approaches.
- **AIM 2**: Quantify the benefits of different COTS control scenarios for coral reef health.
- **AIM 3**: Engage with managers, control programs, and other researchers to understand their key issues and support rapid uptake of research results.

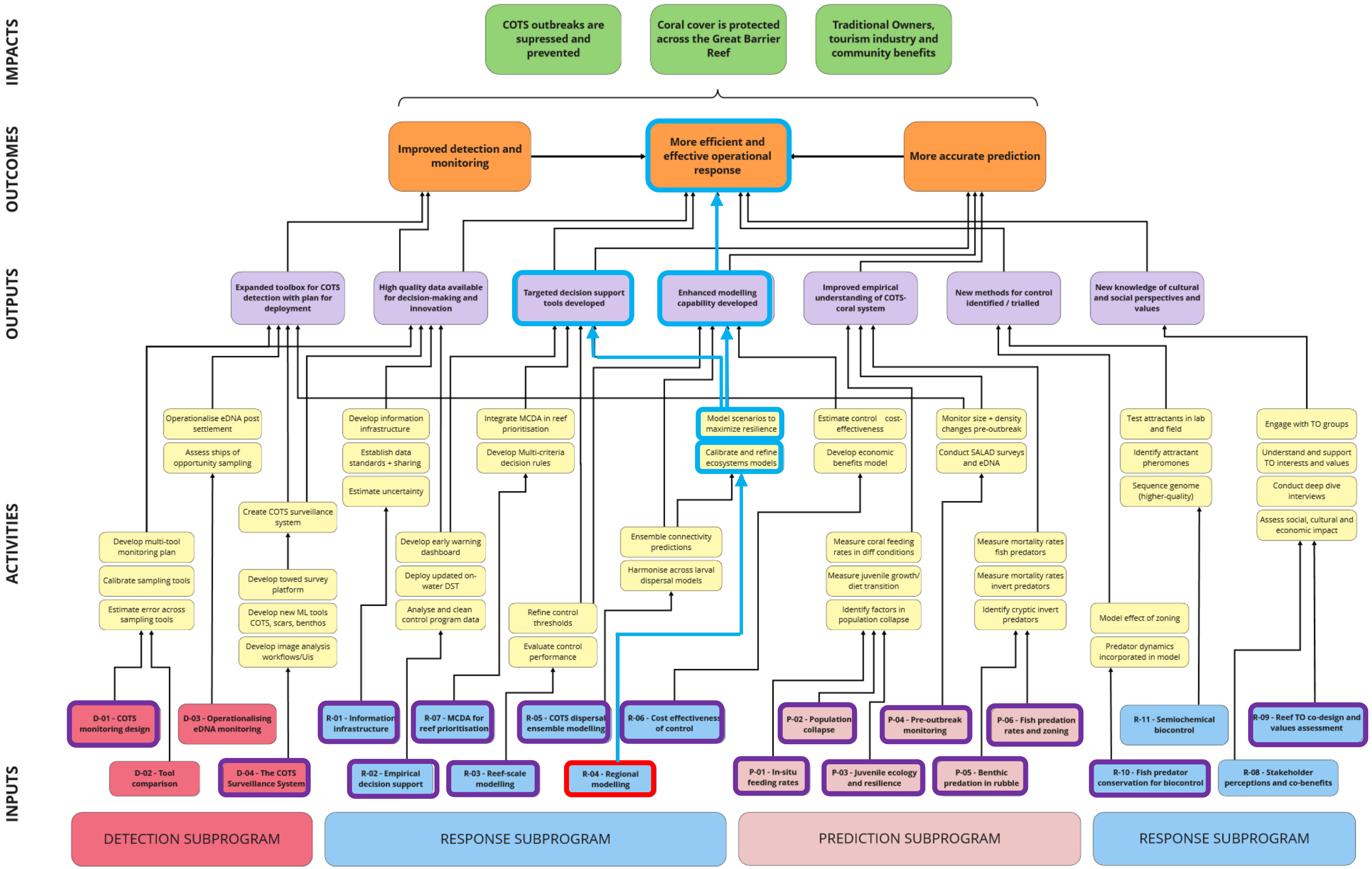

Figure 2. CCIP Program Logic with current project and its impact pathway highlighted. The current project (R-04: Regional modelling) is highlighted in red, its impact pathway in blue, and projects with which there are key current and potential future synergies in purple.

2. METHODS

Two spatially explicit ecosystem models of the GBR were employed to simulate various control scenarios that the CCP might implement to improve ecological outcomes and long-term coral health benefits: ReefMod-GBR (Mumby 2006; Mumby et al. 2007) and CoCoNet (Condie et al. 2018; Condie et al. 2021).

2.1 ReefMod-GBR

ReefMod (Mumby 2006; Mumby et al. 2007) simulates coral and COTS population dynamics along the ~2,300 km of the GBR in six-month timesteps. The model is described in detail in Bozec et al. (2022), so is only explained briefly here. In short, 3,806 individual reefs are represented by 20 x 20 m (400 m^2) grids which were colonised by individual coral colonies belonging to six morphological groups (acroporids: arborescent, plating, corymbose; non-acroporids: pocilloporids, encrusting/submassive, large massive) and by COTS. Both coral and COTS populations are driven by demographic processes: settlement, growth, reproduction, and mortality. The 4-km resolution eReefs hydrodynamic model provides particle tracking simulations for determining coral and COTS larval dispersal, and concentrations of total chlorophyll-*a* (Steven et al. 2019), which enhances COTS larval survival due to their dependence on phytoplankton availability (Wolfe et al. 2017).

COTS outbreak dynamics are simulated by structuring starfish into 6-month age classes and subjecting individuals to reproduction, chlorophyll-limited larval survivorship, food availability, and age-specific mortality (Bozec et al. 2022). Age-specific COTS mortality rates were sourced from the literature by first estimating daily mortality rates, then using these to fit an empirical model for mortality for each 6-month age class, up to a maximum of 16, i.e. 8 years (Pratchett et al. 2014). This was then calibrated to hindcast a time series (3 years) of monitoring data of COTS density from Lizard Island (Pratchett 2005). However, average COTS densities are 2.8-fold higher on fished reefs than on protected reefs (i.e. Green zones) (Kroon et al. 2021), suggesting that COTS mortality should be lower on fished reefs to reflect reduced natural predation from the removal of top predators (e.g. emperors, groupers). As such, on protected reefs (i.e. Green and Pink zones), COTS mortality rates were the same as those calibrated to Lizard Island (a Green zone), while on unprotected reefs (i.e. Blue and Yellow zones), each age-specific COTS mortality rate was reduced by 0.76 (Skinner et al. 2024) to reflect reduced mortality rates in fished zones from removal of top predators (Kroon et al. 2021). The mortality rate for the first age class (≤ 6 months) was kept uniform across all reefs as their primary predators are invertebrates, not reef fish (Cowan et al. 2017). Protection status for each reef was determined by the Great Barrier Reef Marine Park Reef Authority (Reef Authority, unpublished data). After 8 years (i.e. maximum age), die-back from disease (any time between 2 and 5 years) or starvation (total cover of preferential coral prey falls below 5%), COTS populations on reef patches were reset to background levels of 0.01 COTS per 400 m^2 grid (~0.004 COTS/tow) or 0.1 COTS per 400 m^2 grid (~0.04 COTS/tow) for reefs in the Initiation Box (an assumed area of high COTS density between <= -14.6 and >= -17 latitude; Pratchett et al. 2014). The full parameterisation and calibration of COTS dynamics is detailed in Bozec et al. (2022) and Castro-Sanguino et al. (2023).

For coral, individual reefs are initialised (2008) with coral cover (Australian Institute of Marine Science Long-Term Monitoring Program: AIMS LTMP) and community composition (214 reefs; Sweatman et al. 1998). Predictions of coral cover (2009–2018) show good congruence with 67 LTMP sites (Bozec et al. 2022). For COTS, individual reefs are initialised (2008) with adult COTS density predictions from the Coral and COTS network metacommunity model (CoCoNet), which is validated against LTMP COTS data (Condie et al. 2018). Only for COTS, where data exist, the model is forced with survey observations (COTS Control Program (CCP), Field Management Program (FMP), and LTMP), which overrides model predictions at individual reefs/years. While COTS densities are simulated as individuals per 400 m^2 grid, they are converted to COTS per tow densities to allow comparison with monitoring data. Manta tow densities are the total number of individual COTS recorded per 2-minute tow along a reef (COTS per tow).

Coral and COTS are also subjected to environmental pressures (e.g. heat stress, cyclones, water quality) that vary spatio-temporally. The model hindcast (2008–2023) uses realistic information for these (Bozec et al. 2022). For the model forecast, future heat stress regimes are derived from daily temperature predictions from the MIROC5 climate model under the RCP2.6 scenario (Mason et al. 2023), future cyclone regimes from synthetic cyclone tracks for the GBR (Wolff et al. 2016), and future water quality by randomly selecting the hindcast spatial layers of suspended sediments from the *eReefs* 4-km hydrodynamic model (Steven et al. 2019).

2.2 CoCoNet

The current version of the CoCoNet model is described in detail elsewhere (Condie and Porobic 2024), with only a brief overview provided here. The model simulates coral, COTS, and fish population dynamics across the GBR at 12-month timesteps. Each reef is resolved at the scale of individual COTS cull sites (10 ha – 500 x 200 m), where coral, COTS, benthic invertebrates, and fish populations are tracked through phases of settlement, growth, reproduction, and mortality.

Corals are represented by five coral groups (staghorn *Acropora*, tabular *Acropora*, *Montipora*, Poritidae, and Favids) that differ in growth rate and vulnerability to predation and environmental impacts. COTS are structured into six age classes, with juveniles only maturing to adults when their preferred coral prey is available (Deaker et al. 2020). While COTS outbreaks (> 15 COTS per ha) are an emergent property of the model, to ensure that their timing aligns with historical data, the probability of successful spawning is varied over a cycle that aligns with the observed outbreak cycle with a mean period of approximately 15 years. Benthic invertebrate and fish groups relevant to the predation of COTS (Kroon et al. 2021) are also represented in CoCoNet. These include an emperor fish group that prey directly on both juvenile and adult COTS (e.g. redthroat and spangled emperors), a benthic invertebrate group that prey on juvenile COTS (e.g. decorator crab), invertivorous fish that prey on benthic invertebrates (e.g. triggerfish), and a grouper group that prey on invertivorous fish (e.g. coral trout).

Larval dispersal and settlement estimates are based on probability density functions that describe the probability of larvae dispersing to a certain distance and direction from a source reef. These functions are referred to as dispersal kernels and were derived for every GBR reef using particle tracking methods applied to 10 years of *eReefs* ocean currents modelled at 1-km resolution (Steven et al. 2019; Condie et al. 2021). Cyclone and heatwave stresses are based on historically observed patterns, followed by stochastic projections based on climate model forecasts from 2024 (Condie and Porobic 2024).

2.3 COTS Control Program

The GBR COTS Control Program (CCP) is simulated from 2019 onwards, where COTS are culled across the entire GBR by 5 vessels (assuming 3,840 hours of in-water effort per vessel per year), largely following Castro-Sanguino et al. (2023). However, 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. The goal of the CCP is to reduce COTS densities below the ecological threshold (ET), which is where the rate of coral growth is higher than the rate of COTS consumption (Babcock et al. 2014). When COTS abundances are above the ET, control is implemented at individual cull sites (10 ha) (in ReefMod-GBR, each reef is split into individual cull sites). The number of cull sites for each reef was determined as follows; 1) **Existing Data**: If the number of cull sites for a reef is already available from the Reef Authority (unpublished data), this value is used. 2) **No Existing Data**: If the number of cull sites is not available for a reef, a linear regression model based on the Control Program data and the Reference Area is applied. The Reference Area represents the two-dimensional (2D) area (km²) of the reef polygons used by the Reef Authority, which considers a total area of 24,776.37 km^2 for all 3,806 reefs (Table A1). The equation (1) for the fit is:

$$Number\ Of\ Cull\ Sites = 12.1289 + 0.767723 * ReferenceArea \quad (1)$$

which has an adjusted R^2 of 0.69. The result is then rounded to the nearest integer. This resulted in 64,944 cull sites across the 3,806 reefs (**Table A1**). While several regressions were tested using a range of different reef area metrics, this was the most parsimonious. The Reef Authority identifies 500 Priority Reefs (PR) for control based on ecological, economic, and cultural values. From this, a dynamic Target Reef (TR) list is generated each year to guide and prioritise control activities. In the models, a fixed TR List was created (n = 224) by selecting all PR that were controlled at least twice over a three-year period (21/22, 22/23, and 23/24; Reef Authority, unpublished data). At each timestep, control starts first at TR, then PR, then Non-Priority Reefs (NPR), until all effort has been used. Within each run, a consistent randomisation is maintained so the order of reef visitation is the same at each timestep.

2.4 Stakeholder engagement

Continuous engagement with stakeholders occurred throughout the project. Most importantly, all control scenarios were initially developed with key stakeholders (Reef

Authority, Great Barrier Reef Foundation (GBRF)) and collaborators (University of Queensland (UQ), Commonwealth Scientific and Industrial Research Organisation (CSIRO)). Potential scenarios aimed to address management objectives that might be realistically achieved through the current CCP, so all scenarios were fully aligned with current management priorities and research capabilities. Specific stakeholder engagement activities also took place on a regular basis to ensure adequate communication and knowledge transfer across key groups. For example, during the first year of the project (Feb 2023), Christina Skinner joined one of the COTS control vessels (RV Infamis - Blue Planet Marine) for a culling voyage. This allowed for detailed discussions of the candidate scenarios with the on-water operators and a better understanding of how to model the complex on-water decision making process. Outputs from initial scenarios were also presented to a wider group of stakeholders at the COTS Action Group Meeting (May 2023), which provided an opportunity to share knowledge across the modelling and on-water teams. Furthermore, during the November 2023 CCIP workshop, there were discussions with CCIP-R-09 ("Reef TO co-design and value assessment", Backhaus et al. 2025) and Trevor Tim (ExperienceCo) on how to develop scenarios involving Traditional Owner (TO) vessels specifically surveying or culling on their own Sea Country. While there are still details which need to be considered to test these appropriately in the regional models, this was a useful initial conversation to understand some of the complexities and will serve as a starting point for future discussions. Finally, there has been continuous communication with the Reef Authority throughout the project to ensure that the scenarios remain well aligned with their needs. Interim results from the model outputs were also used to help guide the regional allocation of vessels for the 2024/25 financial year. The culmination of this was a meeting in May 2024 where all final outputs were communicated to representatives from both the Reef Authority and GBRF.

2.5 Scenarios

The final list of 18 control scenarios (**Table 1**) is separated into three major groups, each containing several sub strategies: 1) *Spatial* (n = 13); 2) *Effort Sink* (n = 2); and 3) *Connectivity* (n = 3). All scenarios use the same future climate scenario (Shared Socio-economic Pathway 2.6) based on the same climate model (General Circulation Model *CNRM-ESM2-1)* for ReefMod-GBR, or the same probability distributions based on a set of climate models for CoCoNet. In ReefMod-GBR, scenarios start in summer 2008 and end in winter 2040, with each scenario repeated 20 times to account for stochasticity in the systems. CoCoNet scenarios start in 1956 and end in 2040, with each scenario repeated 20 times. The counterfactual scenario for both models excluded COTS control, while for all other scenarios the CCP started in 2019 as this timing corresponds with the expansion of the CCP and on-water implementation of IPM. All 18 scenarios were run in ReefMod-GBR, whereas project resources limited CoCoNet runs to a subset of 10 that could be readily accommodated within the existing model structure.

2.5.1 Spatial

Regional

Eight of the spatial scenarios allocate control effort amongst the four Reef Authority management regions (Far North, North, Central, South; **Figure 1**). For these, the total effort pool from all five vessels is restricted to specific combinations of regions: 1) *GBR wide* – control operates across the entire GBR (R_GBR); 2) *Far North* (R_FN); 3) *Far North and North* (R_FNN); 4) *North* (R_N); 5) *North and Central* (R_NC); 6) *Central* (R_C); 7) *Central and South* (R_CS); 8) *South* (R_S) (**Table 1**). The rationale behind these scenarios is that focusing control efforts in specific regions where outbreaks are thought to initiate may help to stop the downstream spread of COTS.

Protection Status

Two of the spatial scenarios consider reef protection status. Reefs are either protected (i.e. Green/Pink zones) or unprotected (i.e. Blue/Yellow zones). Here, the CCP operates across the entire GBR but exclusively controls on 1) *unprotected reefs* (PS_UNP); or 2) *protected reefs* (PS_P) (**Table 1**). The rationale behind this is that protected reefs may have higher COTS mortality due to predation (Kroon et al. 2021), thereby offering an inherent degree of natural resilience by suppressing COTS populations. Required control efforts to reduce COTS below the ET will likely be lower on protected reefs, allowing resources to be spread more broadly. In contrast, on unprotected reefs, more concentrated effort might be required, resulting in fewer controlled reefs. *Note: while these two extreme scenarios are unlikely to be implemented, they help ascertain how reef zone status may impact control activities.*

Outbreak Front

Three of the spatial scenarios focus on controlling the dynamic front of outbreaking reefs. For these, the CCP still operates across the entire GBR, but follows the outbreak front based on different criteria: 1) *latitude*: at each timestep, TR are controlled first, then any PR or NPR with outbreaks in the immediate vicinity (i.e. within +/-0.5-degree latitude) are also controlled (OF_LAT); 2) *COTS densities across all reefs*: at each timestep, the sector (**Figure 3**) with the highest total density of COTS (per manta tow) across all reefs (TR, PR, NPR) is controlled first. Within that sector, control is applied to all reefs (subject to effort availability). The process is then repeated for remaining sectors, with sector order recalculated at each timestep (OF_AR); 3) *COTS densities across TR and PR*: At each timestep, the sector (**Figure 3**) with the highest total density of COTS across TR and PR only is controlled first. Within that sector, control is applied to TR and PR only (NPR are excluded). The process is then repeated for remaining sectors, with sector order recalculated at each timestep (OF_PR) (**Table 1**). The rationale behind these scenarios is that controlling the outbreak front will slow the downstream spread of COTS, helping to suppress outbreaks.

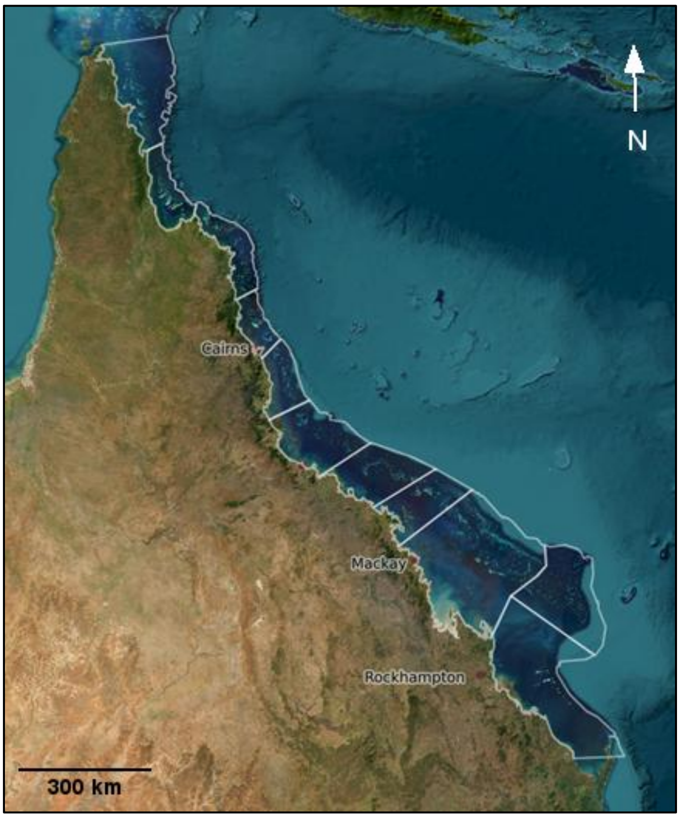

Figure 3. The eleven management sectors of the Great Barrier Reef Marine Park.

2.5.2 Effort Sink

The two effort sink scenarios implement a starting rule to avoid controlling reefs that may take a disproportionate amount of effort. The CCP still operates across the entire GBR, but reefs are not controlled under two conditions: 1) high COTS: any reef with > 3 COTS per tow is removed from the control list (ES_HC); and 2) high COTS with limited coral to save: any reef with > 3 COTS per tow is removed from control unless coral cover is > 20% (ES_HCC) (**Table 1**). The rationale for these is that certain reefs may take a disproportionate amount of effort to control when COTS densities are high, so effort is concentrated on one reef rather than distributed among many. However, in some instances, e.g. if there is high coral cover worth saving, it may still be worth using a substantial amount of effort. The 20% coral cover threshold was chosen based on empirical evidence that, beyond this point, coral recruitment levels off after bleaching events (Gilmour et al. 2013) and the GBR enters an exponential recovery phase (Halford et al. 2004).

2.5.3 Connectivity

The connectivity scenarios adopt a more dynamic approach than the previous scenarios (only implemented in ReefMod-GBR). While they still operate across the entire GBR, there are no TR, and so these scenarios are considered separately. For the first scenario (C_COTS_CC), at each timestep, all PR are ranked by coral cover (minimum threshold >

20% coral cover; Halford et al. 2004; Gilmour et al. 2013) and then by the amount of COTS larvae they will spread to adjacent reefs. PR with the greatest coral cover and greatest risk of spreading COTS larvae are controlled first, and then the remaining PR in order. This is repeated for PR with < 20% coral cover. The same process is then applied to NPR. The ranking is recalculated at each timestep. The other two scenarios in this group follow the same process, except when reefs have a similar ranking. Then for scenario C_COTS_CC_P, preference is given to protected reefs (i.e. Green or Pink zones), whereas for C_COTS_CC_UNP, preference is given to unprotected reefs (i.e. Blue or Yellow zones). The rationale behind these is that forecasting the spread of COTS larvae, while saving as much coral as possible, may reduce outbreaks and save coral cover.

Table 1. Full list and description of all scenarios implemented in the ecosystem models. TR = Target Reefs; PR = Priority Reefs; NPR = Non-Priority Reefs; ts = timestep. [a] = only run in ReefMod-GBR. * = scenarios closest to the current COTS Control Program (CCP). SSP = Shared Socioeconomic Pathway.

Strategy	Sub strategy	Code	Brief description
Counterfactual	SSP2.6	CF_SP2.6	No CCP; climate scenario SP2.6.
Spatial	Regional - GBR*	R_GBR*	CCP across the whole GBR.
Spatial	Regional - Far North	R_FN[a]	CCP across FN regions only.
Spatial	Regional - Far North, North	R_FNN	CCP across FN, N regions only.
Spatial	Regional - North	R_N[a]	CCP across N regions only.
Spatial	Regional - North, Central	R_NC	CCP across N, C regions only.
Spatial	Regional - Central	R_C	CCP across C region only.
Spatial	Regional - Central, South	R_CS	CCP across C, S regions only.
Spatial	Regional - South	R_S[a]	CCP across S region only.
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 reefs that are protected (i.e. no fishing).
Spatial	Outbreak Front - Latitude	OF_LAT[a]	CCP across whole GBR, but control at TR first, then all PR or NPR with outbreaks within +/-0.5-degree latitude of the TR.
Spatial	Outbreak Front - All Reefs	OF_AR	At each *ts*, rank sectors by total COTS density across all reefs (TR, PR, NPR). Control all reefs in the highest-ranked sector, then continue

Strategy	Sub strategy	Code	Brief description
			in order until effort is used. Re-rank sectors each *ts*.
Spatial	Outbreak Front - Priority Reefs	OF_PR[a]	At each *ts*, rank sectors by total COTS density across TR and PR only. Control TR and PR in the highest-ranked sector (NPR excluded), then continue in order until effort is used. Re-rank sectors each *ts*.
Effort sink	High COTS	ES_HC	CCP across whole GBR but no control when COTS density > 3 per manta tow.
Effort sink	High COTS, with coral to save	ES_HCC	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*[a]	At each *ts*, rank PR by COTS larval output and coral cover. Then do same for NPR.
Connectivity	COTS Larvae, Coral Cover, Protected Reefs	C_COTS_CC_P[a]	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[a]	As in C_COTS_CC, but when reef rankings are similar, unprotected reefs (i.e. fishing) are prioritised.

2.6 Benefit metrics

There are a vast number of metrics that could be calculated to provide information on the effectiveness of the different control scenarios compared to the counterfactual. For simplicity, and to align with previous studies (Castro-Sanguino et al. 2023), here we primarily consider two key benefits across all scenarios: 1) change in coral area (hectares); and 2) change in outbreaking reefs (percentage of reefs) where a reef is classified as outbreaking when its mean COTS density exceeds 0.22 COTS per manta tow or 15 COTS per hectare. Both metrics represent the difference in the variable between the control scenario and the counterfactual, i.e. 1) change in coral area = coral area scenario - coral area counterfactual, and 2) change in outbreaking reefs = outbreaking reefs scenario - outbreaking reefs counterfactual. For 1), the coral area for each reef was calculated by summing the percentage of coral cover across all 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. For all scenarios and for both benefit metrics, we consider how these vary across PR (n = 500), and 2) all reefs (n = 3,806).

For all scenarios, changes in coral area and outbreaking reefs were calculated as follows: 1) for each reef in each year, the delta (scenario – counterfactual) was calculated for each individual scenario run; 2) for each reef in each year, the mean delta was taken across all runs within the scenario; 3) for each year, all mean or median delta values were averaged across 1) PR and 2) all reefs. For outbreaking reefs, the number was converted to a % relative to the number of reefs (500 PRs and 3,806 total reefs) using the following equation 2:

$$\frac{OR}{(R * Y)} \times 100 \qquad (2)$$

where OR is the change in the number of outbreaking reefs, R is the number of reefs, and Y is the number of years of control.

An additional metric, the maximum annual mean change, identified the year with the largest gain in coral area or the greatest reduction in outbreaking reefs between 2020 and 2040, based on the mean of the 20 individual runs for that year.

3. RESULTS

3.1 ReefMod-GBR

3.1.1 Counterfactual

For the counterfactual scenario with no COTS control, mean (10th and 90th percentiles) coral cover across the GBR declined from ~23% (22.5–23.6%) to 11% (8.6–14.9%) between 2020 and 2040 (**Figure 4a**). Similarly, mean (10th and 90th percentiles) coral area across the GBR declined from 169.2 ha (52.4–293.1 ha) to 79.2 ha (22.1–154.6 ha) (**Figure 4b**), and the mean (10th and 90th percentiles) percentage of outbreaking reefs declined from 13.6% (12.5–15.1%) to 2% (0.6–4.3 %) (**Figure 4c**).

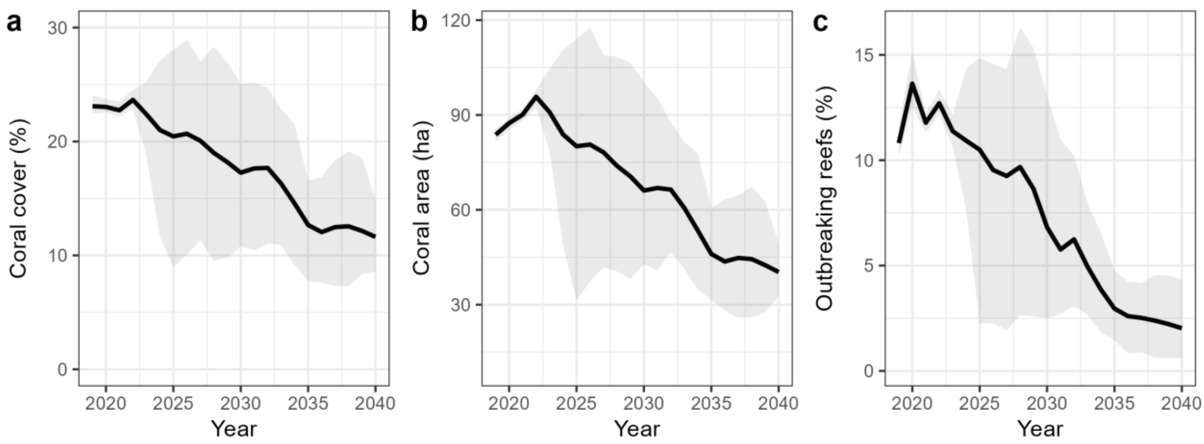

Figure 4. a) Coral cover (%), b) coral area (ha), and c) outbreaking reefs (%) for the counterfactual scenario with no COTS control from 2020 to 2040. The black line represents the mean across all simulation runs while the ribbons represent the 10th and 90th percentiles.

3.1.2 Control scenarios

There was substantial variability in the benefits derived from the 15 control scenarios belonging to the Spatial and Effort Sink groups (**Table 2**; A2; A3). The benefits also varied depending on whether considering only Priority Reefs or all reefs. All changes in mean coral area (ha) were positive across all scenarios. For Priority Reefs, mean (10th–90th percentile) coral area change averaged across 2020–2040 ranged from 464 ha (320–610 ha) for the scenario targeting the outbreak front across all reefs (OF_AR), to 6,379 ha (1,834 – 10,385 ha) for the effort sink scenario that also saved hard coral (ES_HCC). For all reefs, mean coral area change (ha) ranged from 676 ha (445–862 ha) for the scenario targeting the outbreak front across all reefs (OF_AR) to 6,738 ha (1,900–10,876 ha) for the effort sink scenario that also saved hard coral (ES_HCC) (**Table 2**; A2).

For Priority Reefs, changes in the mean percentage of outbreaking reefs across 2020–2040 ranged from -0.09% (-0.31 to 0.27%) for the scenario targeting the outbreak front across all reefs (OF_AR) to -2.10% (-4.23 to -0.36%) for the scenario focusing on the Central and South regions (R_CS). For all reefs, changes in the mean percentage of outbreaking reefs ranged from -0.2% (-0.48 to 0.00%) for the scenario focused solely on the North region (R_N) to -1.26% (-2.04 to -0.33%) for the scenario focused solely on the Far North region (R_FN) (**Table 2**; Table A3).

Table 2. Change in mean coral area (ha) and outbreaking reefs (%) across the 500 Priority Reefs and all 3,806 reefs from the 15 control scenarios compared to the counterfactual in ReefMod-GBR. Values represent the mean change across 20 simulation runs for each year, averaged over the period 2020–2040. Top five performing scenarios are highlighted in green and the worst performing scenario is highlighted in red.

		Coral area (ha)		Outbreaking reefs (%)	
Group	**Scenario**	**Priority**	**All**	**Priority**	**All**
Regional	R_GBR	6,220	6,585	-2.00	-0.65
	R_FN	1,265	2,440	-0.49	-1.26
	R_FNN	3,954	4,256	-0.72	-0.38
	R_N	3,802	4,136	-0.49	-0.20
	R_NC	4,086	4,286	-0.93	-0.24
	R_C	1,577	2,179	-0.82	-0.80
	R_CS	2,589	3,122	-2.10	-0.91
	R_S	1,840	2,344	-1.73	-0.98
Protection Status	PS_UNP	4,573	4,883	-1.53	-0.55
	PS_P	1,925	2,304	-1.36	-0.53
Outbreak Front	OF_LAT	4,224	4,442	-1.27	-0.40
	OF_AR	464	676	-0.09	-0.30
	OF_PR	5,184	5,491	-2.02	-0.57
Effort Sink	ES_HC	6,352	6,709	-2.09	-0.64
	ES_HCC	6,379	6,738	-2.09	-0.64

Coral area

Patterns in mean coral area change across scenarios were similar whether considering only Priority Reefs (**Figure 5** or all reefs (**Figure A1**), suggesting limited propagation of benefits beyond Priority Reefs. Within scenario groups, certain scenarios led to greater gains in coral area compared to others: GBR-wide control among the regional scenarios (**Figure 5**a; A1a); controlling unprotected reefs compared to protected reefs (**Figure 5b; A1b**); and for the outbreak front, prioritising sectors with the highest density of COTS across Priority Reefs (**Figure 5c; A1c**). Both effort sink scenarios led to high gains in coral area and there was little difference between the two (**Figure 5d; A1d**).

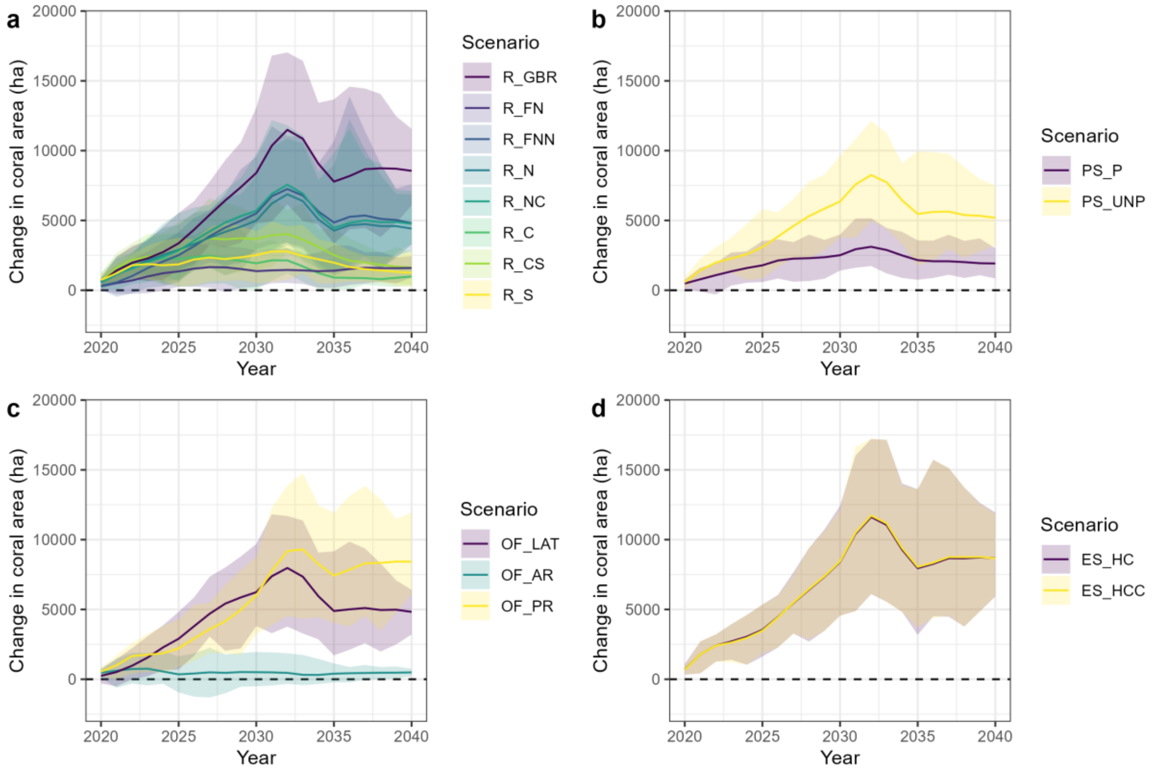

Figure 5. Change (scenario – counterfactual) in mean coral area (ha) of Priority Reefs each year for 15 control scenarios in ReefMod-GBR. Groups are a) regional, b) protection status, c) outbreak front, and d) effort sink. The lines represent the mean across all simulation runs while the ribbons represent the 10th and 90th percentiles.

Comparing the best scenarios from all groups revealed that the GBR-wide scenario (R_GBR) and the two effort sink scenarios (ES_HC; ES_HCC) performed similarly and led to the greatest gains in coral area for both Priority Reefs (**Figure 6a**) and all reefs (**Figure 6b**) up until ~2035. From 2035 onwards, the scenario focusing on the outbreak front across Priority Reefs (OF_PR) also had similar gains in coral area for both Priority Reefs and all reefs (**Figure 6**).

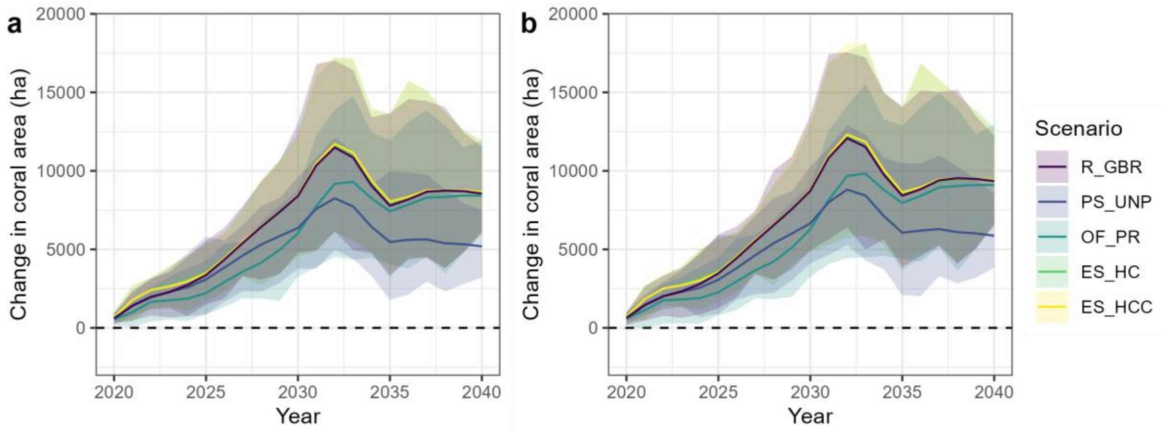

Figure 6. Change (scenario – counterfactual) in mean coral area (ha) of a) Priority Reefs and b) all reefs each year for the most promising control scenarios in ReefMod-GBR. The lines represent the mean across all simulation runs while the ribbons represent the 10th and 90th percentiles.

Maximum coral area gains within the period 2020–2040 followed similar patterns to the scenario means (**Table 3**). For PR, maximum benefits were seen from 2023–2033, with most scenarios having maximum coral area benefits in 2032. For all reefs, maximum coral area benefits occurred exclusively post-2030, from 2032–2040. This is likely as all PR would have been managed by then, allowing the focus to be redirected to the remaining NPR. The largest maximum annual mean gains in coral area (ha) occurred under the ES_HCC scenario for both Priority Reefs (11,719 ha) and for all reefs (12,321 ha).

Table 3. Maximum annual mean coral area (ha) gain between 2020 and 2040 across the 500 Priority Reefs and all 3,806 reefs from the 15 control scenarios compared to the counterfactual in ReefMod-GBR (mean across 20 simulation runs). The year in which the largest single-year gain occurs is reported. Values in bold indicate the highest gain for each metric across all scenarios.

	Priority Reefs		All Reefs	
Scenario	**Year maximum benefit occurs**	**Change (ha)**	**Year maximum benefit occurs**	**Change (ha)**
R_GBR	2032	11,492	2032	12,083
R_FN	2027	1,657	2033	3,496
R_FNN	2032	7,252	2032	7,874
R_N	2032	6,875	2032	7,683
R_NC	2032	7,558	2032	7,998
R_C	2027	2,457	2032	3,312
R_CS	2032	4,022	2032	5,100
R_S	2031	2,776	2032	3,799
PS_UNP	2032	8,252	2032	8,806
PS_P	2032	3,114	2032	3,962
OF_LAT	2032	7,971	2032	8,348
OF_AR	2023	755	2040	887
OF_PR	2033	9,298	2033	9,824
ES_HC	2032	11,626	2032	12,247
ES_HCC	2032	**11,719**	2032	**12,321**

Outbreaking reefs

In the counterfactual scenario, outbreaking reefs are initially common across the GBR (~10–15% of reefs in 2020; **Figure 4b**). Their subsequent decline toward 0% by 2040 is likely driven by climate-induced losses of coral cover, which reduce food availability for COTS, rather than by natural outbreak cycles or direct thermal effects on COTS, which are not yet included in the model. Consequently, the effects of different control scenarios are most pronounced between 2020 and 2035, with the percentage of outbreaking reefs plateauing near zero by the end of 2040. This suggests that the benefits of control for reducing outbreaking reefs diminish toward the end of 2040, as there is limited scope for further improvement once outbreak prevalence is already low.

Patterns across scenarios were different whether considering only PR (**Figure A2**) or all reefs (**Figure A3**). Within groups, certain scenarios led to greater decreases in the percentage of outbreaking reefs compared to others. For PR, this was the GBR wide (R_GBR) and Central-South (R_CS) among the regional scenarios (**Figure A2a**), controlling protected reefs (PS_P) up until 2025 and then focusing on unprotected reefs (PS_UNP; **Figure A2b**), and for the outbreak front, prioritising sectors with the highest density of COTS across PR (OF_PR; **Figure A2c**). When considering all reefs, the Far North (R_FN) or South (R_S) scenarios led to the greatest reductions in outbreaking reefs among the regional scenarios (**Figure A3a**), controlling protected reefs (PS_P) until 2030 and then unprotected reefs until 2040 (PS_UNP; **Figure A3b**), and for the outbreak front, prioritising sectors with the highest density of COTS across PR (OF_PR; **Figure A3c**). Both effort sink scenarios (ES_HC; ES_HCC) led to similar reductions in outbreaking reefs, whether considering PR (**Figure A2d**) or all reefs (**Figure A3d**).

Unlike for coral area change, the best scenarios for reducing outbreaking reefs across all reefs, or just PR, changed over time. For PR, initially (~2020 to 2027), the Central-South (R_CS) scenario from the regional group led to the greatest reductions in outbreaking reefs, whereas from 2027–2032 the scenario focusing on the outbreak front across PR (OF_PR) did (**Figure 7a**). From 2032 until 2040, several scenarios (R_GBR, OF_PR, ES_HC, ES_HCC) were equally effective. For all reefs, the Far North (R_FN) regional scenario led to the greatest reductions in outbreaking reefs across the entire timeframe, though the regional scenario focusing on the Southern region (R_S) also performed well (**Figure 7b**).

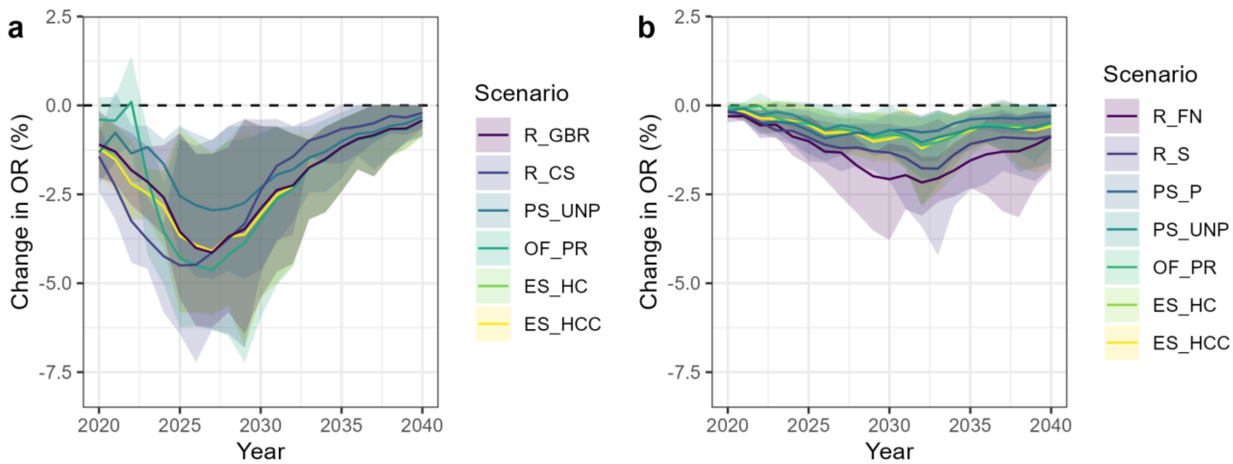

Figure 7. Change (scenario – counterfactual) in mean outbreaking reefs (OR; %) across a) Priority Reefs and b) all reefs each year for the most promising control scenarios in ReefMod-GBR. The lines represent the mean across all simulation runs while the ribbons represent the 10th and 90th percentiles.

Maximum reductions in outbreaking reefs across 2020–2040 followed similar patterns to the scenario means (**Table 4**). For PR, maximum benefits were seen from 2022–2029, with most scenarios having maximum outbreaking reef benefits in 2027. For all reefs, maximum outbreaking reef benefits occurred later from 2026–2039, with most in 2032. As with coral area, this is likely as all PR would have been managed by then, allowing the focus to be redirected to the remaining NPR. The largest maximum annual mean change in outbreaking reefs (%) occurred under the OF_PR scenario for Priority Reefs (-4.63%) and under the R_FN scenario for all reefs (-2.17%).

Table 4. Maximum annual mean change in outbreaking reefs (%) between 2020 and 2040 across the 500 Priority Reefs and all 3,806 reefs from the 15 control scenarios compared to the counterfactual in ReefMod-GBR (mean across 20 simulation runs). The year in which the largest single-year change occurs is reported. Values in bold indicate the largest change for each metric across all scenarios.

	Priority Reefs		All Reefs	
Scenario	**Year maximum benefit occurs**	**Change (%)**	**Year maximum benefit occurs**	**Change (%)**
R_GBR	2027	-4.14	2032	-1.18
R_FN	2022	-0.76	2032	**-2.17**
R_FNN	2029	-1.46	2029; 2032	-0.72
R_N	2028	-1.22	2029	-0.61
R_NC	2029	-2.11	2029	-0.70
R_C	2028	-1.62	2032	-1.20
R_CS	2025	-4.50	2032	-1.66
R_S	2023	-3.77	2033	-1.78
PS_UNP	2027	-2.95	2032	-1.04
PS_P	2023	-2.99	2026	-0.92
OF_LAT	2026	-3.07	2029	-0.83
OF_AR	2029	-0.47	2039	-0.86
OF_PR	2027	**-4.63**	2032	-1.13
ES_HC	2027	-4.13	2032	-1.19
ES_HCC	2027	-4.09	2032	-1.21

Connectivity scenarios

Unlike the previous scenarios, the three connectivity scenarios did not use a Target Reef list. For both PR and all reefs, the scenario that did not consider reef protection status (C_COTS_CC) had the greatest gains in mean coral area (10th – 90th percentile) across PR of 5,954 ha (2,053–9,227 ha) and for all reefs of 6,478 ha (2,051–9,928 ha) (**Table 5**; A2). The greatest reduction in outbreaking reefs was achieved by prioritising unprotected reefs (C_COTS_CC_P), leading to a mean reduction of -2.53% (-4.58 to -0.70%) for PR, and -0.84% (-1.22 to -0.30%) for all reefs (**Table 5**; A3).

Table 5. Change in mean coral area (ha) and mean outbreaking reefs (%) across the 500 Priority Reefs and all 3,806 reefs from the connectivity control scenarios compared to the counterfactual in ReefMod-GBR. Values represent the mean change across 20 simulation runs for each year, averaged over the period 2020–2040. Values in bold indicate the largest change for each metric across all scenarios.

	Coral area (ha)		Outbreaking reefs (%)	
Scenario	**Priority**	**All**	**Priority**	**All**
C_COTS_CC_P	5,578	6,021	-2.47	-0.81
C_COTS_CC_UNP	5,696	6,181	**-2.53**	**-0.84**
C_COTS_CC	**5,954**	**6,478**	-2.31	-0.79

All three connectivity scenarios led to similar management benefits as the most promising scenario (R_GBR) from the initial group of scenarios (**Figure 8**). The connectivity scenario that did not consider protection status (C_COTS_CC) had the greatest gains in coral area (ha) from 2020–2024 and from 2035–2040, while the GBR scenario (R_GBR) had the greatest gains in coral area from 2024–2035 (**Figure 8a**). In terms of reducing the number of outbreaking reefs, the most effective connectivity scenario was predominantly the connectivity scenario that also prioritised unprotected reefs (C_COTS_CC_UNP), though all connectivity scenarios were more effective than the GBR scenario (**Figure 8b**).

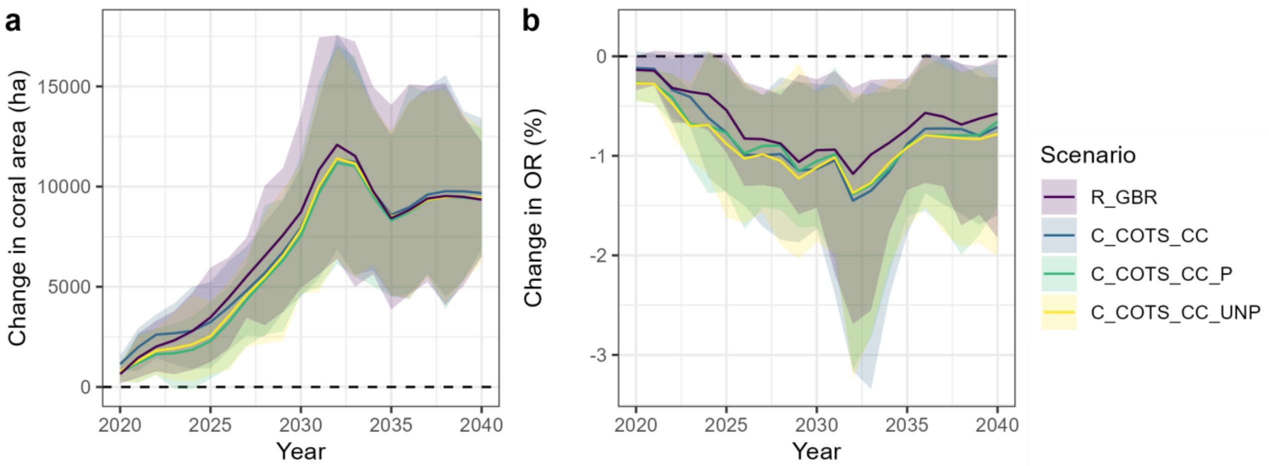

Figure 8. Change in mean a) coral area (ha) and b) outbreaking reefs (%) across all reefs for the three connectivity scenarios, with the most promising initial scenario (R_GBR) included as a reference. The lines represent the mean across all simulation runs while the ribbons represent the 10th and 90th percentiles.

Maximum gains in coral area did not follow the same patterns as the scenario means, though absolute values were very similar across the three scenarios. For both PR and all reefs, maximum coral area benefits were derived from the scenario that focused on unprotected reefs (C_COTS_CC_UNP) rather than the scenario that did not consider protection status (C_COTS_CC) (**Table 6**). For reductions in outbreaking reefs, patterns for PR were the same with the scenario that focused on unprotected reefs (C_COTS_CC_UNP) as the most effective, while for all reefs maximum reductions in outbreaking reefs were seen in the scenario that did not consider protection status (C_COTS_CC). For both PR and all reefs, maximum gains in coral area occurred in 2032, while for outbreaking reefs, maximum benefits occurred in 2026 for PR and in 2032 for all reefs.

Table 6. Maximum annual mean change in coral area (ha) and outbreaking reefs (%) between 2020 and 2040 across the 500 Priority Reefs and all 3,806 reefs from the connectivity control scenarios compared to the counterfactual in ReefMod-GBR (mean across 20 simulation runs). The year in which the largest single-year change occurs is reported. Values in bold indicate the largest change for each metric across all scenarios.

	Coral area (ha)				Outbreaking reefs (%)			
	Priority		All		Priority		All	
Scenario	Year	Change	Year	Change	Year	Change	Year	Change
C_COTS_CC_P	2032	10,364	2032	11,186	2026	-4.90	2032	-1.39
C_COTS_CC_UNP	2032	**10,604**	2032	**11,404**	2026	**-5.08**	2032	-1.37
C_COTS_CC	2032	10,489	2032	11,384	2026	-5.00	2032	**-1.45**

3.2 CoCoNet

3.2.1 Counterfactual

For the counterfactual scenario with no COTS control, mean (10th and 90th percentiles) coral cover across the GBR declined from 23.9% (21.6–27.1%) to 22.5% (14.6–30.2%) between 2020 and 2040 (**Figure 9**a). During the same period, the mean (10th and 90th percentiles) percentage of outbreaking reefs increased from 6.5% (3.4–10.7%) in 2020 to 7.1% (2.2–10.8%) in 2040 (**Figure 9**b). These changes are much less than those generated by ReefMod-GBR (**Figure 4**).

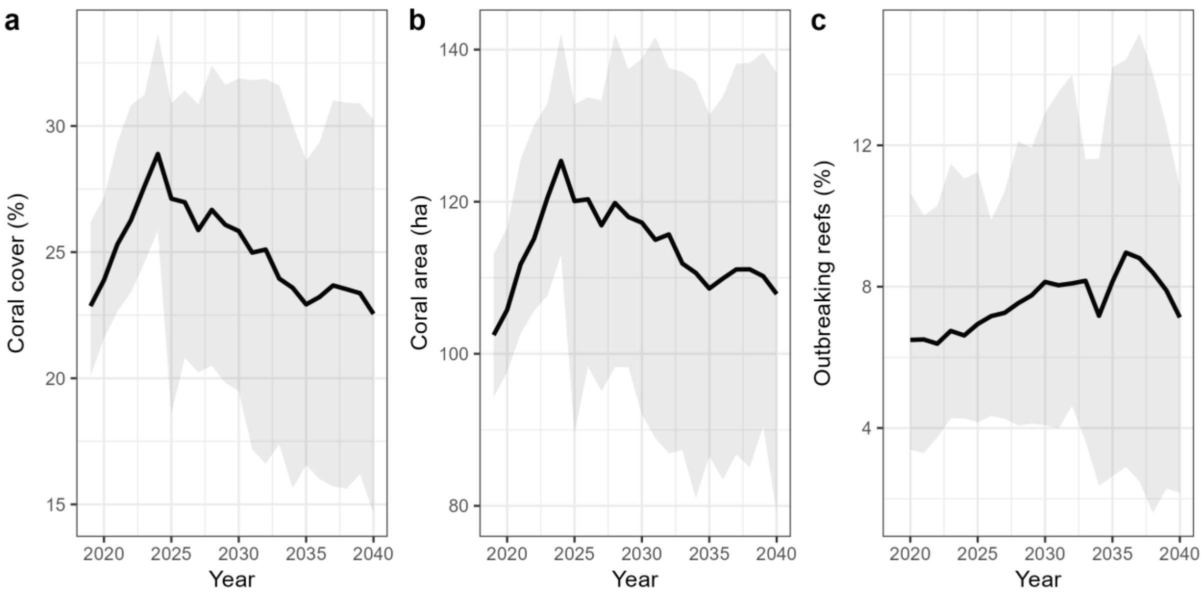

Figure 9. a) Coral cover (%) and b) outbreaking reefs (%) for the counterfactual scenario with no COTS control from 2020 to 2040. The black line represents the mean across all simulation runs while the ribbons represent the 10th and 90th percentiles.

3.2.2 Control scenarios

There was substantial variability in the benefits derived from the 10 initial control scenarios that were run in CoCoNet (**Table 7**). The benefits also varied depending on whether considering only PR or all reefs. For changes in mean coral area (ha), not all scenarios led to positive gains in coral area compared to the counterfactual. For PR, scenario mean coral area change averaged across 2020–2040 ranged from -2 ha for R_NC, to 512 ha for ES_HC and ES_HCC, while for all reefs, it ranged from -761 ha for R_NC to 1,700 ha for PS_UNP. All but one of the control scenarios led to declines in the number of outbreaking reefs compared to the counterfactual scenario. For PR, changes in the mean percentage of outbreaking reefs across 2020–2040 ranged from –0.55% for R_NC, to -1.72% for ES_HC and ES_HCC. For all reefs, changes in outbreaking reefs ranged from a net increase of 0.08% for R_NC to a decrease of -0.89% for OF_AR.

Table 7. Change in mean coral area (ha) and outbreaking reefs (%) across the 500 Priority Reefs and all 3,806 reefs from the 10 control scenarios compared to the counterfactual in CoCoNet. Values represent the mean change across all simulation runs for each year, averaged over the period 2020–2040. Top five performing scenarios are highlighted in green and the worst performing scenario is highlighted in red.

		Coral area (ha)		Outbreaking reefs (%)	
Group	**Scenario**	**Priority**	**All**	**Priority**	**All**
Regional	R_GBR	300	-28	-1.68	-0.30
	R_FNN	194	42	-1.01	-0.17
	R_NC	-2	-761	-0.55	0.08
	R_C	262	722	-0.84	-0.26
	R_CS	348	1,289	-0.86	-0.29
Protection Status	PS_UNP	499	1,700	-1.27	-0.73
	PS_P	64	-333	-1.03	-0.37
Outbreak Front	OF_AR	129	628	-0.92	-0.89
Effort Sink	ES_HC	512	1,108	-1.72	-0.43
	ES_HCC	512	1,108	-1.72	-0.43

Coral area

As with ReefMod-GBR, there was substantial variability in the change in coral area across the different control scenarios. Across PR, the most promising scenarios were the two effort sink scenarios (ES_HC and ES_HCC), followed by focusing on unprotected reefs (PS_UNP), the Central-South (R_CS) strategy, and then the GBR-wide scenario (**Table 7**, **Figure 10a,c**). However, when benefits to all reefs are considered, the GBR-wide strategy performed relatively poorly, leaving Central (R_C) and Central-South (R_CS) as the best performing regional strategies (**Table 7**, **Figure 10b,d**). The strategies that performed well across all reefs, were all characterised by strong flow-on of benefits to non-priority reefs, with gains in coral area typically a factor of 2–4 higher than on priority reefs alone (**Table 7**). The two effort sink scenarios performed identically well, as there were no controlled reefs with COTS density > 3 per manta tow that had coral cover > 20%. Interestingly, while focusing control on unprotected reefs provided the largest overall coral gain, focusing control on protected reefs led to a small net loss in mean coral cover (**Table 7**).

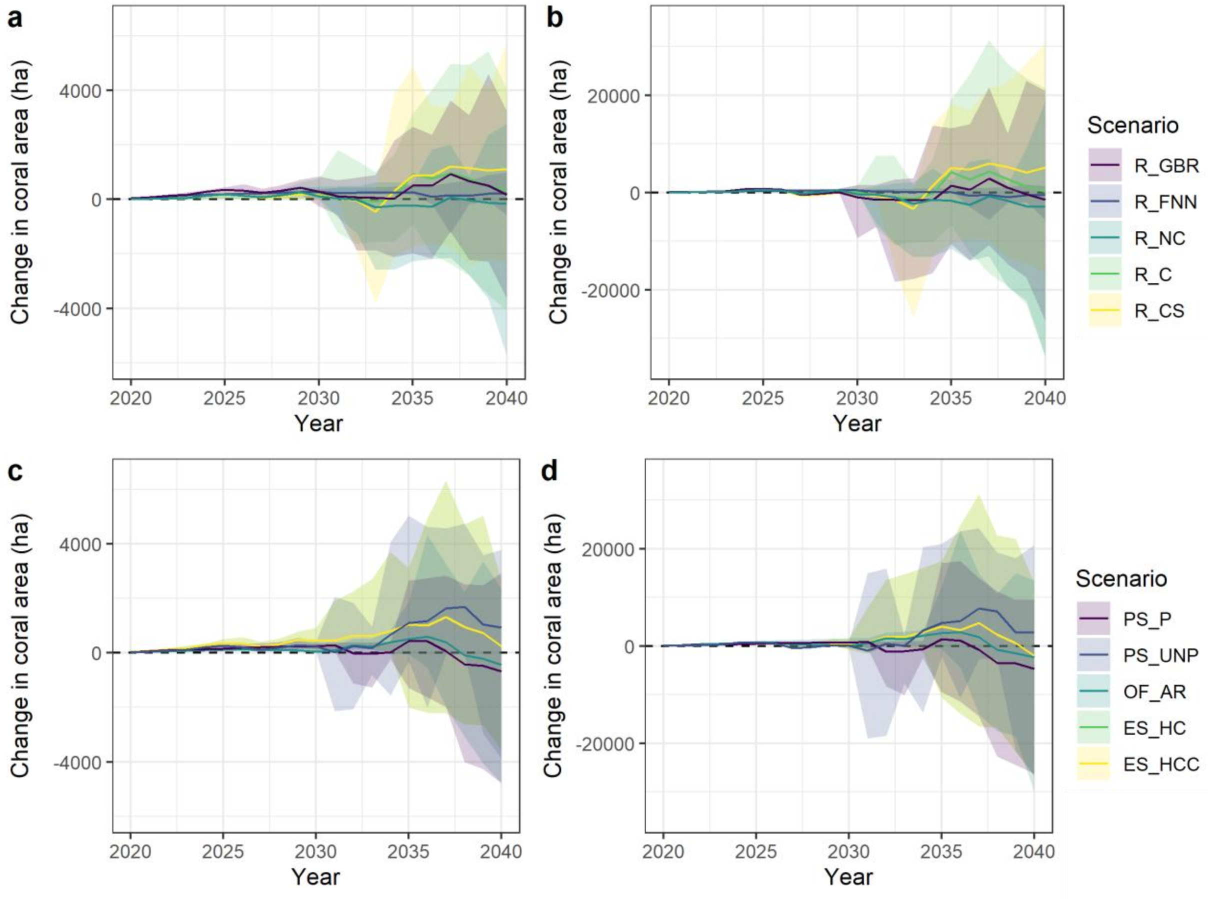

Figure 10. Change (scenario – counterfactual) in mean coral area (ha) across a,c) Priority Reefs and b,d) all reefs each year for 10 control scenarios in CoCoNet. Scenarios groups are a,b) regional and c,d) protection status, outbreak front, and effort sink. The lines represent the mean across all simulation runs while the ribbons represent the 10th and 90th percentiles. Note the different y-axis scales for the PR (a, c) and all reefs (b, d).

Maximum coral area gains within the period 2020–2040 followed similar patterns to the scenario means (**Table 8**). For PR, maximum benefits were seen from 2029–2040, with most scenarios having maximum coral area benefits around 2037. For all reefs, maximum coral area benefits occurred post-2035, except for two scenarios where the maximum benefit remained well below 1,000 ha (R_FNN and R_NC). Benefits to all reefs were generally 2–5 times larger than the benefit to Priority Reefs only. The largest maximum annual mean gains in coral area (ha) occurred under the PS_UNP scenario for both Priority Reefs (1,700 ha) and for all reefs (7,148 ha).

Table 8. Maximum annual mean coral area (ha) gain between 2020 and 2040 across the 500 Priority Reefs and all 3,806 reefs from the 10 control scenarios compared to the counterfactual in CoCoNet (mean across 20 simulation runs). The year in which the largest single-year gain occurs is reported. Values in bold indicate the highest gain for each metric across all scenarios.

	Priority Reefs		All Reefs	
Scenario	**Year maximum benefit occurs**	**Change (ha)**	**Year maximum benefit occurs**	**Change (ha)**
R_GBR	2037	925	2037	2,925
R_FNN	2029	264	2030	504
R_NC	2029	261	2025	613
R_C	2037	977	2037	4,382
R_CS	2040	1,115	2037	6,047
PS_UNP	2038	**1,700**	2038	**7,148**
PS_P	2035	430	2035	1,458
OF_AR	2036	597	2036	2,886
ES_HC	2037	1,319	2037	4,711
ES_HCC	2037	1,319	2037	4,711

Outbreaking reefs

The control scenarios that led to the greatest percentage reduction in outbreaking Priority Reefs for 2020–2040 were the two effort sink scenarios (ES_HC and ES_HCC), followed by the GBR-wide control scenario (R_GBR), focusing on unprotected reefs (PS_UNP), and then on protected reefs (PS_P) (**Table 7**, **Figure 11a,c**). When considering the reduction across all reefs, the five non-regional strategies (**Figure 11d**) all outperformed the five regional strategies (**Figure 11b**), with following the outbreak front across all reefs (OF_AR) performing particularly well (**Table 7**).

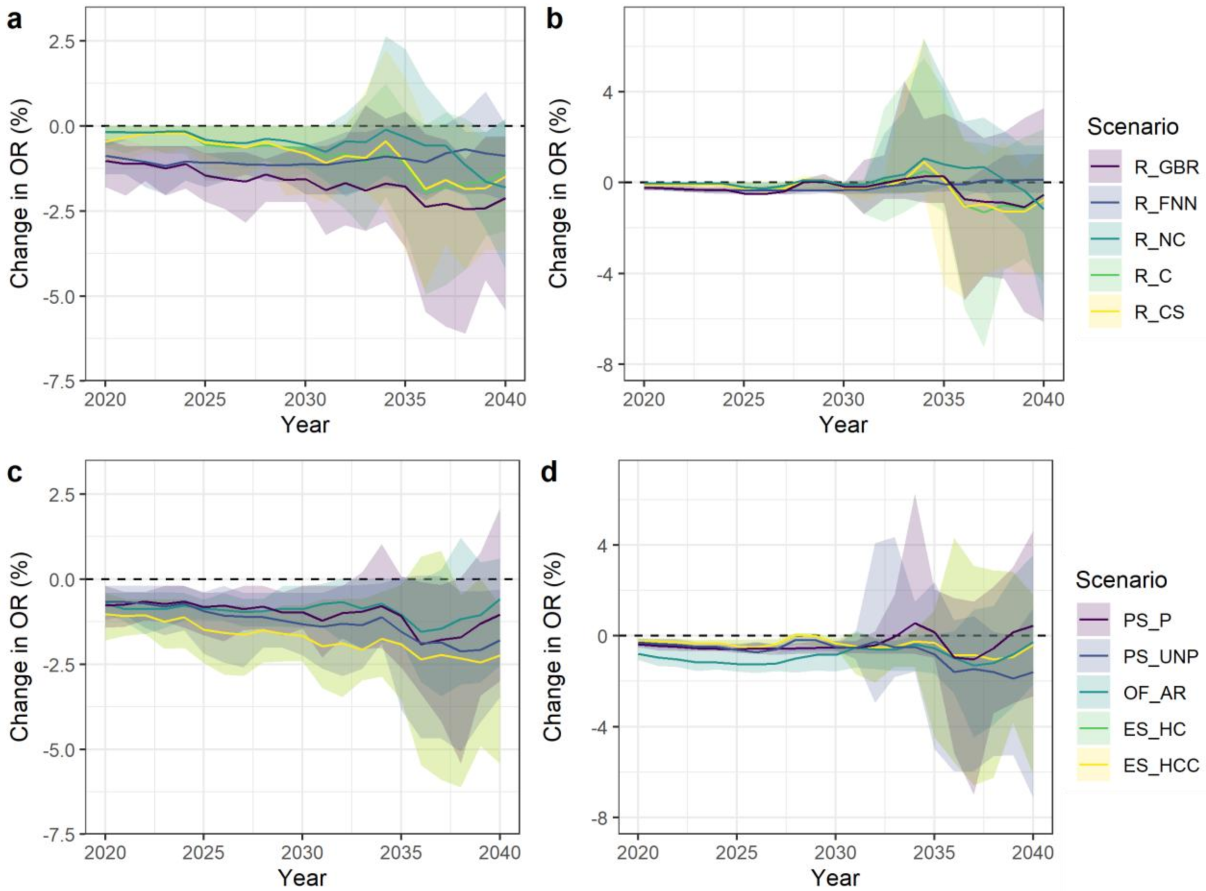

Figure 11. Change (scenario – counterfactual) in mean outbreaking reefs (%) across a,c) Priority Reefs and b,d) all reefs each year for 10 control scenarios in CoCoNet. Scenarios groups are a,b) regional and c,d) protection status, outbreak front, and effort sink. The lines represent the mean across all simulation runs while the ribbons represent the 10th and 90th percentiles.

Maximum reductions in outbreaking reefs across 2020–2040 followed similar patterns to the scenario means (**Table 9**). For PR, maximum benefits were seen post-2035, except for R_FNN, which peaked in 2029. All reefs followed a similar pattern, with maximum outbreaking reef benefits mostly occurring post-2036. The largest maximum annual mean changes in outbreaking reefs (%) occurred under the R_GBR, ES_HC and ES_HCC scenarios for Priority Reefs (-2.44%) and under the R_C scenario for all reefs (-1.30%). However, differences between scenarios were often much smaller than the variability between runs within the 20-run scenarios (**Figure 11**).

Table 9. Maximum annual mean change in outbreaking reefs (%) between 2020 and 2040 across the 500 Priority Reefs and all 3,806 reefs from the 10 control scenarios compared to the counterfactual in CoCoNet (mean across 20 simulation runs). The year in which the largest single-year change occurs is reported. Values in bold indicate the largest change for each metric across all scenarios.

	Priority Reefs		All Reefs	
Scenario	**Year maximum benefit occurs**	**Change (%)**	**Year maximum benefit occurs**	**Change (%)**
R_GBR	2038	**-2.44**	2039	-1.07
R_FNN	2029	-1.16	2027	-0.36
R_NC	2040	-1.81	2040	-1.18
R_C	2036	-1.94	2037	**-1.30**
R_CS	2038	-1.85	2038	-1.29
PS_UNP	2038	-2.12	2039	-1.88
PS_P	2036	-1.92	2037	-1.04
OF_AR	2036	-1.55	2037	-1.29
ES_HC	2039	**-2.44**	2038	-1.03
ES_HCC	2039	**-2.44**	2038	-1.03

3.3 ReefMod-GBR and CoCoNet

The best performing scenarios can be compared across ReefMod-GBR and CoCoNet in terms of both gains in coral area and reductions in the percentage of outbreaking reefs (**Table 10**). While gains in coral area were substantially larger in ReefMod-GBR, the two models were remarkably consistent in identifying top strategies across the scenarios that were run in both models: four of the five best-performing strategies for protecting coral area on Priority Reefs, and three of the five for all reefs, were shared. Focusing control on unprotected reefs (PS_UNP) and avoiding effort sinks (ES_HC and ES_HCC) were highly effective across both models and reef subsets, while the regional GBR-wide strategy was also supported for coral area gains on Priority Reefs. There was less agreement regarding regional focus, with CoCoNet favouring more control in the Central (R_C) and Central-Southern (R_CS) regions.

Reductions in the percentage of outbreaking reefs predicted by the two models were comparable in magnitude. For Priority Reefs, both models identified the GBR-wide strategy (R_GBR) and avoiding effort sinks (ES_HC and ES_HCC) as highly effective. However, ReefMod-GBR also highlighted the Central-South strategy (R_CS), while CoCoNet favoured strategies based on protection status (PS_UNP; PS_P). In contrast, there was no overlap in their top five strategies when considering all reefs (**Table 10**). ReefMod-GBR ranked regional strategies highest (R_GBR, R_FN, R_C, R_CS, R_S), whereas CoCoNet favoured protection status (PS_UNP, PS_P), tracking the outbreak front across all reefs (OF_AR), or avoiding effort sinks (ES_HC, ES_HCC). These differences likely reflect the models' contrasting counterfactual projections: ReefMod-GBR forecasts steep declines in both coral and COTS over the next 15 years (**Figure 4**), whereas CoCoNet predicts only modest changes (**Figure 9**). The sharper decline in ReefMod-GBR COTS predictions likely provided greater scope for control to demonstrate benefits in terms of protecting coral.

Table 10. Five best performing control scenarios and worst performing scenario in ReefMod-GBR and CoCoNet in terms of gains in coral area (ha) and reductions in outbreaking reefs (%) across Priority Reefs and all reefs. Grey = scenario not run in CoCoNet.

		Coral Area				**Outbreaking Reefs**			
		ReefMod		**CoCoNet**		**ReefMod**		**CoCoNet**	
Group	**Scenario**	**PR**	**All**	**PR**	**All**	**PR**	**All**	**PR**	**All**
Regional	R_GBR	✓	✓	✓		✓	✓	✓	
	R_FN						✓		
	R_FNN								
	R_N								
	R_NC			X	X			X	X
	R_C				✓		✓		
	R_CS			✓	✓	✓	✓		
	R_S						✓		
Protection Status	PS_UNP	✓	✓	✓	✓			✓	✓
	PS_P							✓	✓
Outbreak Front	OF_LAT								
	OF_AR	X	X			X	X		✓
	OF_PR	✓	✓			✓			
Effort Sink	ES_HC	✓	✓	✓	✓	✓		✓	✓
	ES_HCC	✓	✓	✓	✓	✓		✓	✓

4. DISCUSSION AND OUTPUTS

Identifying control strategies that are most effective for maintaining coral cover and suppressing COTS outbreaks across the entire GBR is challenging due to its size. Here, we used two spatially explicit ecosystem models to simulate different COTS control scenarios to guide the management of COTS outbreaks. While there are many similarities in the structures of the two models (similar coral groupings and age-structuring of COTS), there were also fundamental differences in aspects such as the spatial representation of their dynamics (tracking individual colonies over a small area and extrapolating across the reef in ReefMod, versus tracking populations at the scale of COTS control sites in CoCoNet); reef connectivity (ocean currents resolved at 4 km in ReefMod versus 1 km in CoCoNet, and differing parameterisations of reef larval retention); demographic processes (termination of COTS outbreaks by randomly collapsing populations in ReefMod, versus random spawning failures in CoCoNet); and representation of environmental forcing (direct application of climate model outputs in ReefMod, versus stochastic representations informed by climate model outputs in CoCoNet). These differences have contributed to the emergence of some distinct behaviours within the two models. Perhaps most important for current application are differences in COTS projections over the next 15 years. Specifically, the climate-related decline in COTS outbreaks predicted by ReefMod-GBR, driven by reduced food availability, provides more opportunity to control COTS than the more gradual coral decline and greater persistence of COTS outbreaks within CoCoNet scenarios. Consequently, the timeframes needed to substantially influence COTS populations were less in ReefMod-GBR (early 2030s) than in CoCoNet (late 2030s). Indeed, for some of the CoCoNet scenarios control had only a marginal influence on COTS densities and coral cover.

4.1 Varying the spatial distribution of effort

Gains in coral area were positive for all control scenarios in ReefMod-GBR, and for all but one scenario in CoCoNet when considering only PR. This indicates that control strategies are preferable to the alternative of not controlling at all, particularly for reefs that are actively targeted. Indeed, targeted and continuous control of COTS populations enhances coral cover and wider reef resilience, protecting ecosystem function in the face of climate change (Rogers and Plagányi 2022; Castro-Sanguino et al. 2023; Matthews et al. 2024). Summarising the outputs from both models revealed two sets of scenarios that led to the greatest gains in coral area throughout the entire timeframe. In ReefMod-GBR, the five most promising scenarios (R_GBR, PS_UNP, OF_PR, ES_HC, ES_HCC) were consistently effective whether considering gains across PR or all reefs. Similarly, the five most promising scenarios in CoCoNet (R_C, R_CS, PS_UNP, ES_HC, ES_HCC) provided gains across PR and all reefs. Importantly, results from both models support the strategies of focusing control on unprotected reefs (Blue Zones) and away from effort sinks. Consistently, the weakest-performing strategy in ReefMod-GBR across all benefit metrics and reef groups was the scenario targeting the outbreak front across all reefs (OF_AR), whereas in CoCoNet it was the scenario focusing control exclusively in the North-Central region (R_NC).

The GBR-wide strategy is closest to the current strategy employed by the CCP (Matthews et al. 2024) and in ReefMod-GBR provided some of the greatest gains in coral area and largest reductions in outbreaking reefs for both PR and all reefs (**Table 2**). In CoCoNet, it also performed well on PR, although these benefits did not extend to all reefs (**Table 7**). Indeed, the CoCoNet results suggest that higher gains in coral area may be achieved by concentrating more control effort in the Central and Southern regions of the GBR, where ReefMod-GBR also reveals substantial reductions in COTS outbreaks. This finding is likely influenced by ocean current patterns that contribute to outbreak progression, in addition to the distribution of the reefs and the cull sites (Moran et al. 1988; Miller et al. 2015; Matthews et al. 2024). For example, in the short-term (i.e. until 2030), COTS outbreaks will be moving towards the Southern region, so a strategy that focuses on the Central-Southern region (where 47% of reefs and 57% of currently established cull sites are located) will be highly effective at suppressing outbreaks, while in the longer term (i.e. post-2030), the start of a new outbreak will be at the southern end of the Far Northern region (which has 40% of reefs and 31% of currently established cull sites), so a strategy focusing control there will help to suppress the southward spread of the outbreak across all reefs. Indeed, in ReefMod-GBR, the scenario focusing control solely in the Far Northern region ranked the highest when considering reductions in outbreaks across all reefs. This likely reflects the distribution of reefs and cull sites: although the FN contains fewer PR, it encompasses a large total reef area and has a high number of cull sites. As a result, targeting this region could substantially reduce outbreaks across all reefs.

Prioritising control on unprotected reefs consistently ranked among the top five strategies in both models, delivering some of the greatest gains in coral area for both PR and all reefs, and in CoCoNet, also achieving some of the largest reductions in the percentage of outbreaking reefs across both groups. In contrast, prioritising control to protected reefs produced much smaller gains in in GBR-wide coral cover or even net losses in the case of CoCoNet (as downstream reefs better support the propagation of outbreaks via other reef network pathways). Protected reefs, such as those in Green or Pink zones, have higher densities of targeted fish groups (e.g. Lethrinidae, Lutjanidae, Serranidae) (Evans and Russ 2004; Castro-Sanguino et al. 2017), which may increase the natural mortality of COTS through direct predation or indirectly via trophic cascades. The predator removal hypothesis proposes that overfishing on the GBR releases COTS from direct predation pressure, allowing populations to reach outbreaking densities (Endean 1969). Indeed, COTS densities are lower on protected reefs compared to fished reefs (Kroon et al. 2021), and outbreaks are more likely on the latter (Sweatman 2008). This suggests that protected reefs benefit from higher predator populations that naturally suppress COTS densities, enhancing the resilience of these reefs. Prioritising control on unprotected reefs, where fishing has reduced predator populations and COTS densities are consequently higher, allows the culling program to substitute for natural top-down control, reducing larval export and subsequent outbreaks. Further work on the optimal prioritisation criteria for including reef protection status to maximise control benefits is recommended.

In ReefMod-GBR, targeting the outbreak front on Priority Reefs (OF_PR) was highly effective, delivering substantial coral gains and reducing outbreaking PR. By contrast, targeting the outbreak front across all reefs (OF_AR) was consistently the least effective scenario in ReefMod-GBR across both benefit metrics and reef groups. While targeting the outbreak front on Priority Reefs (OF_PR) was not evaluated in CoCoNet, targeting the outbreak front across all reefs (OF_AR) ranked among the best scenarios in that model for reducing the total number of outbreaking reefs. Controlling connected outbreaking reefs is crucial to stem the downstream supply of COTS larvae, given their exceptionally high reproductive capacity which leads to rapid population growth (Caballes and Pratchett 2014; Babcock et al. 2016; Pratchett et al. 2021a). Currently, however, much remains unknown about the drivers of COTS population dynamics, particularly the factors that lead to the initiation or termination of an outbreak or exceptionally high population densities (Pratchett et al. 2014; Pratchett et al. 2017b; Pratchett et al. 2021b). While prioritising control of high-density COTS populations may help maintain coral area and reduce the number of outbreaking reefs in the ecosystem models, managing the logistics of dynamically moving the fleet to target outbreaks as they occur in the real world presents significant challenges. While the current scenarios consider a fleet of five vessels only, an expanded fleet of 10–12 vessels could allow for all regions to be covered, while also allowing flexibility to dynamically increase capacity around the outbreak front (e.g. Castro-Sanguino et al. 2023). Nonetheless, given the uncertainty in the efficacy of these scenarios across both models, and the availability of other more consistently effective strategies, large-scale outbreak-front targeting is unlikely to be a priority management option at present.

Avoiding effort sinks provided modest additional benefits compared to the current GBR-wide strategy (R_GBR) in ReefMod-GBR, with a relatively small and diminishing number of reefs removed each year (**Figure A4; Table A4**), while the benefits in CoCoNet were more sustained and substantial. These results tend to affirm current concerns of the CCP around the large effort required to control certain reefs (Rogers et al. 2023) and point to potential efficiency gains by removing effort-sink reefs. Not controlling these effort sink reefs would mean accepting that they are likely to experience significant impacts due to their high density of COTS, however. Ultimately, the decision to control effort-sink reefs will be context-dependent and likely involve other management considerations (e.g. cost, logistics, team morale, cultural and touristic value of the reef), especially in the short term while they remain problematic. It is also important to note that these scenarios only implement a *starting* rule, meaning control does not begin on reefs under certain conditions. Since it is not always apparent that a reef is an effort sink before starting control (e.g. due to lack of information on COTS densities in the reef matrix or the structural complexity of the reef habitat), implementing scenarios with a *stopping* rule—a maximum threshold of control effort (diver hours) that can be used at a reef or cull site—may provide better insights into the most effective management strategies for these reefs.

4.2 Moving towards a dynamic approach

Compared to the GBR-wide scenario, which was the most promising scenario among the initial strategies, all connectivity scenarios (run using ReefMod-GBR) resulted in similar gains in coral area but greater reductions in the number of outbreaking reefs. This is perhaps unsurprising given that these strategies employ a dynamic approach that prioritises reefs with high coral cover that may aid in reef recovery. For example, reefs with coral cover exceeding 20% may enter an exponential recovery phase (Halford et al. 2004), acting as vital sources of coral larvae for adjacent reefs. These strategies also continuously target reefs with the highest risk of spreading COTS larvae. During outbreaks, COTS larvae disperse rapidly, forming an extensive cloud detectable up to 100 km ahead of current adult outbreaks (Uthicke et al. 2015). COTS larvae are also exceptionally resilient to various food availability conditions (Wolfe et al. 2017) and may not settle until 17 to 43 days post-fertilisation (Pratchett et al. 2017a). Across all three connectivity scenarios, the dynamic approach without additional prioritisation for protected or unprotected reefs (i.e., C_COTS_CC) proved to be marginally more effective for coral area gains. This likely stems from the reefs already being ranked in a highly effective order. Incorporating prioritisation based on protection status may disrupt this effective ranking. While it Iis important to note that different management objectives could result in different optimal rankings of reefs, the current measure of coral area gains indicates that adding protection status does not improve performance. Consequently, further research is necessary to determine how to best integrate reef protection status and leverage natural resilience to enhance these rankings for even more effective outcomes in these scenarios. Regardless, focusing control efforts on reefs that are potential "superspreaders" (Hock et al. 2014) of COTS larvae, while simultaneously safeguarding coral cover on reefs acting as refugia, is likely crucial for supporting the recovery of damaged reefs across the GBR (McCook et al. 2009; Mumby et al. 2021).

Employing a dynamic approach (i.e. ranking reefs based on their coral cover and the greatest risk of spreading COTS larvae) while also prioritising control on unprotected reefs where reefs had a similar ranking (i.e. C_COTS_CC_UNP) led to the greatest reduction in outbreaking reefs for both PR and all reefs across all scenarios. As mentioned in Section 4.1, unprotected reefs tend to have higher COTS densities due to reduced predator populations (Sweatman 2008; Kroon et al. 2021), so directing control there can provide additional benefits by substituting for natural top-down regulation. However, further research to refine how reef protection status is integrated into prioritisation schemes, considering differences in food web structure, would help maximise the effectiveness of control programs.

A caveat to these dynamic scenarios is that they currently assume perfect knowledge of coral cover and the risk of COTS larval spread at each reef, i.e. that modelled estimates are ecological reality. Although continued refinement of ecosystem models will enable more accurate predictions that can support management decisions, this underlines the importance of continued COTS and coral monitoring across the GBR. While it is recommended to test control strategies that account for imperfect knowledge, adopting a dynamic approach to COTS control clearly leads to the best management outcomes for reef health and future resilience of the GBR. While the current Annual Reef Prioritisation Process does change dynamically each year and already includes variations of the Coral and COTS larval supply metrics used here, accounting for 14% of the total value assigned to each reef (S. Matthews Reef Authority, *pers. comm.*), these scenario outputs suggest that they could be upweighted in this process in the future.

4.3 Key assumptions

As with any modelling, in the absence of biological parameters from empirical studies, there are assumptions that must be made. For example, there is still much that is unknown about COTS biology and the drivers of their population dynamics (e.g. duration of juvenile life stage, predatory processes; Pratchett et al. 2021a), including the factors that lead to the initiation of an outbreak (Pratchett et al. 2014). However, quantifying the potential management benefits of different control scenarios in the models relies on the accuracy of the COTS density predictions. In ReefMod-GBR, COTS density predictions were validated against in situ observations from manta tow surveys, revealing high congruence: ~81% of categorical reef level COTS densities were the same level or only differed by one (Skinner et al. 2024), though there were underpredictions in the Swains and Townsville sectors, which could lead to an underestimation of the potential impact of the Control Program. In CoCoNet, COTS predictions have been validated against data from the LTMP (Condie et al. 2018). As our understanding of COTS biology and population dynamics improves through empirical studies (including many projects within CCIP), the models will continue to be refined accordingly. However, these validations confirm the models' effectiveness for informing targeted control measures.

Another assumption involves the chosen Global Circulation Model and the Shared Socio-economic Pathway (SSP). The current scenarios use a single future climate scenario (SSP1-2.6), and in ReefMod-GBR a single Global Circulation Model (*CNRM-ESM2-1)*. This climate scenario assumes that warming is limited to around 1.8°C by 2100. However, it is recommended to account for multiple climatologies (Dubos et al. 2023) to accurately assess projected COTS risks and the benefits of various control scenarios. Additionally, the likelihood of warming exceeding 2°C (and therefore SSP1-2.6) is increasing (IPCC 2023), which has serious implications for coral communities and the COTS that depend on them for food. Under this scenario, projected changes in coral cover may indirectly affect COTS populations, although thermal effects on COTS are not yet represented in the model. However, while these factors are critical for long-term projections (i.e. > 2040), in the short-term (≤ 2040), the simulated climate remains consistent with current conditions.

Finally, parameters used in the models are updated as empirical data become available, however there may still be differences between the models and reality. For example, bleaching-related coral mortality in ReefMod-GBR is based off data from surveys on reefs up to 2 m depth (Hughes et al. 2018) and then calibrated against data from 6–9 m (LTMP). This may lead to discrepancies in coral cover from overestimating bleaching-induced mortality, which in turn would underestimate the potential benefits derived from COTS control. However, despite potential discrepancies, the outcomes of the control scenarios are still promising, and this conservative approach suggests that the potential benefits of control may be more substantial than projected, particularly as climate stressors increase from 2030 onwards.

4.4 Outputs

Overall, there were seven final outputs of four types:

Modelling capability

- Expansion and validation of ecosystem model – ReefMod-GBR.
- Expansion and validation of ecosystem model – CoCoNet.

Dataset

- ReefMod-GBR predictions on coral cover and COTS densities per reef to inform reef prioritisation (2022, 2023, 2024).
- Scenario coral cover benefit estimates input to cost-effectiveness analyses for project CCIP-R-06 – Cost-effectiveness of control (Scheufele et al. 2025).

Knowledge recommendation

- Regional ensemble model assessment of benefits of a range of strategic management scenarios co-developed with the COTS Control Program (e.g. spatial, effort sink, larval source/sink, split of effort).
- Recommendations on optimal strategies to maximise benefits of control based on regional ensemble model outputs.

Capacity building

- Dissemination of results from scenario testing to key stakeholders and managers.

5. RESEARCH SYNERGIES AND NEXT STEPS

5.1 Research synergies

There are research synergies (incoming and outgoing) with multiple other projects across CCIP (highlighted in **Figure 2**), but also with related programs such as the Reef Restoration and Adaptation Program (RRAP).

5.1.1 Incoming synergies

Ecosystem models can continually be refined and updated to reflect the latest research from empirical studies and other models. Within CCIP, this project (CCIP-R-04) has incoming synergies with a range of other projects. Within the Response Subprogram, project CCIP-R-05 ("COTS dispersal ensemble modelling", Choukroun et al. 2025) has developed new COTS connectivity matrices for the whole GBR. These will be fully integrated into the regional models, but this is a complex process that will require extensive testing and sensitivity analyses to understand resulting changes in the ecological outputs. Project CCIP-R-03 ("Reef-scale modelling", Rogers et al. 2025) continues to test the implications of different ecological thresholds for COTS control and of the impact of controlling effort sink reefs. These findings can also be directly integrated into the regional models. Lastly, almost all the projects within the Prediction subprogram can contribute new information or refined parameters from their empirical studies, enhancing the accuracy and effectiveness of the models and ensuring that simulated control strategies remain robust. Beyond CCIP, there are ongoing synergies with RRAP, which help to enhance the ReefMod-GBR and CoCoNet models. These improvements include incorporating updated climate models and a more precise delineation of individual reef polygons. Lastly, while not yet incorporated, collaborating with project CCIP-R-09 ("Reef TO co-design and values assessment", Backhaus et al. 2025) to enhance model capacity and develop scenarios for using Traditional Owner (TO) vessels for culling is a recommended next step (see section 5.2: Next Steps).

5.1.2 Outgoing synergies

Within the Response sub-program, the primary outgoing synergy is with project CCIP-R-06 ("Cost-effectiveness of control", Scheufele et al. 2025). Ecological outputs and reef condition indices (developed under RRAP, see Scheufele et al. 2025) were generated from each scenario in ReefMod-GBR and shared directly with CCIP-R-06 for economic assessments of different control strategies. The refined predictions of coral cover and COTS densities and overall enhanced modelling capacity contributed to CCIP-R-03 ("Reef-scale modelling", Rogers et al. 2025) and CCIP-R-05 ("COTS dispersal ensemble modelling", Choukroun et al. 2025), but also to several projects within the Detection subprogram, specifically CCIP-D-01 ("COTS monitoring design", Lawrence et al. 2025) and CCIP-D-04 ("The COTS surveillance system", Bainbridge et al. 2025). Sharing recommendations and results on optimal strategies to maximise control benefits provided valuable insights to all projects across the Response subprogram. Scenarios that specifically consider reef protection status, and thus differences in COTS mortality due to predation by fish predators, were particularly useful for CCIP-R-10 (“Fish predator conservation for biocontrol”, Ceccarelli et al. 2025). All outputs from the current project were shared with and input to CCIP-R-01 ("Information infrastructure", Fletcher and Rezvani 2025) and CCIP-R-02 et al. 2025), feeding a PowerBI Dashboard delivering interpreted project results to COTS Control Program management staff at the Reef Authority to allow them to compare benefits across different scenarios. Beyond CCIP, integrating the findings from these scenarios into RRAP will aid in planning reef restoration projects and improved modelling of coral adaptation and climate change impacts.

5.2 Next steps

While substantial progress has been made towards identifying the most effective control strategies for COTS management, there are several areas that have emerged through this project that should be prioritised for further research and development. These broadly fall into two categories: 1) ecosystem model expansion; and 2) advanced scenario testing.

5.2.1 Ecosystem model expansion

- **Further calibration:** While the coral and COTS predictions from both models have been calibrated to in situ observations from empirical studies, a formal calibration of the disturbance events used in the models would ensure that coral mortality is attributed to the correct disturbance and that the magnitude is appropriate (e.g. the relationship between thermal stress, measured as Degree Heating Weeks (DHW), and coral mortality).
- **Restoration and adaptation:** RRAP has advanced the modelling of various restoration methods and of coral adaptations to climate change. For CoCoNet, these have been combined with COTS modelling reported here and a similar integration is now required for ReefMod-GBR. This will provide a more comprehensive modelling approach to management of the GBR.
- **Capacity dependence**: Developing the models to include variations in control fleet capacity, and particularly the inclusion of TO vessels in their specific Sea Country, should be explored.
- **Improved connectivity**: Integrating new COTS connectivity matrices (CCIP-R-05, Choukroun et al. 2025) from a broader range of hydrodynamic models and assessing the sensitivity of control scenario efficacies to these inputs is recommended.

5.2.2 Advanced scenario testing

- **Scenario switching**: Currently, a single control strategy is run throughout the duration of the scenario. Exploring how to run and interpret scenarios which employ the current CCP strategy (GBR wide; R_GBR) from 2019 to the present day, with alternative strategies implemented for future years, is needed.
- **Additional scenarios**: Improved management of effort sink reefs might be achieved by implementing a stopping rule to move on from reefs based on dive time thresholds

at the reef-level or cull-site level. However, additional information is needed to define this stopping rule before it can be implemented.

- **Dynamic scenarios**: As dynamic disturbances such as bleaching events become more frequent (Hughes et al. 2017), defining and running scenarios to understand how the CCP should respond to these and which management decisions could support the best outcomes will be crucial.

6. MANAGEMENT IMPLICATIONS AND IMPACT

This study highlights significant variations in the benefits of different COTS control scenarios. Both models showed positive gains in coral area for almost all tested control scenarios, underlining the importance of targeted and continuous control efforts. The GBR-wide strategy, which closely mimics the current CCP and applies consistent control across all regions, was particularly effective for Priority Reefs. This emphasises the effectiveness of broad, consistent control strategies, providing retrospective support for the current CCP and suggesting that maintaining or expanding effort in the Far North could be an important component of effective management. Avoiding "effort sink" reefs provided additional benefits, particularly in the CoCoNet model where outbreaks were more acute.

Overall, dynamic control approaches that continually re-ranked and reprioritised reefs with high coral cover and high risks of COTS larval spread proved to be the most effective in maintaining coral cover and reducing outbreaks (only tested in ReefMod-GBR). Their performance was only marginally better than the GBR-wide strategy (R_GBR) however. Moreover, their implementation requires a scale of up-to-date GBR-wide intelligence and predictive ability that is not currently available. This indicates that the R_GBR strategy remains a robust option for now, while future improvements to monitoring and prediction, and the integration of these information streams into adaptive management, will be crucial for responding to the ever-changing conditions of coral and COTS communities on the GBR.

The findings of this study and the final outputs have several important implications for COTS management, providing valuable entry points across various areas:

1. **Governance, Engagement and Communications**: Dissemination of results from scenario testing to key stakeholders and managers will enhance governance and engagement. Sharing knowledge and recommendations based on model outputs can improve strategic decision-making and the efficacy of COTS control management strategies. For example, outputs will provide support for improved financial investment in COTS control, potentially contributing to achieving the Reef 2050 targets for corals. One notable example is the integration of scenario outputs into dashboards (Fletcher et al. 2025) to enhance visualisation and interrogation of the findings for rapid management uptake.
2. **COTS Strategic Management Framework**: The expansion and validation of both ReefMod-GBR and CoCoNet provides a scientific underpinning and ecological understanding of COTS population dynamics and the impacts of control, supporting the Strategic Management Framework. The recommendations provided herein on the optimal control strategies based on regional ensemble model outputs can inform the framework, ensuring effective deployment of resources during outbreaks. For example, outputs from these scenarios were used to support the regional-scale prioritisation decisions for the 2024/2025 financial year. They also contribute to the reef health indicator and cost-effectiveness analyses (Scheufele et al. 2025). These provide another way to assess the health of the reef while also considering the economic implications of different strategies, ensuring a comprehensive approach to management of COTS populations on the GBR.

3. **Annual Reef Prioritisation Process**: Predictions from ReefMod-GBR on coral cover and COTS densities per reef continue to inform the Annual Reef Prioritisation Process each year. This dataset is crucial for setting the reefs to prioritise for control and the proportion of resources allocated to each sector, ensuring that resources are allocated efficiently to maximise coral cover benefits.
4. **On-water Operations and Data Collection**: Outputs from the control scenarios will help to optimise resource allocation and improve operational efficiency. For example, there are key benefits to allocating resources across the entire GBR. Furthermore, understanding that the control of effort sink reefs is context-dependent provides autonomy and better decision-making control to on-water teams. In the long-term, integrating dynamic control approaches that adaptively target critical reefs based on real-time data will also help to optimise resource allocation.

The study also identifies several key entry points for integration with RRAP. For instance, the expansion and validation of both ReefMod-GBR and CoCoNet enhance ecological understanding of COTS dynamics, supporting RRAP's efforts to design effective restoration and adaptation strategies. The assessment of the benefits from different control scenarios provides a conceptual framework for resource deployment during outbreaks, guiding the development of best practices and informing strategic decisions for coral conservation. Sharing these results with key stakeholders and managers builds capacity and fosters informed decision-making within RRAP. This dissemination ultimately ensures that the latest scientific findings and management recommendations are integrated into broader reef restoration and adaptation initiatives, ultimately strengthening the resilience and health of the GBR.

This research contributes significantly to achieving the overarching outcomes and impacts identified in the CCIP's Research Impact Plan (**Figure 2**). Regarding outcomes, the study enhances our capacity to detect and monitor COTS outbreaks through validated and refined ecosystem models leading to *Improved detection and monitoring* and *More accurate prediction*. Thorough ecological assessments of the benefits derived from different control scenarios from two ecosystem models provides data-driven recommendations, contributing to a *More efficient and effective operational response*. Regarding impacts, the recommendation of effective and targeted COTS control strategies will ensure that the frequency and severity of *COTS outbreaks are suppressed and prevented* and that *Coral cover is protected across the GBR*. Combined, these ensure that the GBR remains healthy, thus supporting the livelihoods and cultural values of *Traditional Owners, the tourism industry, and the community*.

In summary, this research provides critical insights and practical recommendations for improving the CCP and management of COTS, ensuring the resilience and long-term ecological health of the GBR. While the current GBR-wide strategy is highly effective, other strategies also show promise, especially for achieving secondary objectives such as reducing the number of outbreaking reefs. Ultimately, however, adopting a dynamic approach that integrates real-time monitoring and adaptive management will be the most effective. By aligning with the CCIP's Research Impact Plan, this study supports sustainable management practices that can adapt to future challenges, safeguarding the health of the reef into the future.

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8. DATA ACCESSIBILITY

Outputs from all scenarios for both models are stored in the system developed by CCIP-R-01 ("Information Infrastructure", Fletcher and Rezvani 2025). All outputs are also available to Reef Authority managers on the custom PowerBI Dashboard created as part of the CCIP Research Translation activity. ReefMod-GBR is available on GitHub (https://github.com/ymbozec/REEFMOD.7.2_GBR), while CoCoNet is described in Condie and Porobic (2024). ReefMod-GBR outputs are available at https://doi.org/10.48610/a15c7be and CoCoNet outputs are available at https://doi.org/10.25919/cyey-ja73.

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APPENDIX A – RESULTS

The appendix provides additional detailed figures and tables summarising changes in coral area and outbreaking reefs for all control scenarios compared to the counterfactual across various reef groups using ReefMod-GBR. It also includes the distribution of reefs and cull sites across all management areas, and summarises the number of reefs removed from the control list during effort sink scenarios.

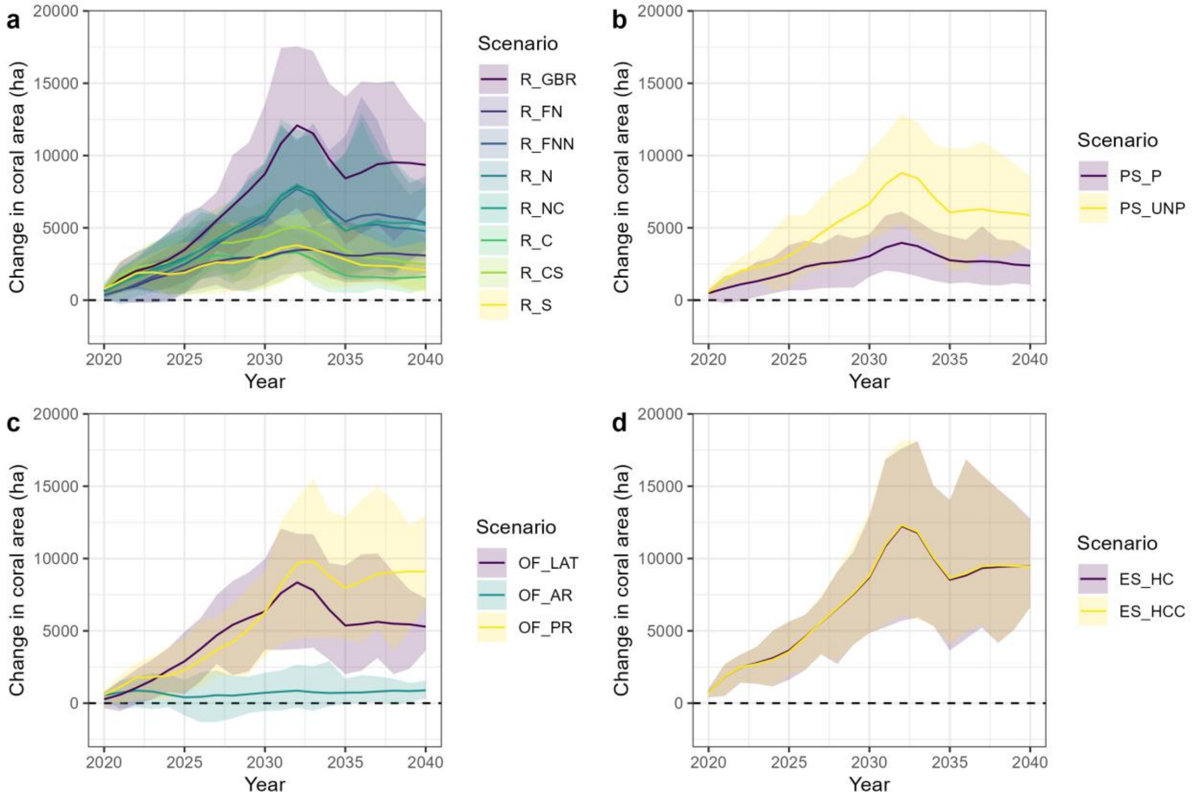

Figure A1. Change (scenario – counterfactual) in mean coral area (ha) across all reefs each year for 15 control scenarios in ReefMod-GBR. Groups are a) regional, b) protection status, c) outbreak front, and d) effort sink. The lines represent the mean across all simulation runs while the ribbons represent the 10th and 90th percentiles.

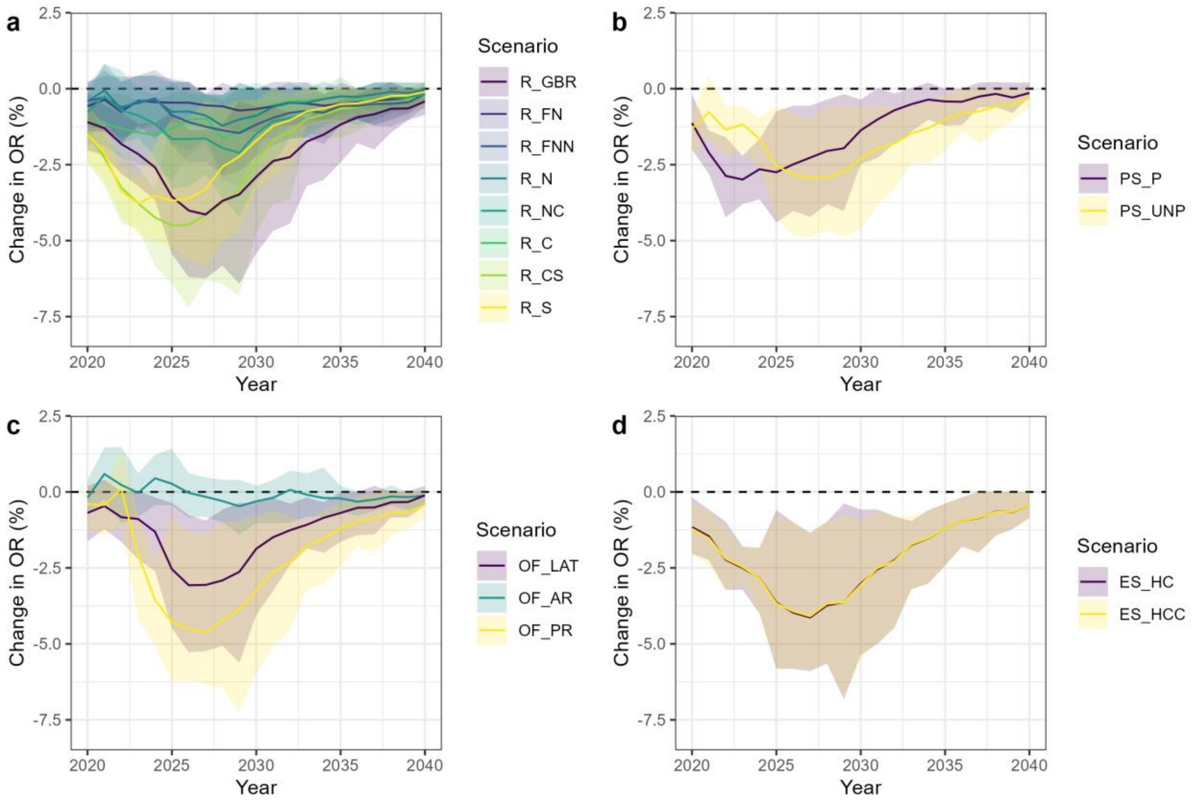

Figure A2. Change (scenario – counterfactual) in mean outbreaking Priority Reefs (OR; %) each year for 15 control scenarios in ReefMod-GBR across four groups a) regional, b) protection status, c) outbreak front, and d) effort sink. The lines represent the mean across all simulation runs while the ribbons represent the 10th and 90th percentiles.

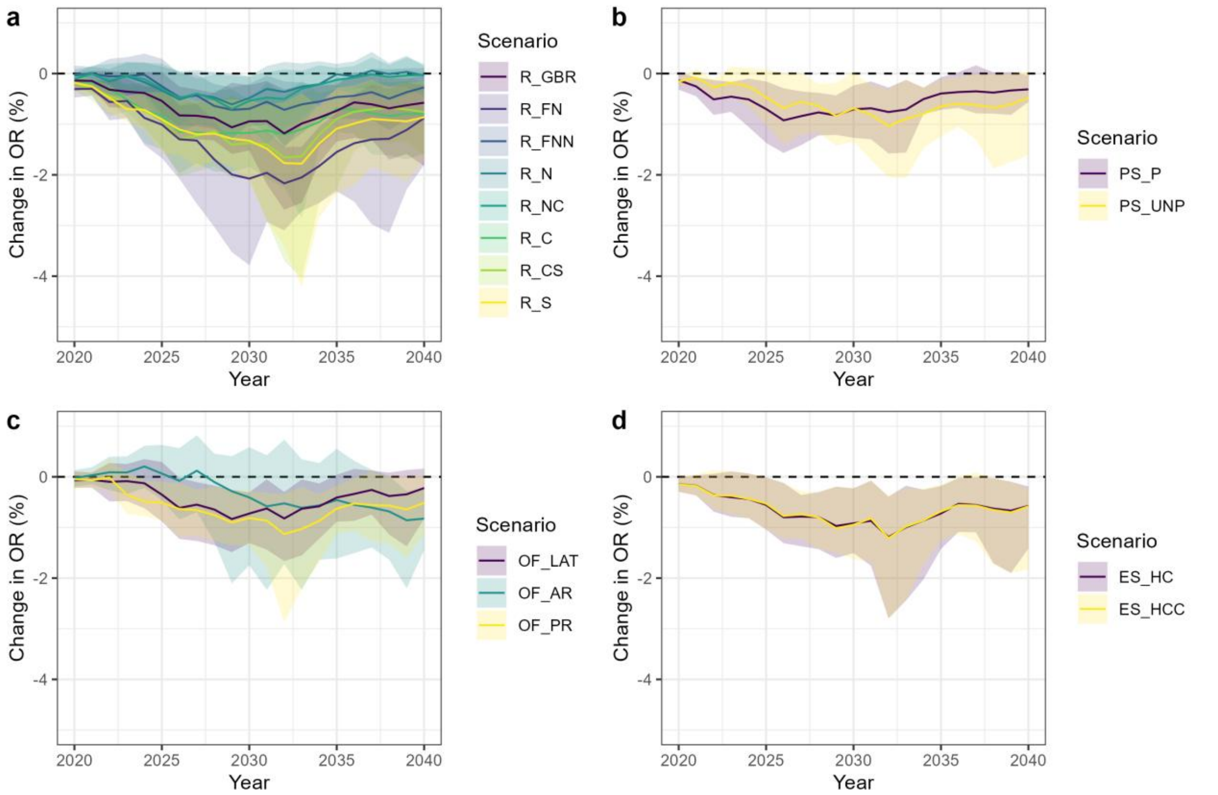

Figure A3. Change (scenario – counterfactual) in outbreaking reefs (OR; %) across all reefs each year for 15 control scenarios in ReefMod-GBR. Groups are a) regional, b) protection status, c) outbreak front, and d) effort sink. Ribbons represent the 10th and 90th percentiles.

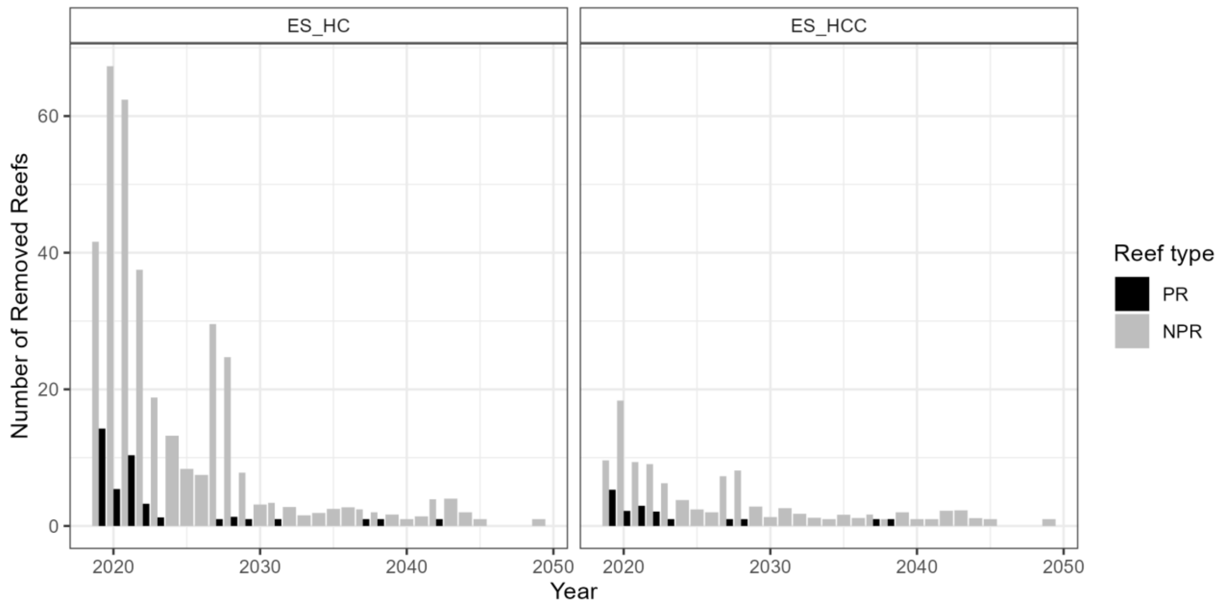

Figure A4. Mean (across 20 runs) number of Priority (PR) or Non-Priority (NPR) reefs identified as "effort sinks" (i.e. requiring disproportionate effort to control effectively) and therefore removed from the control list each year in ReefMod-GBR. For scenario ES_HC, reefs are removed when COTS per tow > 3, and for scenario ES_HCC, reefs are removed when COTS per tow > 3 and coral cover < 20%.

Table A1. Distribution of reefs, cull sites, and their area across the four management regions (FN = Far North, N = North, C = Central, S = South). No. = number. The area of reefs and cull sites is based on the Reference Area (km^2) which is the 2D area of the reef polygon used by the Reef Authority.

	FN	N	C	S
No. reefs	1034	400	789	1583
No. cull sites	20,194	7571	13,540	23,639
Total area of reefs (km^2)	9991.42	3166.36	5374.06	6244.52
Total area of reefs (ha)	999,142.60	316,635.70	537,406.50	624,452.40
Total area of sites (ha)	201,940	75,710	135,400	236,390

Table A2. Change in mean coral area (ha) across the 500 Priority Reefs and all 3,806 reefs from the 18 control scenarios compared to the counterfactual in ReefMod-GBR. Values represent the mean change across 20 simulation runs for each year, averaged over the period 2020–2040, with 10th and 90th percentiles.

	Priority			All		
Scenario	**10th**	**Mean**	**90th**	**10th**	**Mean**	**90th**
R_GBR	1463	6220	10,225	1519	6585	10,727
R_FN	525	1265	1608	712	2440	3337
R_FNN	609	3954	6623	702	4256	7122
R_N	1174	3802	6098	1197	4136	6785
R_NC	1204	4086	6782	1237	4286	7124
R_C	799	1577	2294	1516	2179	3089
R_CS	1597	2589	3719	1704	3122	4707
R_S	1220	1840	2509	1350	2344	3492
PS_UNP	1479	4573	7469	1489	4883	7915
PS_P	813	1925	2845	838	2304	3597
OF_LAT	563	4224	7234	633	4442	7493
OF_AR	320	464	610	445	676	862
OF_PR	1064	5184	8428	1184	5491	9102
ES_HC	1834	6352	10,311	1896	6709	10,782
ES_HCC	1834	6379	10,382	1905	6738	10,876
C_COTS_CC_P	1252	5578	8996	1241	6021	9661
C_COTS_CC_UNP	1318	5696	9275	1350	6181	9971
C_COTS_CC	2053	5954	9227	2051	6478	9928

Table A3. Change in mean outbreaking reefs (%) across the 500 Priority Reefs and all 3,806 reefs from the 18 control scenarios compared to the counterfactual in ReefMod-GBR. Values represent the mean change across 20 simulation runs for each year, averaged over the period 2020–2040, with 10th and 90th percentiles.

	Priority			All		
Scenario	**10th pc**	**Mean**	**90th pc**	**10th pc**	**Mean**	**90th pc**
R_GBR	-3.68	-2.00	-0.67	-0.98	-0.65	-0.16
R_FN	-0.66	-0.49	-0.35	-2.04	-1.26	-0.33
R_FNN	-1.24	-0.72	-0.33	-0.69	-0.38	-0.03
R_N	-0.89	-0.49	-0.11	-0.48	-0.20	0.00
R_NC	-1.66	-0.93	-0.28	-0.51	-0.24	-0.03
R_C	-1.44	-0.82	-0.26	-1.18	-0.80	-0.20
R_CS	-4.23	-2.10	-0.36	-1.40	-0.91	-0.33
R_S	-3.60	-1.73	-0.25	-1.47	-0.98	-0.28
PS_UNP	-2.80	-1.53	-0.59	-0.84	-0.55	-0.16
PS_P	-2.74	-1.36	-0.26	-0.82	-0.53	-0.26
OF_LAT	-2.88	-1.27	-0.35	-0.72	-0.40	-0.07
OF_AR	-0.31	-0.09	0.27	-0.68	-0.30	0.09
OF_PR	-4.28	-2.02	-0.40	-0.90	-0.57	-0.05
ES_HC	-3.72	-2.09	-0.68	-0.97	-0.64	-0.19
ES_HCC	-3.68	-2.09	-0.68	-0.98	-0.64	-0.20
C_COTS_CC_P	-4.37	-2.47	-0.70	-1.15	-0.81	-0.29
C_COTS_CC_UNP	-4.58	-2.53	-0.70	-1.22	-0.84	-0.30
C_COTS_CC	-4.57	-2.31	-0.70	-1.16	-0.79	-0.15

Table A4. Mean number (across 20 runs) of Priority (PR) or Non-Priority (NPR) reefs identified as "effort sinks" (i.e., requiring disproportionate effort to control effectively) and therefore removed from the control list each year in ReefMod-GBR. For scenario ES_HC, reefs are removed when COTS per tow > 3, and for scenario ES_HCC, reefs are removed when COTS per tow > 3 and coral cover < 20%.

Scenario	Reef type	Removed Reefs
ES_HC	NPR	357
ES_HC	PR	41.8
ES_HCC	NPR	104
ES_HCC	PR	17.6

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