REEF RESTORATION & ADAPTATION PROGRAM

# Integrated Population Model Framework (IPMF) Research and Development (R&D) (M&DS-06)

## Final Report June 2025

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**RRAP Integrated Population Model Framework (IPMF) Research and Development (R&D) (M&DS-06) Final Report June 2025**

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*Cover Page: Coral reef, Credit: Gary Cranitch, Queensland Museum*

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This report summarises work undertaken under *Integrated Population Model Framework (IPMF) Research and Development (R&D) (M&DS-06)* in accordance with the Reef Restoration and Adaptation Program's *Modelling and Decision Support* Project Agreements. It provides a summarised, point-in-time synopsis of activities, methods, findings and outcomes completed in accordance with the approved project scope up to 30 June 2025.

All information reflects project scope and outcomes as of May-June 2025. Subsequent updates, analyses, or scientific developments are not included. This report should be read alongside any associated and publicly available technical reports, datasets, and publications for full detail. This report does not provide scientific inferences, policy guidance or operational instructions beyond the project's defined scope and duration.

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The RRAP partners acknowledge Aboriginal and Torres Strait Islander Peoples as the first marine scientists and carers of Country. We acknowledge the Traditional Owners of the places where RRAP works, both on land and in sea Country. We pay our respects to elders; past, present, and future; and their continuing culture, knowledge, beliefs, and spiritual connections to land and sea Country.

We specifically acknowledge and thank the following Traditional Owners of sea Country that this report relates to:

| Location | Traditional Owner Group |
|---|---|
| Torres Strait | Masigalgal, Porumalgal, Warraberalgal |
| Northern Great Barrier Reef | Gunggandji, Ngurruumungu, Dingaal |
| Central Great Barrier Reef | Manbarra, Bindal |
| Southern Great Barrier Reef | Woppaburra, Bailai, Gurang, Gooreng Gooreng, Taribelang Bunda |

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# 1 Executive Summary

Developing and implementing interventions that can mitigate the impact of climate change on coral reefs is a critical and time sensitive need given the projected increase in frequency and intensity of acute thermal disturbances even in the most optimistic climate change scenarios. However, given the biophysical complexity of coral reefs systems, identifying the specific characteristics these interventions must have, and describing the potential impact that deploying them at different scales could generate, requires modelling tools that can represent the network of processes that interact through the cascading impact of these interventions. Importantly, it is critical that these modelling tools can describe system dynamics at the spatial scale that interventions are deployed (e.g. half a hectare to a few hectares in the case of coral centric interventions).

C~scape was developed over the past five years to complement two other ecosystem models available in the RRAP Modelling and Decision Support (M&DS) Sub-program (ReefMod and CoCoNet) by targeting coral community dynamics at a higher spatial resolution (sites within reefs).

C~scape's strategic development plan was centred around ensuring that the modelling architecture was based on the best available data at the time of development, but with an architecture that would facilitate rapid uptake of new data that was planned to be generated by RRAP's Sub-programs, including the Ecological Intelligence for Reef Restoration Sub-program. This approach allowed the implementation and application of successive versions of the model to respond to program and stakeholder needs as they arise including the modelling required for two business cases in response to funding opportunities and an intervention efficacy study that was critical for stablishing specific targets for coral centric intervention development and to help design the business case and research plan for future phases of RRAP.

The final version of C~scape as an output of the first phase of RRAP is a model that outperforms original expectations and contracted research and development goals. Of particular relevance are the following characteristics and outcomes:

- **Rapid development of a relatively mature ecosystem model that is fit for purpose** and can reproduce within reefs dynamics that are site specific for any mid-shelf or offshore reef on the Great Barrier Reef (GBR).
- **Rapid uptake of EcoRRAP (another RRAP Sub-program) data within a year of the data being available**.
- **Only ecosystem model in the modelling suit that represent the impact of chronic increases in temperature on the growth rate of GBR corals** (based on EcoRRAP experiments).
- **Only Ecosystem model from the modelling suit that includes a brooding coral type**.
- **Critical role in developing and standardising a unified approach** for representing thermal adaptation and the spread of thermal enhancement in all three ecosystem models.
- **Developed, in stages, facilitating the use of C~scape from the second year of the Program** to fulfill specific RRAP and stakeholder needs.
- **Lead and contributed to multiple scientific publications and reports.**
- **Helped identify critical intervention research and development targets** and instigated collective international efforts for the development of research and development guidelines for assisted evolution interventions (Coral Research and Development Accelerator Platform (CORDAP) landscape study).
- **Characterised the future ecological dynamics of GBR reefs** under different climate change scenarios from a within reef perspective.

In a short period of time C~scape has become a trusted and recognised modelling tool that has been used to help guide research and development priorities withing RRAP.

C~scape functionality makes it the only coral reef ecosystem model targeting high resolution (sites within reef) dynamics capable of including the main processes and mechanisms required to characterise the effectiveness of novel interventions on the future of coral reefs at within reef scale.

# 2 Background and Justification for the Research

Climate change related disturbances have become the most serious threat to the Great Barrier Reef (Outlook Report 2024). Ocean acidification, increase in intensity of storms, increase in frequency of flooding and particularly increase in frequency and intensity of Marine Heat Waves (MHW) are among the main climate change related threats to the Reef.

Over the last three decades, the frequency of MHW's affecting the GBR has increased significantly (Lough et al. 2018, Emslie et al. 2023). During the past ten years alone there has been five mass bleaching events, reducing coral cover by between 15 and 95 percent in reefs across the GBR (Hughes et al. 2018, Alvarez-Noriega et al. 2024, Great Barrier Reef Marine Park Authority 2024).

Given that climate predictions suggest that even under the most optimistic climate change scenarios there are likely to be MHW causing significant mortality at least five times per decade across the GBR by mid-century (McWhorter et al. 2022), there is a growing need to develop management interventions that can either reduce the intensity of the disturbances or increase the tolerance of coral populations to these pressures (Anthony et al. 2020).

The Reef Restoration and Adaptation Program (RRAP) was created to explore avenues to develop interventions that can help mitigate the impact of climate change related disturbances in the GBR at different spatial scales (from single reefs - hundreds of meters to a few kilometres, through to clusters of reefs with a small number of reefs- tens of kilometres) to sub-regions of the GBR (hundreds of kilometres).

To achieve this goal, RRAP has assembled teams of scientific experts from multiple disciplines and institutions focused on specific interventions (RRAP Sub-programs) including interventions aiming at reducing temperatures during MHW's (cloud brightening and fogging), restoring substrate available for coral recruitment (rubble stabilisation), aid community recovery after disturbance moving larval slicks and guiding high density strategic recruitment (RRAP Moving Corals Sub-program), and increasing the thermal tolerance of wild coral populations (selective breeding of corals and symbiotic larvae, assisted gene flow and coral acclimation through probiotics treatment).

To aid the research and development of these interventions and to predict the potential ecological benefits that each intervention could provide which helps prioritise resources and calculate cost-benefits, it is critical to:

a) Generate critical eco-evolutionary baseline information that can characterise the interaction between the multiple ecological processes involved in the cascading effect of each intervention (main goal of the cross-cutting RRAP Sub-program EcoRRAP), and,

b) Develop mechanistic models that can uptake the information produced by EcoRRAP and other RRAP Sub-programs and represent the main ecological processes and mechanisms controlling coral population dynamics at different spatial scales (RRAP Modelling and Decision Support Sub-program (M&DS)).

During the past five years RRAP M&DS has developed and matured a series of ecosystem models that collectively characterise the predicted future ecological state of the GBR at different scales and under different climate change and intervention scenarios.

As all coral centric interventions are expected to be deployed at a number of specific areas within a reef ranging from a quarter of a hectare to two hectares (referred as 'sites' hereafter), it is critical that ecosystem models resolving a similar spatial scale are available to the program. In response to this need we developed C~scape (formerly named IPMF) over the past five years.

C~scape is a spatially explicit mechanistic coral community model focusing on characterising coral population dynamics at sites within reefs.

The biology and ecology of the model is informed by demographic data produced by the RRAP EcoRRAP Sub-program both empirically and experimentally.

The ecological engine of C~scape is a collection of site-specific Integral Projection Models (IPMs) that predict the number of coral individuals in each size class for each one of six coral types from one year to the next, as a function of the environmental conditions of the site (depth and wave exposure) and the geographical location of the reef.

C~scape explicitly models the dynamic of population thermal tolerance as a function of natural variability in tolerance, natural selection through MHW mortality and the interaction between the local population and newly deployed corals with enhanced thermal tolerance. C~scape uses the principles of landscape ecology accounting for all areas of the focused reefs that are suitable for coral inhabitancy taking advantage of high-resolution habitat maps.

C~scape is a fit-for-purpose model that was developed from scratch to fulfill an essential role within the RRAP Modelling and Decision Support (M&DS) Sub-program, and is therefore capable of being informed by, and interacting with the other models in the program.

The unique opportunity of developing a new ecosystem model and in close collaboration with the developers of the other more mature models in the sub-program enable the team to achieve a significant level of model maturity and readiness in record time. As a result, different versions of C~scape have been used over the past three years to service critical end-user needs (two business case developments in 2022 and 2023) as well as informing critical strategic targets for RRAP intervention research and development both for the current phase and the planned activities for future phases of RRAP.

# 3 Research Objectives and Key Findings

A current list of project outputs are listed on the RRAP website: gbrrestoration.org. Key research objectives and findings are detailed below.

*Table 1: Key findings of the Project aligned to the overarching and specific research questions for each sub-project.*

| Objective | | Key Findings and/or Outcomes |
|---|---|---|
| 1. | Develop the Integrated Population Model Framework (IPMF) (now known as C~scape) model so that it can absorb existing and new (from the RRAP EcoRRAP Sub-program) empirical data at multiple hierarchical levels: coral colony level, coral population level, and fine scale (intra-reef) physical and environmental site descriptors. | Over the past four years, C~scape has been developed following a strategic approach based on the expected timing of the generation of critical information by EcoRRAP and other RRAP sub-programs.<br>We developed a model architecture that was originally based on suboptimal data available at the time, but that was capable of rapidly uptaking newly produced data. Accordingly, we have consistently increased the model accuracy, performance and complexity every year. Furthermore, C~scape has already incorporated most of the information generated by EcoRRAP in the last four years, including demographic data for six different coral types across all EcoRRAP sites, temperature growth relationships for all coral types in the models from experimental data and dispersion ranges based on population genetics analysis.<br>As shown in Figure 1, C~scape uses a series of state of the art spatial layers to divide each reef in the focused reef cluster into a set of ecologically relevant sites that represent collectively all the available substrate for coral inhabitancy in the entire cluster (Roelfsema et al. 2021). These sites are characterised by their own depth, wave exposure and proportion of suitable substrate within the site and connected through high resolution connectivity that has been generated specifically for this purpose by other members of the RRAP M&DS Sub-program (Ani et al. 2024). |

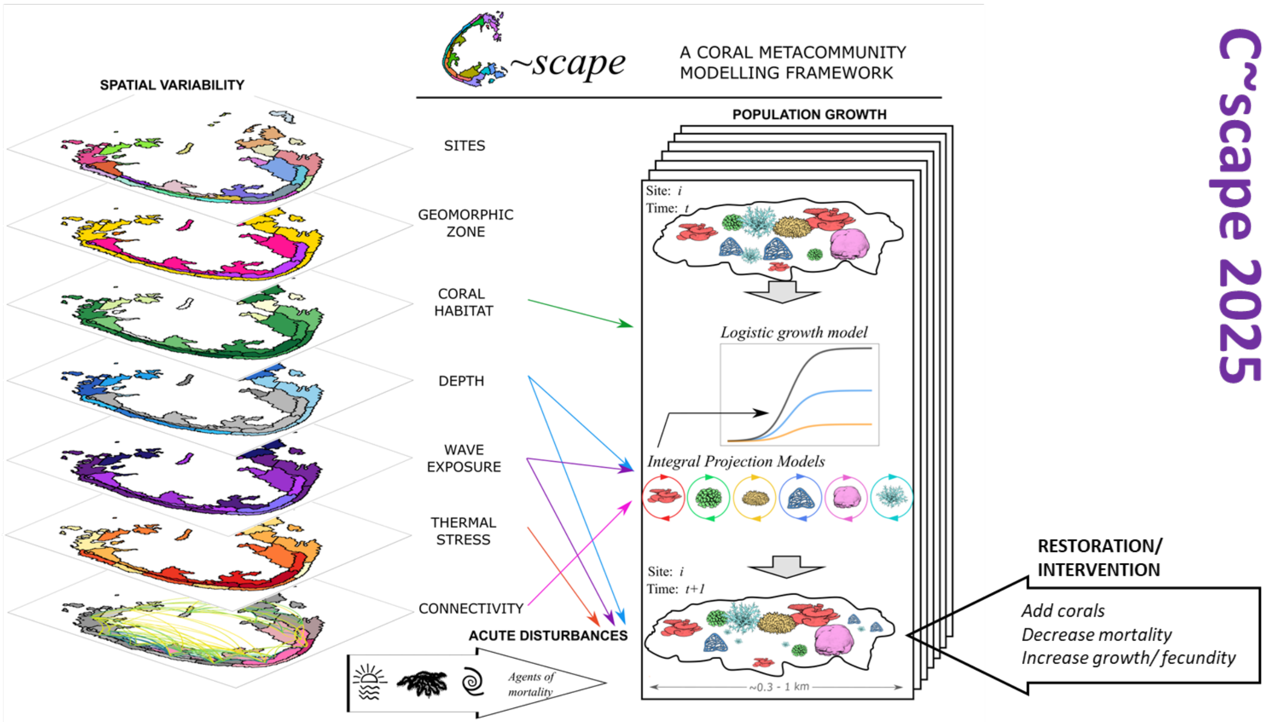


*Figure 1: Hierarchical structure of C~scape ecosystem model.*

For each of the sites, EcoRRAP generated demographic data is used to generate an Integral Projection Model (IPM) that predicts the number of individuals in each size class for each coral type for the next year. These site specific IPMs, are influenced by the temperature experienced each day of the year (based on EcoRRAP temperature growth curve results), the growth and mortality rate expected for that particular wave exposure, depth and region of the GBR, the disturbance regime at the site, and the amount of coral recruits of each coral type coming from other sites within the cluster, or from the reefs surrounding the cluster (informed by ReefMod runs for the entire GBR) (Figure 2).

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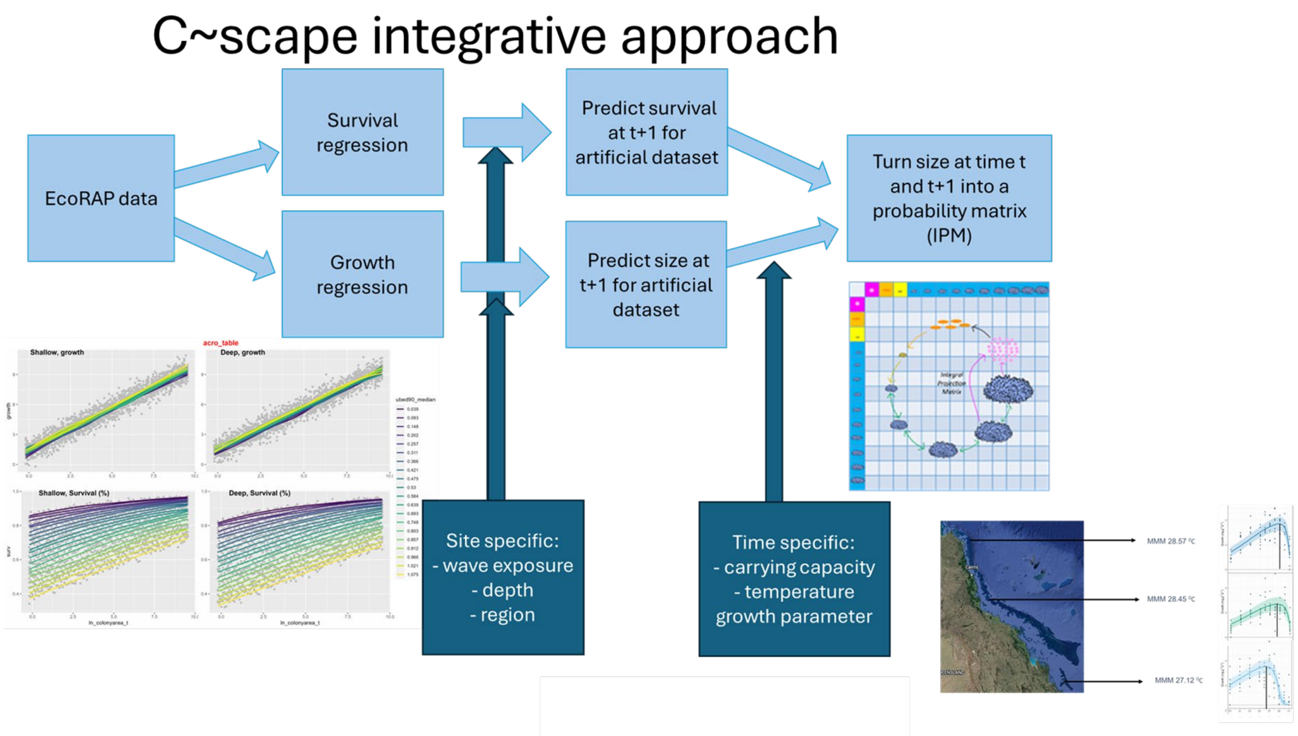


*Figure 2: General integrative architecture for C~scape.*
</td></tr>
<tr><td>2.</td><td>Develop the IPMF (C~scape) to capture uncertainty at the mechanistic level of individual coral growth, survival and fecundity (where many interventions will act) and propagate this through to population level outcomes (where management and conservation are invested).</td><td>C~scape has been developed combining principles from landscape ecology, demographic modelling, and macro-evolutionary dynamics modelling to make sure that it is able to represent both variability and uncertainty within each of the biological and ecological mechanisms incorporated into the models, as well as from disturbance regime predictions.<br><br>In particular the model approach was implemented within a Bayesian framework and allowed us to both predict site specific demographic dynamics as a function of region, wave exposure and depth but also account for the uncertainty in demographic rates (Figure 3).</td></tr>
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$$Growth / Survival \sim coral\ size + depth + waves + region$$

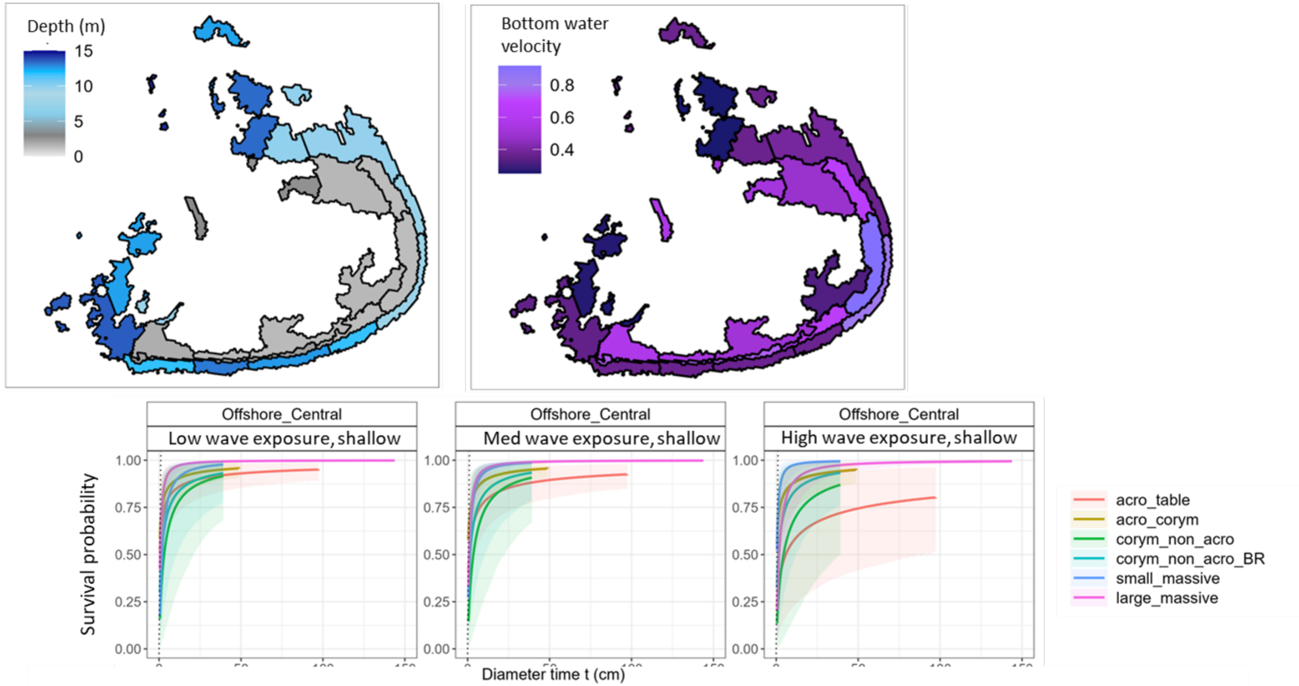


*Figure 3: Variability in survival across regions for specific depths and wave exposures from Bayesian regressions.*

This variability is then propagated across the sea scape generated by the model, and emergent community level trends emerge (Figure 4). Within-reef variability in corals dynamics stayed similar or increased over time under the most optimistic climate change scenario (Shared Socioeconomic Pathways (SSP) 1-2.6) in all clusters, but decreased in warmer climate futures as most trajectories tended to be compressed towards low coral cover by mid-century, with some clusters losing their within reef variability earlier than other regions (Figure 4).

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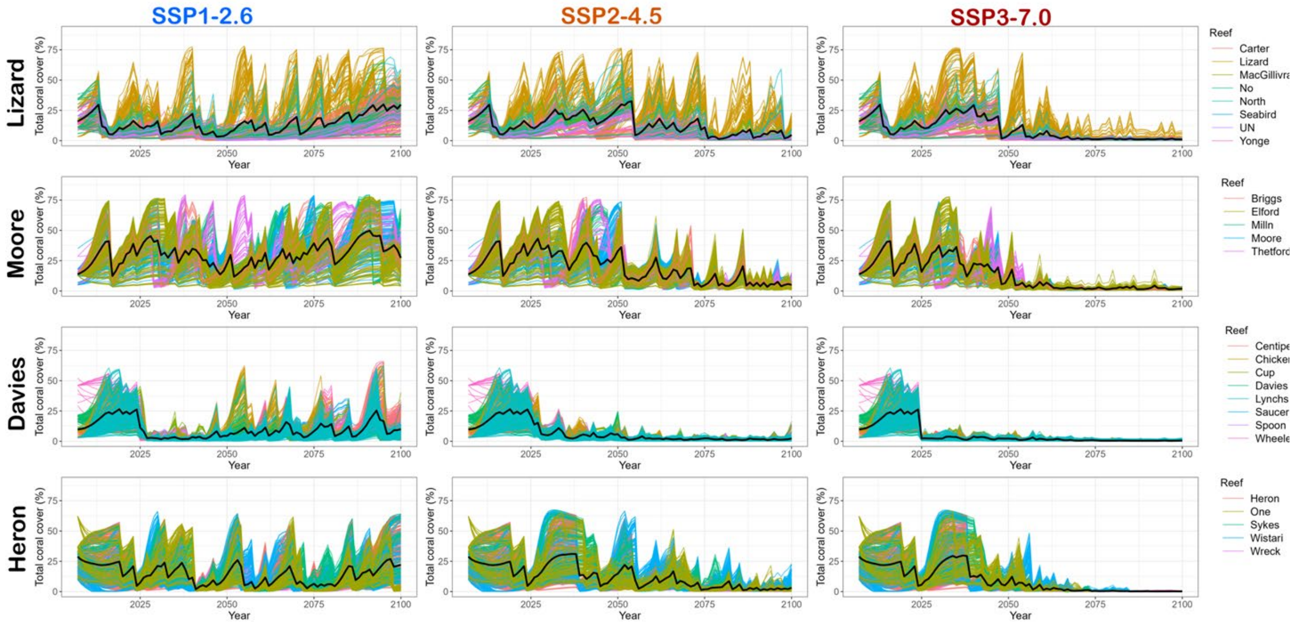
| | | <br><br>*Figure 4: C~scape predicted variability in coral cover across sites within reefs for the four studied clusters across the GBR under different climate change scenarios. (Taken from Creswell et al. in preparation).* |
| 3. | Build capacity to parameterise and model a full portfolio of interventions. | Over the past five years the representation of RRAP interventions in C~scape has progressively improved in response to Program needs.<br>Currently C~scape can represent the implementation of interventions aiming at reducing the local intensity of MHWs (cloud brightening or fogging) within reef scales (although specific differences between these two approaches are not yet incorporated into the model due to lack of empirical data to inform this aspect). Similarly, interventions aimed at |

increasing the thermal tolerance of local wild populations can also be investigated with C~scape. Furthermore, we can explore scenarios with deployment of one or multiple interventions simultaneously (Figure 6).

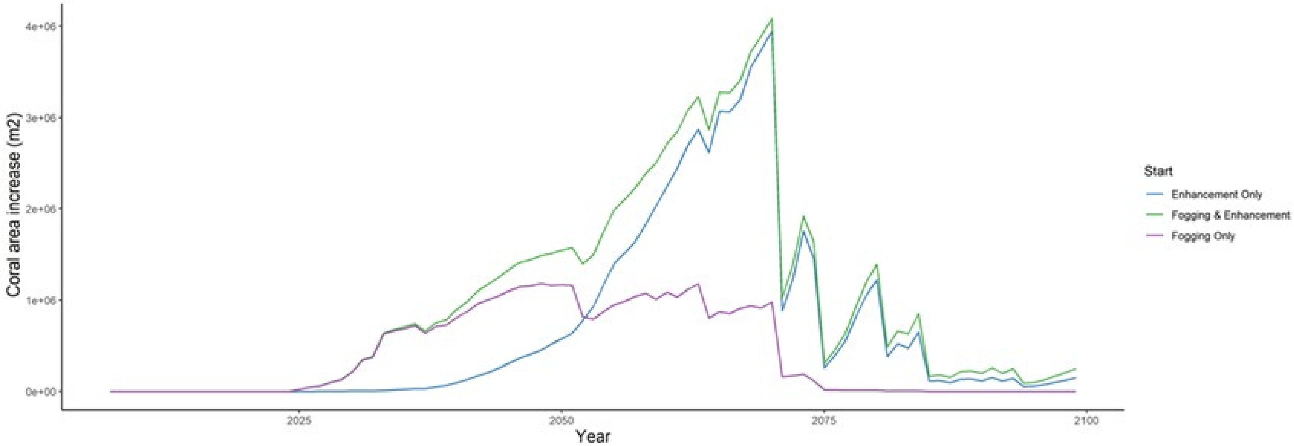



*Figure 5: C~scape predicted comparison of area of coral cover gained in the Moore Reef cluster in Climate Change Scenario SSP 2-4.5 under different combination of interventions. (RRAP-M&DS Interventions Report 2023).*

Importantly, the seascape ecology approach taken in the development of C~scape enables the model to simulate deployments in areas that are smaller than the size of a particular site and then follow the coral dynamics both in the deployed area within the site, and in the non-deployed area within the site (Figure 6). This functionality is particularly useful for setting expectations about the rate at which ecological benefits of intervention are likely to spread from the deployed area over time.

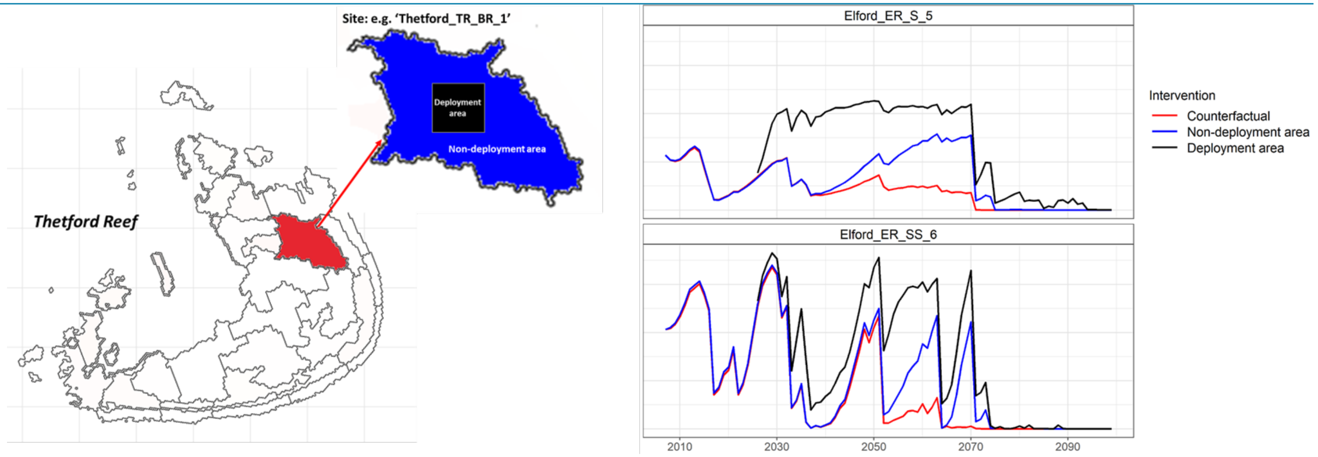



*Figure 6: C~scape within site functionality.*

Example of how an area that is smaller than the targeted site (black square within expanded site in right panel), can be defined for coral deployment. With this functionality, the dynamics of coral communities can be then followed in the small deployed area within a site (black square in left panel, and black line in right panel), within the site but outside the deployment area (blue lines in right panels), and compare them to a scenario with no intervention (red lines in right panels).

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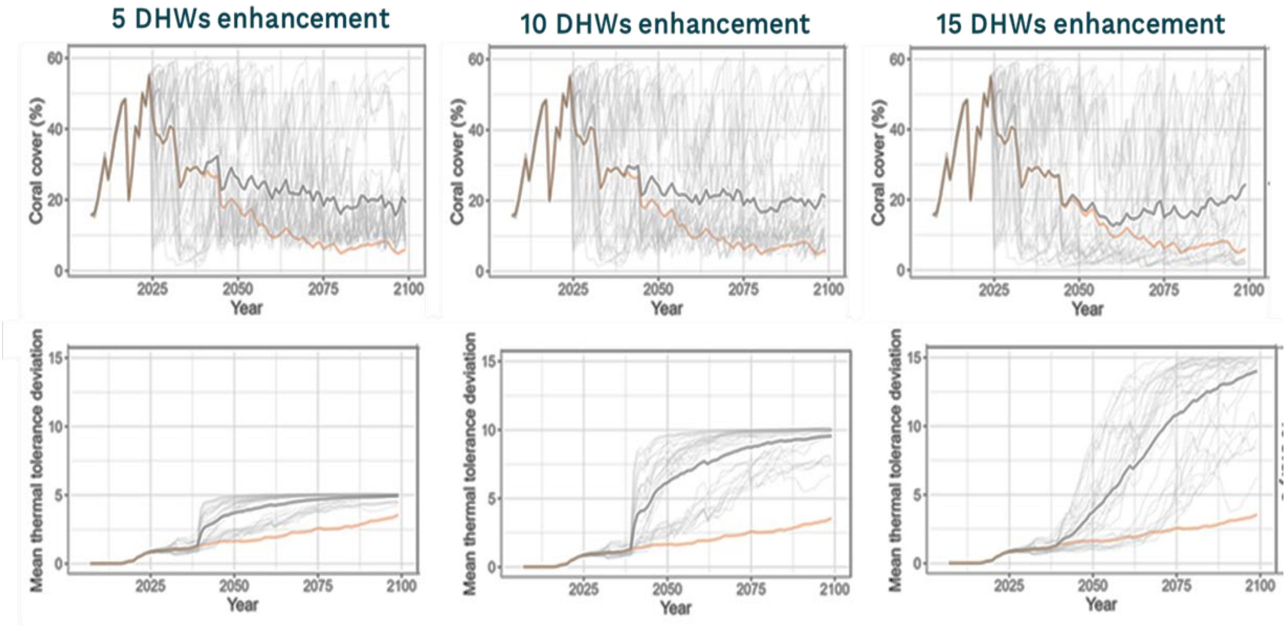
| | | Additionally, in response to intervention specific needs, we have developed the capability to describe the accelerating effect of deploying thermally enhanced corals to positively influence the natural adaptation rate of local wild coral populations (Figure 7).<br><br><br>*Figure 7: C~scape predicted difference in total average coral cover across the Moore Reef Cluster between counterfactual scenario (orange line) and different assisted evolution deployment intensity scenarios (black line) for SSP 2-4.5 (top panels). The corresponding dynamic in average population thermal tolerance over time across taxa (orange line) and assisted evolution acceleration in population thermal tolerance as a function of intervention intensity (black line) is shown in the bottom panels (taken from RRAP Intervention efficacy study 2024).* |
| 4. | Identify sensitivities in the coral life cycle (i.e. where increasing the abundance of a demographic stage leads to the greatest change in the overall population growth). This will allow interventions to be optimised to target these sensitivities and will likely help to better parameterise ReefMod. | The combination of field based coral demographic data integrated within a seascape ecology framework enables C~scape to inform on the sensitivity of coral populations to different demographic processes in different environments.<br>To illustrate this capability, we explore a theoretical simple reef comprised of four sites with different depths and wave exposure. We then ran C~scape on that reef, using the demography from the different GBR regions (Figure 8).<br>We found that demography had a much bigger impact in the north and in shallow sites with population dynamics of total coral cover in these conditions that are up to six times faster. |

Interestingly, demography had a stronger impact when interacting with wave exposure in the central and southern GBR, compared with the north.

These results indicate that overall, deploying corals in shallow sites with high wave exposure is likely to be more effective than in other sites.

Furthermore, it is likely that a lower number of juvenile corals will need to be deployed in the north GBR compared to the central or southern GBR to achieve similar ecological benefits.

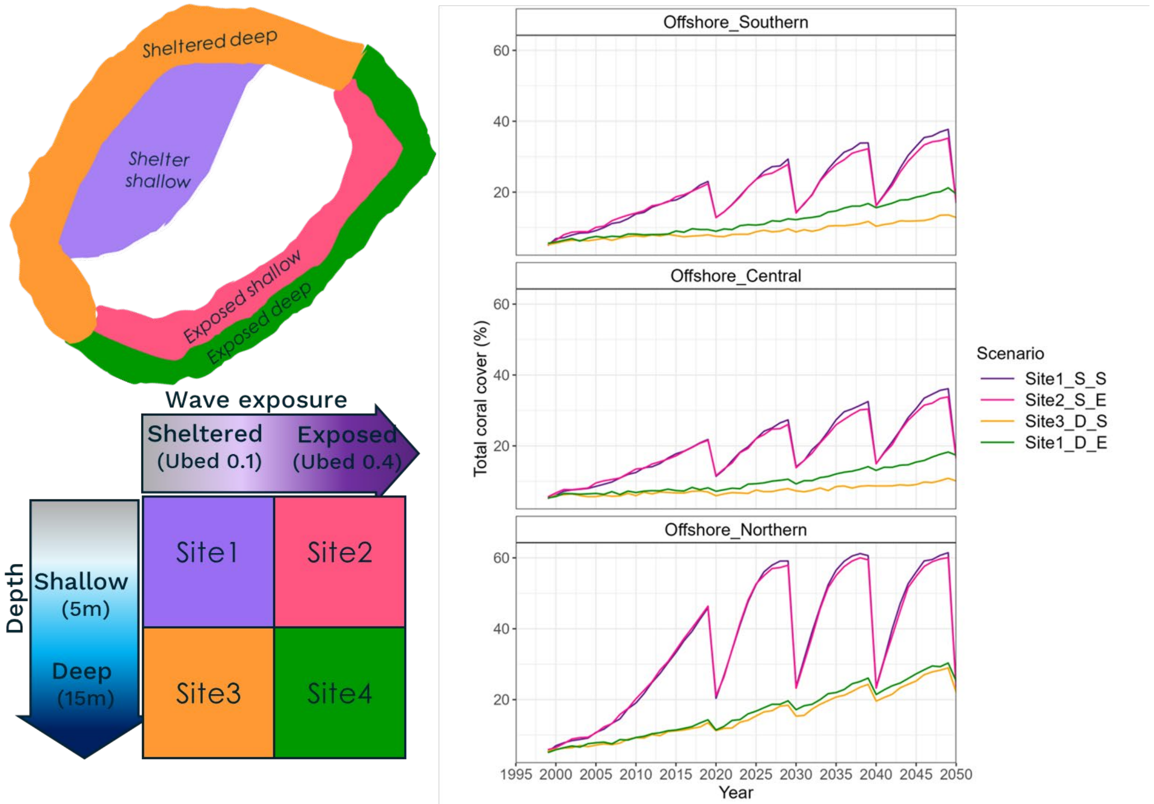
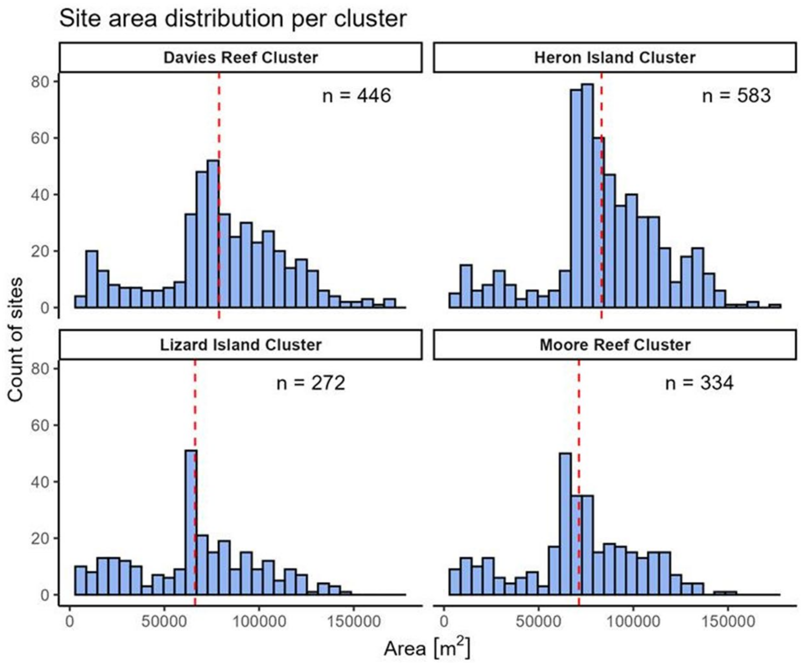



*Figure 8: Impact of demographic variability of community dynamics across GBR sites with different environmental conditions. Left panels describe a theoretical reef with four sites with different depths and wave exposures. Right panels show the community dynamics (average total coral cover over rime) for sites like these across the latitudinal gradient of the GBR.*

| | | |
|---|---|---|
| | | These results suggest that the ecosystem models focusing on the whole of GBR scale simulation (ReefMod and CoCoNet) should update their parameterisation as they currently assume static biological rates across the latitudinal gradient of the GBR. |
| 5. | Improve the capacity of the model to capture fine-scale connectivity. | The principles of seascape ecology applied when developing C~scape facilitate the generation of sites within reefs that have an ecologically relevant scale.<br>Over the past five years we have improved the site characterisation of C~scape to align it better with the resolution of the available within-reefs connectivity<br>The most recent site clustering pipeline developed by the team provides a distribution of site sizes that is ideal to maximise its compatibility with the available connectivity, as it generates median site sizes that are similar to the pixel size of the current connectivity products (Figure 9).<br>Furthermore, the resulting site size frequency distribution is very similar to the planned targeted size of sites for deployment of enhanced corals during pilot deployments in the GBR.<br><br><br>*Figure 9: Distribution of size sizes generated in C~scape across four clusters through the GBR latitudinal gradient. Red dashed line denotes the median site size. Note that the current connectivity available has a pixel resolution of 62,500 $m^2$ (very similar to the median size of sites for all clusters).* |

| | | |
|---|---|---|
| 6. | Expand the capacity to include intra-reef site variables in the integral projection model (IPMind) and integrated population model (IPMpop) which may influence population growth and the success of interventions. | As discussed in previous sections, C~scape has been developed with the goal of representing ecological mechanisms at a site level considering the geographical and local environmental characteristics of each site.<br>Figure 10 illustrates how each site within a small cluster of reefs (in this example Moore Reef), is assigned a specific geomorphic type, wave exposure, depth and carrying capacity (amount of suitable coral habitat).<br>By characterising sites through this approach, it is then possible to generate site specific IPMs based on the posteriors of the Bayesian regression discussed previously (Figures 2 and 3). |

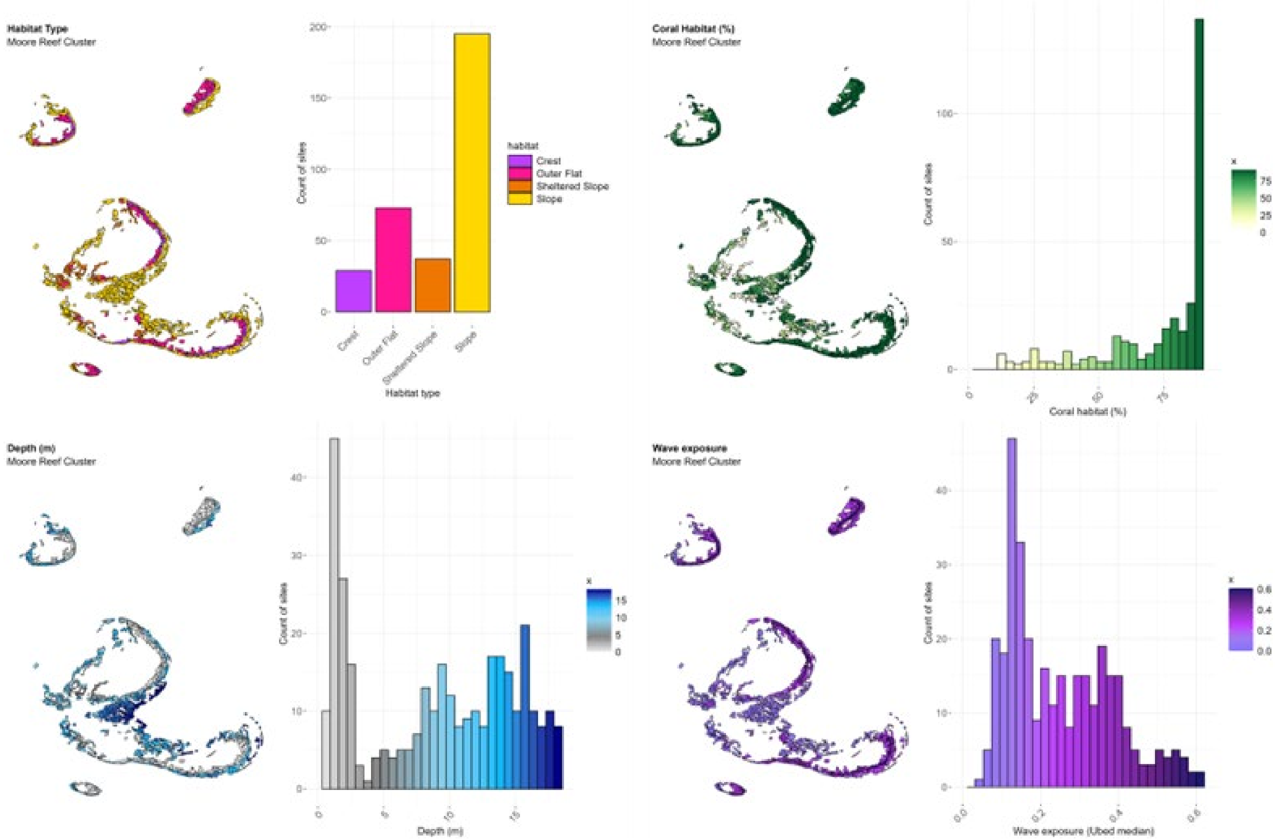
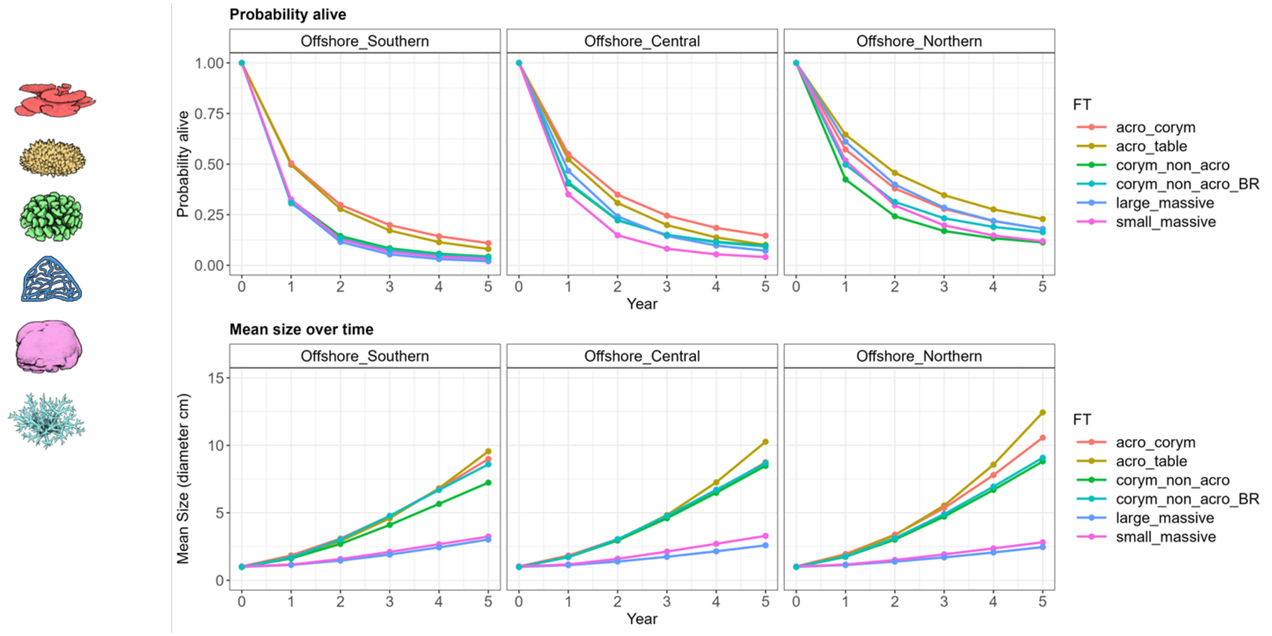



*Figure 10: Site Characterisation within the Moore Reef cluster using the C~scape framework. Each site is assigned a geomorphic type and carrying capacity (amount of available habitat for corals) (top two panels), as well as a depth and wave exposure (bottom two panels) based on available habitat maps and environmental layers (Creswell et al. 2024, Roelfsema et al. 2020.*

| | | |
|---|---|---|
| | | This recent development enables C~scape to explore the impact and potential limitations generated by the interaction between demography, connectivity and disturbance regimes, as demonstrated in previous sections. |
| 7. | Compare the relative importance of demography, intra-reef variability, temporal dynamics, and connectivity in their influence on intervention success. This will allow characterisation of site characteristics that are most influential on intervention, e.g. larvae ‘source’ sites, or refuge sites from disturbance. | As previously discussed, C~scape can inform environmental conditions and demographic patterns that can favour intervention efficacy (Figure 7).<br>An additional illustration is provided by the expected size and cumulative survivorship that deployed corals are expected to have after five years as a function of their taxa and region where they are deployed (Figure 10).<br>This result suggests that interventions may need double the number of corals in the south compared to the north to generate a similar targeted number of reproductive adults. Furthermore, they are likely to become reproductive between two and three years earlier in the north than in the south, therefore increasing the probability they reproduce before an acute disturbance impact them.<br><br><br>*Figure 11: Probability of surviving over time (top panels) and increase in size over time (bottom panels) across the GBR (left to right) for different coral types (different coloured lines).* |

8.

Build capability to partition uncertainty between demographic processes and site level characteristics to determine how this will influence projected intervention benefits and risks across sites within a reef.

All the information presented in the previous sections demonstrate C~scape functionality for propagating uncertainty from different origins across ecological mechanism through populations and communities.

The recent explorations we have presented in this report highlight how variability in demographic process drive different community dynamics across the GBR, and across sites within clusters (Figures 4, 8 and 11).

This demographic variability contributes to drive emerging community level properties like the differential timing of the reduction on site variability within clusters across the GBR (Figure 4) as well as the earlier graphs of coral cover in warm climate change scenarios in some regions of the GBR (Figure 12).

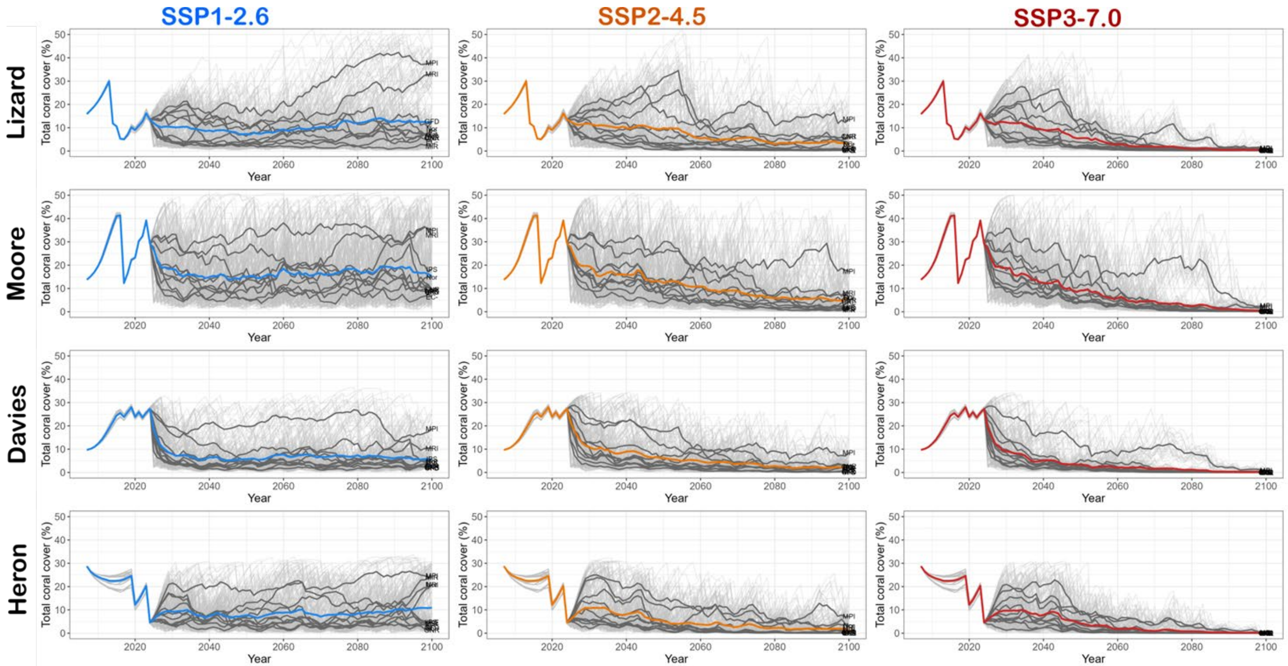



*Figure 12: Average cluster coral cover across climate models for different climate change scenarios across the GBR. Coloured lines represent average across climate models. Dark black lines represent the average of each of the 10 climate models included in each climate change scenario, and grey lines represent each realisation of all climate models.*

### Adjustments to key research objectives

*Table 2: Variation in the Project over time.*

| Initial Research Question | Explain when, how and why the research question changed |
|---|---|
| No adjustments to report | |

# 4 Future Research Recommendations

- **More research on early life stages**

  While the existing parameterisation of C~scape (as well as the other ecosystem models) has produced population dynamics that appear reasonable and are within the variability of what has been seen from empirical data, the largest amount of uncertainty, from the biological point of view, is in the early life stages (from fecundity to recruitment).

  Given that part of the principles proposed to achieve impact at scale is to take advantage of the natural "spill over" from the deployed sites to other areas, making sure that the early dynamics are correct could be the difference between accurate or misleading predictions. Therefore, more research in this area is fundamental for the future improvement of the models.

- **More interpretable and consistent connectivity approaches**

  Similar to the case for more early life stage studies, the current uncertainty in connectivity is large. This is even more significant for high resolution connectivity where even for the GBR there is no readily available product that can be used to link the sites within reefs.

  Furthermore, generating connectivity at this resolution is time consuming and computationally intensive, limiting the reactive ability of new areas that need to be explored, and new connectivity needs to be generated. Accordingly, it would be fundamental to continue research on high resolution connectivity to validate existing modelling approaches and develop more effective faster connectivity pipelines.

- **Include allee effects in the model**

  Currently fertilisation in C~scape (and in the other ecosystem models in the RRAP Modelling and Decision Support (M&DS) suite) is not dependent on the local density of corals of the same type due to the lack of information to parameterise this process. However, this could lead to significant overestimation of future coral cover if prolonged periods of low abundance of a coral causes long delays in recovery due to reduced fertilisation. Recent studies have provided new insights on the abundance-fertilisation success relationship (Ricardo et al. 2025), therefore implementing density dependent fertilisation in these models should be made a priority.

- **Improve implementation and parameterisation of interventions**

  While most interventions being developed by RRAP are now included in C~scape, both the parameterisation and the modelling structure of these interventions is not at the same level of maturity for all of them.

  While all intervention parameterisation should be kept updated over time with new information, particular emphasis on revising the parameterisation and implementation of interventions focused on reducing the intensity of thermal disturbances (developed in the RRAP Cooling and Shading Sub-program) should be prioritised.

- **Explore eco-evolutionary patterns and refine thermal tolerance dynamics representation in the models**

  The interaction between genetics, evolutionary process and demographic rates is a highly topical area of research. The architecture developed in C~scape is ideal to explore this space. However, the shear complexity of the model, and the nature of the complex patterns that are likely to emerge when simulating multiple scenarios requires future exploration of the behaviour of the model to ensure interpretability of results.

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