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Resilience-Based Management Tools for the Great Barrier Reef

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AUSTRALIA

Resilience-Based Management Tools for the Great Barrier Reef

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Cover photographs: Robert A. B. Mason

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ACRONYMS

AIMS .... Australian Institute of Marine Science
CCMA .... Cairns Cooktown Management Area
CoTS .... Crown-of-Thorns Starfish
ENSO .... El Nino-Southern Oscillation
FNMA .... Far Northern Management Area
GBR .... Great Barrier Reef
GBRMP .... Great Barrier Reef Marine Park
GBRMPA ...... Great Barrier Reef Marine Park Authority
LTMP .... Long Term Monitoring Program
MCMA .... Mackay Capricorn Management Area
NESP .... National Environmental Science Program
RBM .... Resilience Based Management
RIMReP .... Reef 2050 Integrated Monitoring and Reporting Program
TWMA .... Townsville Whitsunday Management Area
TWQ .... Tropical Water Quality
WQIP .... Water Quality Improvement Plan

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EXECUTIVE SUMMARY

In 2017, the Great Barrier Reef Marine Park Authority (GBRMPA) convened a summit to discuss the resilience of the reef and explore the benefits of taking a resilience-based approach to its management, RBM (Great Barrier Reef Marine Park Authority 2017). Resilience-based management is defined as "using knowledge of current and future drivers influencing ecosystem function (e.g., coral disease outbreaks; changes in land-use, trade, or fishing practices) to prioritize, implement, and adapt management actions that sustain ecosystems and human well-being" (McLeod et al. 2019).

Despite widespread disturbances, including bleaching, cyclones and crown-of-thorns starfish (CoTS), the impacts on the Great Barrier Reef (GBR) are patchy. Areas that have been less impacted can help other parts of the reef regenerate by supplying new coral larvae. Analyses of coral larval connectivity throughout the GBR reveal that 'key source' reefs exist that are strongly connected to much of the reef yet have a relatively low risk of experiencing coral bleaching or CoTS (Hock et al. 2017). The top 100 key source reefs (~3% of the GBR total) can disperse larvae to nearly half of the ~3800 reefs on the GBR (47%) within a single summer spawning event.

The existence of large-scale variability in the exposure of reefs to stress and their ability to support recovery (through ecological connectivity) highlights the existence of 'systemic resilience'. Systemic resilience is the resilience of the entire ecosystem – the extent to which is resists perturbation following stress exposure and how it recovery occurs through processes of connectivity, recruitment and regrowth. The purpose of this NESP TWQ Hub project, NESP 4.5, was to help operationalise the concept of RBM for the GBR at the system scale in consultation with managers, through developing a sophisticated environment in which to conduct scenario planning. The plan was to integrate a diversity of environmental and ecological datasets with evolving ecological models so that we can 'simulate' how the GBR works. With an understanding of the "patient's" natural processes of vulnerability and recovery potential, we can then begin identifying how practical management interventions, such as water quality control, CoTS control and compliance of fishing regulations, can be targeted to maximise impact at the system scale. In short, the project attempts to help managers compare the benefits of one set of interventions to another, in the context of the disturbance regimes and reef recovery capability applicable at the scale of the intervention, to determine which intervention has the greatest benefit to supporting system resilience. Our intent was to create a set of useful tools but also to start a deeper process of collaboration between researchers and managers that will deliver a mature decision support software for the GBR.

The project developed three RBM approaches culminating in an operational tool as a windows package to support scenario planning and interventions.

1) A dynamic approach to identifying present-day key source reefs that facilitate coral reef recovery

Here, we sought to identify 'which are the most important sources of coral larvae right now, given that many reefs have been damaged by bleaching or other stressors'? An important reef will have a good coral population and be strongly connected to lots of reefs in need of recovery.

We developed and applied an algorithm that uses present-day coral cover and a GBR-scale connectivity model to identify important larval source reefs for supporting recovery of the GBR from its present-day state. We have described the algorithm but also integrated it within the RBM Planning Tool.

To complement the identification of key source reefs, we collaborated with 'Citizens of the GBR' to create a new citizen science initiative entitled the 'Great Reef Census' (https://greatreefcensus.org/). The effort has engaged hundreds of citizens in the collection of reconnaissance data on the state of reefs, specifically targeted to groundtruth the cover predictions that are used in the algorithm for identification of present-day key source reefs. The first Census started in October 2020 and will run until mid-December, after which a broader set of citizens will assist the extraction of reef data from photographic archives. Our secondary objective was to change the narrative over the reef to one that is less of 'the reef is dying' to 'while the reef is in trouble it has healthy areas and recovering areas'. The project has been awarded $700,000 in cash support and is having a strong media engagement.

2) Assessment of how fisheries impacts may affect source reefs of the GBR

Here, we developed methodology to better evaluate the risks posed by fishing and potential non-compliance with zoning laws by interpreting data on these activities within the context of long-term key source reefs. We partnered with GBRMPA's Compliance team to (i) model the risks of commercial fishing, and (ii) extend GBRMPA's modelling of recreational fisheries, across the reef. Fishing can often cause anchor damage (or similar damage from dragged weights) and we identified reefs that were both ecologically important as key source reefs and targeted by fishing. These analyses support two forms of decision-making. First, the analysis contributes to the planning of compliance enforcement efforts in no-take (green and pink) zones of the Park by facilitating evaluation of the potential benefits of reducing damage on some reefs vs. others. Second, more general analyses of the risk of physical damage from fishing, even in fishable (e.g., blue) zones, provides opportunities to ask whether long-term key source reefs are adequately protected. It would allow managers to evaluate whether additional interventions might be considered if a critically important source reef was also the subject of intense fishing.

3) Creation of the RBM Planning Tool for the GBR

To help managers to prioritize management interventions that support ecological resilience, we developed a sophisticated and extensively tested model of GBR coral communities (Ortiz et al. 2014; Ainsworth et al. 2016; Bozec et al. 2020), but the challenge now is to place such information at the hands of managers.

We created a windows desktop software that allows managers to interact with the entirety of the reef, select scenarios of climate change (RCP2.6, 4.5, 6.0, 8.5), and simulate a choice of management measures. At present those measures are (1) four levels of water quality improvement, including the Reef 2050 Water Quality Improvement Plan (WQIP) targets, (2) CoTS control at specified reefs or regions, and (3) ongoing absence of substantial herbivore fishing and (4) boating (anchoring) damage prevention. Thus the user can explore the benefits of the intervention in the context of climate change, the current state (and variation) of reef health, and the diversity of factors influencing reef health.

The model incorporates all of the available data on coral connectivity and the state-of-the-art simulations of water quality from the eReefs models (i.e., sediments and chlorophyll *a*). Whilst prediction of the exact coral cover in space and time is impossible, the aim of the RBM Planning Tool is to inform on the relative efficacy of different management choices by simulating interventions within the context of the most up-to-date state of reef-health and disturbance history. Additional funding from the Queensland and Australian Governments allowed us to extend the modelling to consider a variety of climate change scenarios, which are also included in the tool, including allowing the user to choose from 6 climate models, each of which is relatively good at predicting the El Nino-Southern Oscillation (ENSO) which is important for bleaching predictions. The user can specify the time frame of interest (up to 2070) and define where, when and how often to implement the management intervention.

Managers helped design the tool through several face-to-face workshops before and during tool development, but we emphasize that it is early days in the use of this type of decision support. It is difficult to envisage how it might be used until managers have had the opportunity to explore and 'road test' the tool. Early discussions with GBRMPA have already identified new management objectives that would be well-suited to such approaches (e.g., identifying suites of interventions that offer the potential to achieve a stated outcome for coral health). Thus, while the tool is fully operational, perhaps its greatest value is to provide a functioning test bed to help managers and scientists continue to evolve a set of information and decision-support options, particularly under the Reef 2050 Integrated Monitoring and Reporting Program (RIMReP) - the reef monitoring design program.

Specific deliverables to end-users from this project include:

Management tool	Format
Index of reef recovery that combines water quality and coral connectivity. Adopted by GBRMPA's Resilient Reefs Dashboard	GIS data layer
Map of cyclone risk across the GBR. Adopted by GBRMPA's Resilient Reefs Dashboard. Note additional layers here paid for by GBRMPA project under which we created the layers for the Fortunate Reefs project	GIS data layer
Improved map of recovery potential of all GBR reefs based on ecological model driven by eReefs water quality and larval connectivity. More accurate and easier to communicate than the earlier index. Provided to GBRMPA for dashboard.	GIS data layer and excel file of values by GBRMPA reef ID
Map of predicted reef state (coral cover) in 2020 through hindcasting the last decade of bleaching, cyclones, CoTS and water quality, validated through comparison to Long Term Monitoring Program (LTMP) surveys. Provided to GBRMPA for dashboard	GIS data layer and excel file of values by GBRMPA reef ID
Map of predicted key source reefs in 2020 based on the state of reefs today and their connectivity to reefs in need of larval subsidies to support recovery. Provided to GBRMPA for dashboard and CoTS planning	Excel file of values by GBRMPA reef ID
Analysis of benefits of Water Quality Improvement on future reef health. Co-funded by Qld & Commonwealth Governments to provide climate change projections	Report to Government

Management tool	Format
Maps of commercial fishing intensity across the GBR for use in evaluating risks of reef damage. Information created in collaboration with and provided to GBRMPA Compliance Unit.	GIS layer and excel list
Maps of recreational fishing intensity across the GBR for use in evaluating risks of reef damage. Provided to GBRMPA Compliance Team. This used their model (developed with CSIRO) but we applied it reef wide	GIS layer and excel list
Maps of overall fishing intensity across the GBR for use in evaluating risks of reef damage. Provided to GBRMPA Compliance Team	GIS layer and excel list
Maps of priority reefs that are both highly ecologically important and highly exposed to fishing. Information created in collaboration with and provided to GBRMPA Compliance Unit.	GIS layer and excel list
RBM Planning Tool created as windows software package and delivered to GBRMPA.	Windows software package
Development of impact modelling of ocean acidification for the eReefs biogeochemical model (ongoing)	Component of eReefs model hosted by CSIRO

1.0 INTRODUCTION

In 2017, the Great Barrier Reef Marine Park Authority (GBRMPA) convened a summit to discuss the resilience of the reef and explore the benefits of taking a resilience-based approach to its management, RBM (Great Barrier Reef Marine Park Authority 2017). Resilience-based management is defined as "using knowledge of current and future drivers influencing ecosystem function (e.g., coral disease outbreaks; changes in land-use, trade, or fishing practices) to prioritize, implement, and adapt management actions that sustain ecosystems and human well-being" (McLeod et al. 2019). In practice, this might not necessarily change the types of interventions, but it does seek to apply them where and when they can be most effective at supporting the ecosystem's resilience.

Most studies of coral reef resilience focus on ability of individual reefs to resist disturbance and/or recover swiftly. It is well known that the GBR has been impacted by multiple recent bleaching events (Hughes et al. 2017), which add to the litany of other impacts from cyclones, and crown-of-thorns starfish (CoTS), (De'ath et al. 2012). Recent studies have also shown that the rates of recovery of GBR reefs have reduced as much as 80% in places, particularly after flood events where poor water quality extends farther across the reef than usual (Ortiz et al. 2018). Yet despite such widespread disturbances, the impacts on the GBR are patchy. At any given time there are large regions of the reef in a relatively good state whereas others are in the early stages of recovery. And while the proportion of reefs in 'good state' will likely decline, these areas provide opportunities for reef recovery. Analyses of coral larval connectivity throughout the GBR reveal that 'key source' reefs exist that are strongly connected to much of the reef yet have a relatively low risk of experiencing coral bleaching or CoTS (Hock et al. 2017). There are approximately 3800 reefs on the GBR (classified by the GBRMPA as distinct patch or fringing reefs). Of the top 600 'key source reefs' – the most important hubs of coral connectivity across the system - approximately 100 meet strict criteria of long-term low risk of damage. Yet this paltry 100 reefs (~3% of the GBR total) are poised to disperse larvae to nearly half of the entire GBR (47%) within a single summer spawning event (Hock et al. 2020).

The existence of large-scale variability in both the exposure of individual reefs to stress and their ecological importance (as interlinked contributors to resistance or recovery) highlights the existence of 'systemic resilience'. That is, the resilience of the entire ecosystem, including how it repairs itself through processes of connectivity and larval-assisted recovery (the emphasis of this project). The purpose of the NESP Project 4.5, 'Guidance System for Resilience-Based Management of the Great Barrier Reef', was to help operationalise the concept of RBM for the GBR in consultation with key managers. The plan was to integrate a diversity of environmental and ecological datasets with evolving ecological models so that we can 'understand' how the GBR works. With an understanding of the patient's natural processes of vulnerability and recovery potential, we can then begin to identify how management interventions, such as CoTS control and compliance of fishing regulations, can be targeted to maximise their impact. In short, the project attempts to help managers compare the benefits of one set of interventions to another. Our intent was to create a set of useful tools but also to start a deeper process of collaboration between researchers and managers that will lead to ongoing improvements needed for an advanced decision support software for the GBR.

The project developed three RBM approaches culminating in an operational tool as a windows package to support scenario planning and interventions.

1) A dynamic approach to identifying present-day key source reefs that facilitate coral reef recovery

Long-term key source reefs – those reefs that have been demonstrated to be important sources of larvae to support coral recruitment over many years – are an important component of systemic resilience on the Great Barrier Reef. In this report, we build on the concept of 'long-term' key source reefs to develop a time-responsive definition that is useful for prioritisation. The new concept, present-day key source reefs, identifies the most important sources of coral larvae right now, given the current state of reefs that reflects damage from recent bleaching or other stressors. An important reef will have a good coral population and be strongly connected to lots of reefs in need of recovery.

The present-day key source reefs concept operates via an algorithm that takes into account the requirements of every reef in the GBR for larval subsidies to support recruitment (based on their current coral cover), uses a larval connectivity network to determine the importance of each reef in terms of being highly connected to other reefs in need, and determines the ability of each highly connected reef to actually contribute larval subsidies based on its coral cover level. We describe the algorithm (Chapter 2) and have also integrated it within the RBM Planning Tool.

2) Assessment of how fisheries impacts may affect source reefs of the GBR

Here, we partnered with GBRMPA's Compliance team to model the risks of commercial and recreational fisheries across the reef. This work builds off Damian Weeker's PhD work (GBRMPA employee). The analysis evaluates each reef's risk of experiencing damage from anchoring / fishing gear against the importance of that reef as a key source of coral larvae. In practice, it allows two forms of decision-making. First, the planning of compliance efforts in no-take (green and pink) zones of the Park can consider the potential benefits of reducing damage on some reefs vs. others. Second, more general analyses of the risk of physical damage from fishing, even in fishable (e.g., blue) zones, provides opportunities to ask whether key source reefs are adequately protected. It would allow managers to evaluate whether additional interventions might be considered if a critically important source reef was also the subject of intense fishing.

3) Creation of the RBM Planning Tool for the GBR

The great diversity of scientific knowledge is often best utilised within ecological models that allow multiple processes to interact and potentially generate complex outcomes. The Marine Spatial Ecology Lab has been building simulation models of coral reefs since 2004 and these have been tested rigorously against independent field datasets of long-term reef trajectories. Most recently, this was done against 60 sites of the Australian Institute of Marine Science (AIMS) Long-Term Monitoring Data (Bozec et al. 2020). The models were originally developed for the Caribbean (Mumby et al. 2007; Mumby et al. 2014; Bozec et al. 2016) and then extended for the GBR (Ortiz et al. 2014; Ainsworth et al. 2016; Bozec et al. 2020).

Our main efforts were to improve the models, add functionality for coral reef management interventions, and then provide a software tool that could service a range of needs. This is the first attempt to create a tool that allows coral reef managers to explore the benefits of a bespoke set of actions. It is a significant challenge to achieve this particularly for an ecosystem so extensive and complex while also providing the flexibility for managers to specify interventions at an almost limitless choice of reefs over time.

The tool we created is a windows desktop software that allows managers to explore the simulated impact of a wide variety of management decisions on reef health, under a range of climate change scenarios and disturbance types. The main features of the RBM Planning Tool are:

- Simulations are run within the software itself, for any user-defined period between 2020-2100, using input layers of starting coral cover (for six coral types representing most forms of coral on the GBR), starting crown-of-thorns starfish density, and starting rubble cover. The model incorporates all of the available data on coral connectivity and the state-of-the-art simulations of water quality from the eReefs models (i.e., sediments, chlorophyll *a*, nutrients). From these starting conditions, the ecosystem state is updated every year based on the effect of the projected future disturbance regimes and management interventions.

- The user can select a variety of emissions pathways (RCP 2.6, 4.5, 6.0, 8.5), in order to compare the efficacy of management interventions under varying degrees of climate change severity. In the current version of the tool, only the climate change impact of rising sea-surface temperature is dealt with but ocean acidification impacts will be included in a future version. Within each emissions scenario, sea-surface temperatures are available from six different atmosphere-ocean general circulation models, allowing representation of the range of uncertainty in temperature response within each of the emissions pathways.

Management interventions available for simulation within the tool are (1) four levels of water quality improvement, including the 2050 WQ Improvement Plan targets, (2) CoTS control at specified reefs or regions, (3) prevention of fishing of herbivorous fish and (4) prevention of boating damage (via anchors). This suite of interventions covers those that are currently implemented at some scale within the GBRMPA and adjacent catchments. The timing and geographic extent of each intervention can be user-specified, allowing the systemic effects of interventions to be explored.

Whilst recognising that the exact future cannot be predicted, the aim of the tool is to enable exploration of the relative impacts of different management options deployed within a spatially and temporally realistic disturbance context.

2.0 DYNAMIC APPROACH TO IDENTIFYING PRESENT-DAY KEY SOURCE REEFS THAT SUPPORT CORAL RECOVERY

2.1 Introduction

Coral bleaching is arguably the largest-scale disturbance to impact coral reefs (Baker et al. 2008; Harborne et al. 2017) and the management of such events has been considered at length (West and Salm 2003; Marshall and Schuttenberg 2006; Wilson et al. 2020). Given that the stressor itself – solar radiance at elevated temperature (Enríquez et al. 2005) – cannot yet be mitigated directly with well-tested field interventions, management tools fall into three groups: identify areas where corals avoid or tolerate stress, reduce additional stressors, and enhance recovery.

Some of the earliest conservation suggestions were to identify natural refugia where predictably cooler or shadier conditions prevail (West and Salm 2003). Refugia remain an important principle and uptake will benefit from further study of whether corals in naturally benign environments are more vulnerable to stress even though such events are rare (Cote and Darling 2010). A related strategy has been to predict the physiological responses of corals under multiple stressors – including warming – and identify areas of greater physiological tolerance. Typically, these are areas where conditions have more variable or elevated chronic (seasonal) stress (McClanahan et al. 2007; van Woesik et al. 2012; Mcleod et al. 2012; Chollett et al. 2014; Palumbi et al. 2014) and relatively modest acute (bleaching) stress (Mumby et al. 2011).

The second class of interventions seek to reduce additional stressors that might otherwise interfere with coral health and recovery. Such actions were prescribed well before coral bleaching became a rallying call for greater protection and include improvements in water quality (Smith et al. 1981; Richmond 1993), reductions in destructive fishing (McManus 1997), reductions in overfishing (McClanahan 1995), and control of corallivores such as crown-of-thorns starfish, CoTS (Babcock et al. 2016; Hock et al. 2016). Evidence of a link between nitrogen pollution and coral susceptibility to bleaching (Burkepile et al. 2020; Donovan et al. 2020; Fabricius 2005; Wooldridge 2009; Wooldridge 2020) has strengthened the case for tackling water quality as part of a climate change strategy.

A third class of activities focus explicitly on enhancing coral recovery, though that might involve several of the tools mentioned above. The recent emergence of systemic resilience (Scheffer et al. 2012; Hock et al. 2017) has led to the identification of key sources of coral larval supply from connectivity networks (Hock et al. 2017). Such areas may therefore prove to be ecological priorities for reducing additional stressors including CoTS (Hock et al. 2017; Condie et al. 2018) or siting coral restoration (Doropoulos and Babcock 2018).

Most of the management approaches described above contribute to the broader umbrella of RBM (Maynard et al. 2010; McLeod et al. 2019). Thus, one might evaluate the degree to which key sources of larval supply sit in less stressful environments and which locations might need more aggressive action to reduce manageable stressors. While many countries are implementing aspects of RBM, including fisheries bans (Steneck et al. 2019), there remains considerable scope to operationalise activities and embed them more firmly in the standard operating practices of management.

Here, we describe a method for identifying reefs, following a system-wide acute disturbance (e.g. bleaching), which are important as larval sources due to their continued health and their connection to highly affected reefs. Severely bleached reefs are more likely to have experienced mass coral mortality (Eakin et al. 2010; Hughes et al. 2018) and impaired fecundity (Ward et al. 2000). Under these conditions it is likely that coral replenishment will be driven by the dispersal of larvae from healthier reefs upstream. Our approach identifies the most important sources of post-bleaching recovery: i.e., the reefs that serve as larval sources to many, disturbed reefs in need of coral larval supply. Once such reefs have been identified and prioritised, managers can then evaluate the degree of risk to recovery and decide which, if any, interventions are warranted and where, though decisions on actual intervention type are not guided by this framework *per se*. Our intent is to describe an approach that can be applied in a timely manner after a bleaching event (months) and support RBM. We illustrate the rationale and method on a simple reef network and then demonstrate its implementation for the Great Barrier Reef.

2.2 Methods

The approach we describe here, which we term the connectivity-recovery algorithm, considers each reef in an ecosystem and evaluates its potential to serve as an important source of coral larvae. A reef will score highly as a larval source if it meets the following three criteria. First, the reefs it connects to must be in need of larval supply (i.e., in a state of recent damage with low coral cover). Second, the proportional contribution of larval enrichment to damaged reefs should be high, implying that the reef is a major and important source of larvae. Third, (and optionally – that is, if valued by the user) the reef has connections to many such “reefs in need”.

There exists deliberate overlap between the second and third criteria. Imagine a case where two source reefs achieve similar scores for total larval contribution (measured in criterion 2) but through quite different pathways. The first might have a strong connection to a single reef, whereas the second might have a modest connection to multiple reefs. This comparison places considerable importance on the strengths of larval connections, which will generally be more variable – and therefore uncertain – than a binary determination of whether reefs are connected by larvae or not. Adding a third criterion that explicitly quantifies the number of connections between a source reef and its destinations allows this aspect of the algorithm to be emphasized (i.e., the algorithm rewards source reefs with connections to many destinations). Note, that we provide a mechanism that allows the user to adjust the contribution of the third criterion and even switch it off.

2.2.1 Simple illustration of the algorithm

To illustrate the functioning of the connectivity-recovery algorithm, consider a network of 10 coral reefs (Fig. 2.1) connected by larval supply (Table 2.1). Six of the reefs have been severely impacted by bleaching and have low coral cover (Table 2.2). Even a simple visual interpretation of the network suggests that reef 1 is the most tactically valuable at present. It has fairly high coral cover and connects to three reefs in need of larval supply (reefs 2, 4, 5), with some of those larval connections being relatively strong (1->4; 1->2). In contrast, reef 5 offers little strategic network value at present because it is damaged and is not persistently connected to any other reefs.

Implementation of the algorithm occurs in several steps:

a) Firstly, the contribution of each reef to the larval enrichment (*LE*) of all reefs is calculated. This step takes into account the area-weighted requirement (“neediness”) of other reefs for larval supply to support recovery.

b) The second element of the algorithm calculates the number of reefs (*R*) that are connected to each reef and in need of larval supply because their coral cover sits below the critical coral cover threshold.

c) Given that the two key measures of enrichment at each individual reef - larval enrichment and number of connected reefs - are measured on different scales, each is then normalised to the range 0-1.

d) Then, the importance of the second measure, number of connected reefs, on the overall output of the algorithm is weighted to toggle the relative emphasis placed upon number of connections. The weighting factor α can be set to zero to focus purely on the total larval enrichment offered by reefs, or to 1 to assign equal importance to total larval enrichment and the number of larval connections to reefs in need of supply. Intermediate levels of α can be used to downweight the importance of ‘number of reefs’ as desired. Note that setting α to zero still includes all of the connections among reefs but adjusts their importance by the strength of connectivity.

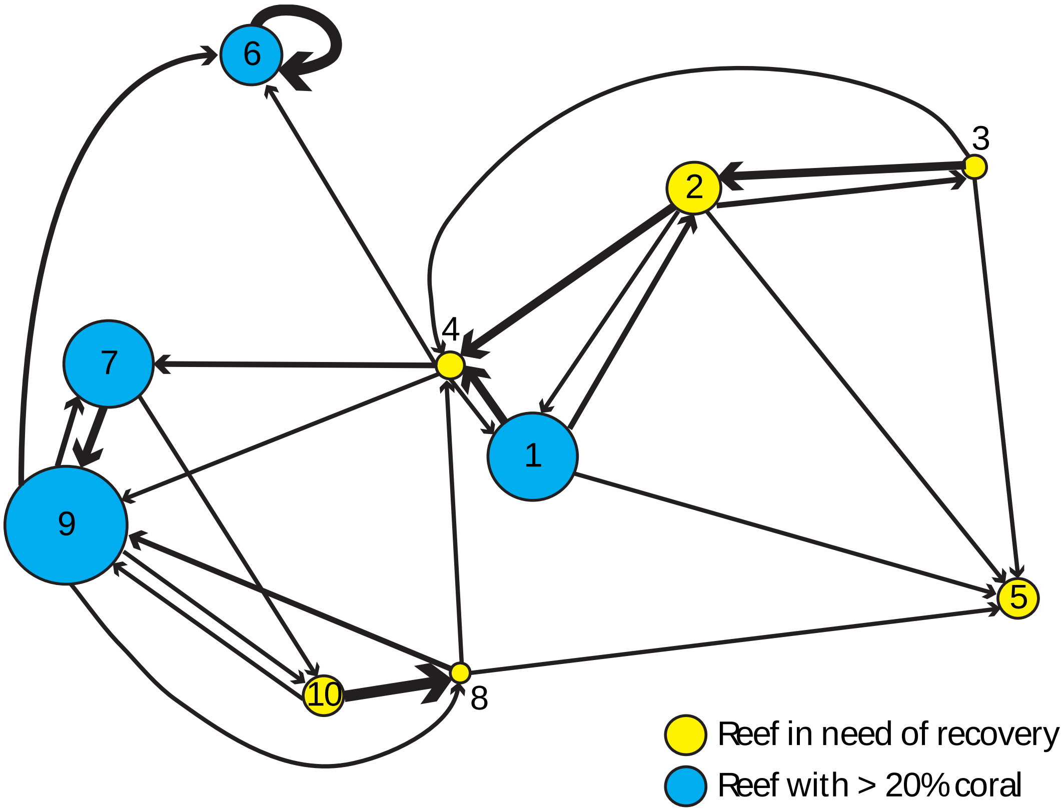


Figure 2.1: Simple network of 10 coral reefs (numbered 1-10) showing the directions and relative strengths of larval supply, including self-retention. The size of each reef is scaled to the current coral cover and reefs whose cover is less than 20% are considered in need of recovery.

Table 2.1: Connectivity matrix to accompany the illustrative reef network (Fig. 2.1), where each value represents the probability of coral larvae departing from each reef (row) and arriving at their destination (column). The diagonal (grey) represents self-retention.

		Destination Reef Number									
		1	2	3	4	5	6	7	8	9	10
Source Reef Number	1	0.1	0.2	0.2	0.3	0.1	0	0	0	0	0
	2	0.1	0.1	0.2	0.3	0.1	0	0	0	0	0
	3	0	0.3	0.1	0.1	0.1	0	0	0	0	0
	4	0.1	0	0	0.1	0	0.1	0.2	0	0.1	0
	5	0	0	0	0	0.1	0	0	0	0	0
	6	0	0	0	0	0	0.4	0	0	0	0
	7	0.05	0	0	0	0	0.1	0.3	0	0.3	0.1
	8	0	0	0	0.1	0.1	0	0	0.1	0.2	0
	9	0	0	0	0	0	0.2	0.2	0.1	0.1	0.1
	10	0	0	0	0	0	0	0	0.4	0.1	0.1

2.2.2 Application of the connectivity-recovery algorithm to the Great Barrier Reef

Although the GBR routinely experiences intense coral mortality from cyclones and crown-of-thorns starfish, it has experienced three major bleaching events in the last five years. The Reef itself, and the typical geographic extent of the Reef hit by any one bleaching event, is too large to survey extensively. It is therefore necessary to use some form of modelling to map expected coral cover and/or the impacts of recent coral bleaching. Here, we applied a calibrated model of the GBR to integrate the impacts of all major disturbances, as well as chronic stressors such as suspended sediment, on the state of the ecosystem (Bozec et al. 2020). The advantage of using a model is that it attempts to integrate the combined impacts of multiple stressors as well as spatial variation in some of the key processes driving recovery. The model predicted coral cover, disaggregated by six functional groups, and we used the total cover post-2020 bleaching as the Current State. Bleaching impacts were quantified using NOAA Coral Reef Watch's index of thermal stress associated with recent bleaching events, where a Degree Heating Week (DHW) of >6 tends to be associated with significant coral mortality (Skirving et al. 2006). Empirical relationships between DHW and coral mortality are available for the Caribbean (Eakin et al. 2010) and GBR (Baird et al. 2018; Hughes et al. 2018). Alternatives to using a model are discussed later.

Reef area was available from the indicative reef boundaries used by the Great Barrier Reef Marine Park Authority, though these maps are currently in the process of being updated using recent satellite data (Roelfsema et al. 2020). Given that most of the reef area occurs around the periphery of the indicative reef boundaries, values were squareroot transformed to better approximate the relative area of coral habitat among reefs. The indicative reef boundaries demarcate 3806 reefs. Connectivity was averaged across coral spawning events across 8 years (Hock et al. 2019).

The model was coded in Matlab using an α of 1, and took approximately 2 minutes to complete on a standard laptop.

2.3 Results

2.3.1 Simple illustration of the algorithm

The algorithm was successfully applied to a simple example reef network (Table 2.2 and Figure 2.2). When applied to even a simple network, the results are only modestly correlated between the two components of the algorithm, *R* and *LE* (r=0.67), despite them both depending on the number of connections among reefs. This reflects the impact of a diversity in connection strength among reefs in the example, though such diversity occurs naturally in real coral reef systems (Foster et al. 2012; Storlazzi et al. 2017; Hock et al. 2019). In practice, the existence of only modest correlation implies that the weighting factor, α, could have a substantial impact upon outcomes.

Table 2.2: Example implementation of the connectivity-recovery algorithm on the simple network assuming structure (Fig. 2.1) and connectivity (Table 2.1). Equation numbers shown in parentheses. Abbreviations are Reef number (Reef num.), coral state (CS), Neediness (ND), Area (A), Larval enrichment (LE), total number of larval connections (NC), number of necessary connections (R), scaled larval enrichment (LE_S), number of necessary connections (R_S), and Recovery Value (RV).

Reef num.	CS (%)	ND (2)	A	LE (1)	NC	R (3)	LE_S (4)	R_S (5)	RV (6)	Reef Narrative
1	30	0	1	1.44	4	4	1	1	2	Most important as healthy and supplies at least 4 reefs that need it
2	15	0.25	1	0.67	4	3	0.46	0.75	1.21	Moderately healthy and good larval source
3	3	0.85	1	0.09	3	3	0.06	0.75	0.81	Unhealthy but a source to reefs in need
4	5	0.75	1	0.02	4	1	0.01	0.25	0.26	Unhealthy and source to reefs that do not need supply
5	10	0.5	1	0.08	0	0	0.05	0	0.05	Unhealthy and not a good source
6	20	0	1	0	0	0	0	0	0	Healthy but not a good source
7	30	0	1	0.15	4	2	0.10	0.5	0.60	Healthy but supplying reefs that have little need
8	2	0.9	1	0.04	3	2	0.03	0.5	0.53	Unhealthy and supplying some reefs in need
9	35	0	1	0.55	4	3	0.38	0.75	1.13	Healthy but supplying only some reefs in need
10	12	0.4	1	0.57	2	1	0.39	0.25	0.64	Moderately unhealthy and a good source to only one reef in need

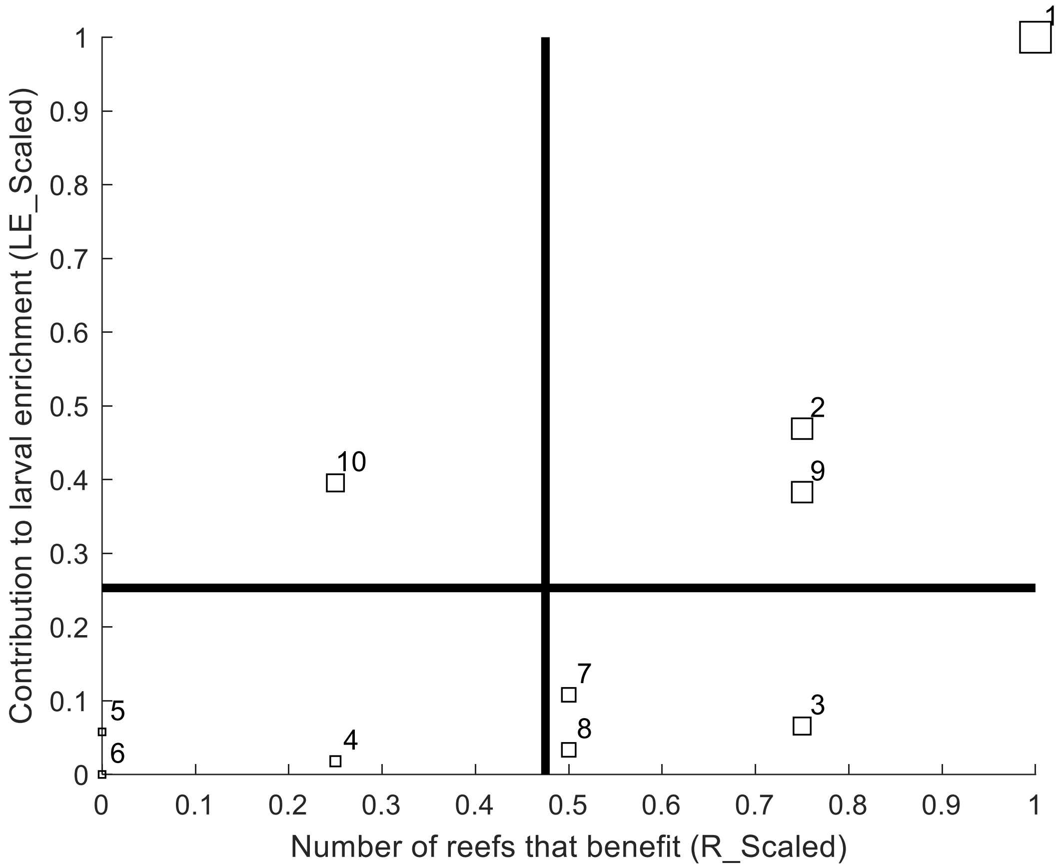


Figure 2.2: Implementation of the connectivity-recovery algorithm on a simple network (Fig. 1) comparing the two elements of the algorithm; larval enrichment and the number of reefs that benefit from larval supply. The size of each symbol is scaled to the overall Recovery Value and the median values of each axis are shown.

2.3.2 Application of connectivity-recovery algorithm

The normalisations of *LE* and *R* were initially carried out for the entire GBR (Fig. 2.3). This approach highlights the most important reefs for driving immediate recovery across the entire system. Not surprisingly, Recovery Value was patchily distributed across the system with higher values in dense reef aggregations of the Hardline Reefs and Far North (Fig. 2.3A), both of which have been impacted by recent bleaching.

In addition to a reef-wide perspective, it is often desirable to obtain a regional evaluation of the potential value of reefs to system recovery. To do this, we adopted the 11 sectors used by the Australian Institute of Marine Science to stratify reef monitoring both latitudinally and across the continental shelf (Fig. 2.3B). Regional assessments of Recovery Value were obtained by normalising *LE* and *R* using only the reefs within a given sector (Fig. 2.3C). The distribution of high Recovery Values was now somewhat uniform across sectors (Fig. 2.3C) but clearly revealed substantial heterogeneity within sectors.

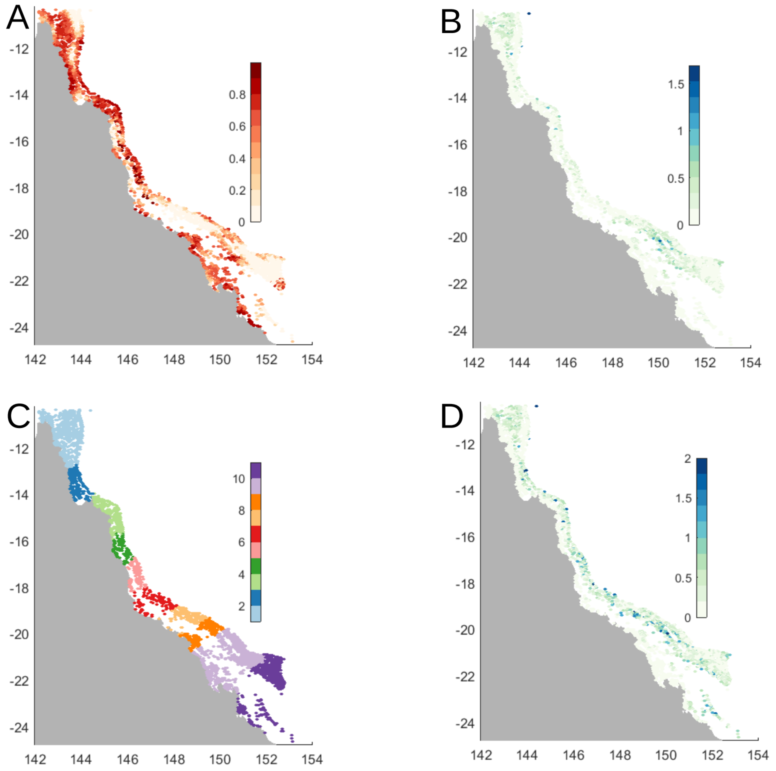


Figure 2.3: Application of the connectivity-recovery algorithm to the GBR showing neediness (A), Recovery Values scaled to the entire GBR (B), the location of AIMS sectors (C), and Recovery Values scaled by sector (D).

2.4 Discussion

As mitigating heat stress or restoration at large scale are not feasible, one option for RBM is to instead facilitate natural reef recovery by preventing further coral losses, particularly on reefs that play an exceptionally important role in driving replenishment. The algorithm presented here identifies reefs with the greatest potential to stimulate the recovery of damaged areas.

Like any simple model, the approach makes a number of assumptions. First, it assumes that larval dispersal and recruitment is an important component of recovery following a disturbance event. This is a reasonable assumption given its support by field data (e.g. Graham et al. 2006). While local larval retention is important and can drive local stock-recruitment in corals (Black 1993; Doropoulos et al. 2012; Gilmour et al. 2013; Hughes et al. 2019), these processes are likely to be relatively weak after mass coral mortality, particularly given the oft-weak functional links between shallow and deeper corals (Bongaerts et al. 2011).

A second assumption is that larval dispersal can be predicted using Lagrangian particle models that simulate coral larvae on ocean currents. While oceanographic models inevitably involve trade-offs between resolution (space, depth, and time) and capturing large-scale boundary conditions (e.g., major circulation, tidal mixing), a number of empirical studies have found genetic congruence with the type of coarse resolution models used here (~ 4 km) (Galindo et al. 2006; Foster et al. 2012). Indeed, predictions of the connectivity model were included in population genetic models for *Acropora tenuis* and *Acropora millepora* and compared to extensive field data. The models were found to predict observed multi-generational gene flow and asymmetric eigenvectors (Riginos et al. 2019). That does not imply that the model is perfect and it may well underestimate the strength of local larval retention and some small-scale processes. Ideally, an ensemble of models will be used in future that combine the benefits of modelling at hierarchical scales (Mumby et al. 2018).

Furthermore, the connectivity network used was an average over seven years of the annual connectivity network resulted from spawning and hydrodynamics patterns. Currents and hydrodynamic patterns on the GBR can change on an annual basis due to variability in regional climate and ocean currents, such as ENSO and the Pacific Decadal Oscillation (Thompson et al. 2018). Spatial patterns in spawning success also can vary due to coral parental condition, fecundity, pre-competency period, survivability, settlement and other biological factors. Use of contemporary patterns of hydrodynamics and spawning success would be ideal for this algorithm. Spawning success is already approximated in this algorithm by the use of the coral cover level of a reef, and future refinements could add other aspects such as the influence of recent non-lethal bleaching on larval condition. Making contemporary hydrodynamic data available will require the evolution of the current hydrodynamic model towards a version with the ability to predict hydrodynamics in the near future (at the immediate next spawning event).

Coming from an ecological model that is informed by a high-resolution biogeochemical model, the reefstate predictions used here implicitly capture several spatial patterns that influence resilience (e.g., water quality). However, it is not currently possible to map the impacts of all relevant stressors and model predictions will improve as the science evolves. For example, while our understanding of the impacts of stress upon coral fecundity is growing (Ward et al. 2000; Foster et al. 2008; Alvarez-Noreiga et al. 2016; Tan et al. 2016; Pratchett et al. 2019), further studies are needed to map this explicitly and facilitate its use directly in this algorithm. Our approach also did not take into account the negative impact of connectivity – that of facilitating the spread of CoTS. A refinement of the algorithm to consider spatial layers of CoTS densities could allow those present-day key source reefs that are also harbouring worrying CoTS densities to be prioritised for CoTS control.

Many jurisdictions do not yet have access to models of larval dispersal though the downscaling of global hydrodynamic models is making data increasingly accessible (Liggins et al. 2013; Paris et al. 2013). Moreover, many development projects fund dispersal modelling as part of their mandate. In addition to having basic data on the total amount of dispersal through a hydrodynamic next, the mixture of species arriving at locations is vitally important in order to support biodiverse recruitment. Hydrodynamic dispersal models are easily adapted to other coral species once some key larval parameters are known, and future versions of this algorithm may incorporate larval diversity into the identification of key source reefs.

The algorithm presented here is designed to target short-term tactical interventions that respond to recent disturbance events. The algorithm could also be used for identifying key source reefs to receive interventions that may minimise bleaching prior to an anticipated bleaching event. In either case, actions might include increasing surveillance and – if necessary – control of CoTS at key reefs to protect their corals, or increasing compliance efforts on these important reefs. However, because disturbances occur frequently and the recovery of reefs can be dynamic, the tactical importance of reefs to recovery is likely to change every few years. Other management tools, such as MPA zoning, operate over longer time scales and are not amenable to the rapid adjustments suggested by this algorithm.

The design of management strategies, including MPAs, that may facilitate long-term adaptation of corals will almost-certainly require design criteria that stratify across rates of warming and connectivity (Quigley et al. 2019; Walsworth et al. 2019). As a hierarchy of RBM strategies emerge, each for a different time scale and purpose (short-term recovery, long-term recovery, genetic adaptation), a corresponding research investment will be required to consider optimisation of such actions to achieve multiple objectives.

2.4.1 Groundtruthing reefstate predictions

Because of the large area of the reef, it is necessary to use modelling to quantify the change in coral cover that occurs as a result of coral bleaching. In smaller jurisdictions, such assessments can be undertaken directly in the field. At the scale of the GBR, field assessments can supplement modelling by enabling coral cover ("reef state") predictions to be groundtruthed, and the geographic coverage of such assessments can be dramatically increased through citizen science. An important development of this project is the joint creation of the Citizen science project, the "Great Reef Census" (https://greatreefcensus.org/) with Citizens of the GBR (Figure 2.4). The project commenced in July 2020 and attracted $700,000 of investment from the RRRC and Great Barrier Reef Foundation. It is using a diversity of tourism, fishing, super yacht, and industrial boats as platforms to enable citizens to perform reconnaissance to groundtruth the coral cover predicted at potential present-day key source reefs. More than 100 reefs (potential key source reefs selected by applying the algorithm described here) are being surveyed before the end of 2020 using simple approaches – at least 10 landscape reef photos with a go-pro – in order to diagnose whether the reef is in a fair state to supply coral larvae or in the early stages of recovery. Photographs are being uploaded in the field, using a system developed and donated by Dell, and then armies of citizens will help interpret the content of the pictures using a web app. Photos are also being quality controlled by experts. The key outcome of 'Census' is to update the model predictions of reef states used in the dynamic algorithm so that it becomes more accurate. When we add field reconnaissance we can provide an improved prediction of the most important source reefs for recovery that allow managers to evaluate their respective threats and needs for management.

Figure 2.4: Landing page of the Great Reef Census website.

2.4.2 Summary

The work described in this chapter has extended the concept of key source reefs, first described in Hock et al. 2017, to a dynamic measure useful for prioritisation following widespread disturbances. The products of this work with direct applications for management have included a map of predicted key source reefs in 2020 based on the predicted state of reefs today and their connectivity to reefs in early stages of recovery, as an excel file of values by GBRMPA reef ID. This has been provided to GBRMPA for use in the Resilient Reefs Dashboard and CoTS control planning.

3.0 INTEGRATING LONG-TERM KEY SOURCE REEFS, FISHING PRESSURE AND COMPLIANCE INTELLIGENCE

3.1 Introduction

The introduction of no-take zones in the Great Barrier Reef Marine Park (GBRMP) has proved an effective integrated management system in reducing negative impacts to fish stocks on the reef (Day & Dobbs, 2013; Emslie et al., 2015). However, fishing in no-take zones of the GBR by commercial and recreational vessels, hereafter referred to as poaching, continues to be a prominent issue with over 500 offences being recorded in the 2018-19 period (GBRMPA & Queensland Gov, 2019). Considerable quantities of lost and abandoned fishing lines found in no-take zones also evidence the existence of non-compliance (Williamson et al., 2014). Abandoned fishing gear such as lines and nets can directly harm coral communities through entangling, damaging and killing organisms (Jennings & Polunin, 1996). Furthermore, anchor scour can destroy benthic communities (Broad et al., 2020) and resulting damage increases the potential for coral disease (Lamb et al., 2015). These accumulated impacts inhibit the critical ecological functions of corals.

The GBRMP's sizeable area (~346,000 km^2) makes conducting surveillance logistically challenging (Bergseth et al., 2015) and without an ecological assessment of which reefs are most vulnerable, reefs that are repeatedly important for coral recovery, termed long-term key source reefs (Hock et al. 2017, 2019) are at risk of reduced biomass and physical damage. The location of long-term key source reefs is distributed unevenly across the GBR (Hock et al. 2017). Likewise, the occurrence of commercial and recreational fishing is also spatially heterogenous across the GBR with some sites being more attractive and accessible to commercial fisheries and recreational fishers.

Currently, compliance patrols are undertaken primarily by vessels, but can also be land based, charter flights or surveillance flights conducted by the Maritime Border Command (GBRMPA & Queensland Gov, 2019) and are guided by intelligence on the risk of poaching (Weekers et al., 2019, Thiault et al., 2019). By comparing reefs of similar vulnerability to fishing but varying ecological importance, it is possible to review compliance measures and decision making at the GBR scale and within each management area (Eakin & Luers, 2006). This analysis aims to investigate in the larval connectivity importance of long-term key source reefs against their risk of (1) commercial fishing, (2) recreational fishing, and (3) the combined risk of both commercial and recreational fishing. We consider the potential benefits of protecting some reefs of higher larval connectivity value and higher risk of fishing over others, and how this can aid management outcomes.

3.2 Methods

3.2.1 Key Source Reefs

The key source reefs used in this study (*n*=687) were based on a connectivity model that uses 7 years of connectivity data and 120 days of pelagic larval duration, as well as additional relevant parameters (Hock et al., 2019), hereafter referred to as long-term key source reefs.

They differ from present-day key source reefs in that they represent reefs that are more important in the long-term for larval replenishment. Each long-term key source reef was given a value of larval connectivity as a way to assess their relative importance. This is a measure that weights each reef according to the number and strength of its outgoing connections to other reefs (Opsahl et al., 2010). Long-term key source reefs with a higher value are generally better at delivering a larger number of coral larvae to a relatively higher number of surrounding reefs. Maps were created highlighting the location of these long-term key source reefs in the appendices (Fig. A1.8-A1.11)

3.2.2 Commercial fishing risk

Records of commercial reef fin fishery vessel sightings were obtained from the Joint Field Management Program Database, GBRMPA (*n*=10,900) and provided as an Excel spreadsheet. The 687 long-term key source reefs were imported as a shapefile into ArcMap 10.7.1, which was overlaid with spatial point data of each commercial vessel sighting from January 2016 – March 2020. The number of sightings per reef with a buffer of 5 nautical miles (9.26km) was calculated. The justification for using a 5 nautical mile buffer around each reef is that this is the distance a commercial dory can legally travel from its primary vessel when undertaking fishing activities, under the Queensland fisheries regulation. Each reef then had a value for commercial fishing intensity which was standardised to a scale of 0-1 by dividing every value by the maximum value.

3.2.3 Recreational fishing risk

To assess the spatial distribution of recreational fishing intensity we used a model created to predict the probability of recreational poaching incidents across Marine National Park zones of the Cairns Management Region of the GBRMP (Thiault et al., 2019). The model accounted for a range of spatial and non-spatial predictors which influence where poaching is concentrated (Weekers et al., 2019). We edited the model’s predictor variables to extend from Marine National Park zones to the entire GBRMP and it was run in R Studio. It used vessel monitoring tracking patrol data from the period June 2019 – June 2020. The predictor variables included are outlined in Table 3.1. Wind and swell were also included as weather variables as well as day and month as temporal variables.

Table 3.1: Description of variables used to predict poaching risk in Marine National park zones of the Cairns Management Region (Thiault et al. 2019) and used in the model to predict recreational fishing intensity across the Great Barrier Reef Marine Park in the current study

Name	Description
Accessibility	Distance to the closest boat ramp access
Aspect	Compass direction that a slope is facing
Coral	Number of coral-dominated cells within a 1km radius
Depth	Distance from the surface to the sea floor
Facilities	Distance to the closest pontoon or mooring
Fishing capacity	Number of registered motorised recreational boats within a 50km radius
Islands	Distance to the closest island
Reefs	Distance to the closest island
Slope	Incline of the sea floor
Boundary	Distance from the nearest boundary

This resulted in a raster layer indicating the probability of recreational fishing intensity throughout the entire GBRMP. In ArcMap 10.7.1 this layer was overlaid with the long-term key source reef shapefile and an overlay analysis was performed to obtain the maximum probability of recreational fishing occurrence per reef. Each reef then had a value for recreational fishing intensity which was standardised to a scale of 0-1 by dividing every value by the maximum value.

We also discerned whether the reef was in a protected area or a zone permitting fishing activities by using the GBRMPA zoning plan spatial layers from the open source Spatial Data and Information Service (https://gbrmpa.maps.arcgis.com/home/index.html). These classifications differed between type of fishing and are outlined in Table 3.2.

Table 3.2: Outline of which GBRMPA zones were classified as Protected areas and Fishing areas for the commercial fishing, recreational fishing and overall fishing (combined) analyses

	Protected area	**Fishing area**
Commercial fishing	Marine National Park zone, Preservation zone, Scientific Research zone, Buffer zone	General Use zone, Habitat Protection zone, Conservation Park zone
Recreational fishing	Marine National Park zone, Preservation zone, Scientific Research zone	General Use zone, Habitat Protection zone, Conservation Park zone, Buffer zone
Overall fishing (Commercial and Recreational fishing combined)	Marine National Park zone, Preservation zone	Scientific Research zone, Buffer zone, General Use zone, Habitat Protection zone, Conservation Park zone

3.2.4 Overall fishing risk

To analyse overall fishing risk across the GBRMP, the mean of the standardised commercial fishing intensity value and recreational fishing intensity value per long-term key source reef was obtained. Each reef then had a value for overall fishing intensity which was standardised to a scale of 0-1 by dividing every value by the maximum value. For the purpose of this analysis, all results were standardised under the assumption that recreational fishing and commercial fishing have the same level of impact in that they are both equally damaging to coral reefs.

3.3 Results

Each long-term key source reef was plotted to observe their spread according to their larval connectivity value and their level of fishing (Commercial: Fig 3.1, Recreational: Fig 3.3, and Overall: 3.5). After standardising both metrics (larval connectivity and fishing intensity on a scale from 0-1), the median was used (0.5) to define 4 equal quadrants. The top left quadrant shows reefs of high value and low fishing intensity, bottom left shows reefs of low value and low fishing intensity, top right shows reefs of high value and high fishing intensity, and bottom right shows reefs of low value and high fishing intensity. The reefs in the top right quadrant are classified as priority reefs due to their high ecological importance and high risk of fishing intensity, for recreational, commercial and overall fishing separately. Dotted lines were included in these graphs to demonstrate the arbitrariness of the quadrant interval values i.e. by shifting the quadrants divisions to 0.25 on both axes instead of 0.5, more priority reefs are identified and can be focused on.

Maps were created in ArcMap 10.7.1 to highlight the location of priority reefs for each type of fishing (Fig 3.2, 3.4, and 3.6). The GBRMP boundary is divided into its four management areas (from north to south): Far Northern Management Area (FNMA), Cairns Cooktown Management Area (CCMA), Townsville Whitsunday Management Area (TWMA), and Mackay Capricorn Management Area (MCMA). Maps of priority reefs were also created for each management area, and these can be found in the appendices (Fig A1.1–A1.7).

3.3.1 Commercial fishing

There were 20 reefs which were classified as commercial fishing priority reefs as visualised in the top right quadrant of Fig 3.1 and listed in Table 3.3. Two of these were in commercial fishing protected areas (Fig 3.2): 'Hardy Reef' (19-135) and 'U/N Reef' (19-250). Priority reefs are clustered around the lower TWMA and the upper MCMA.

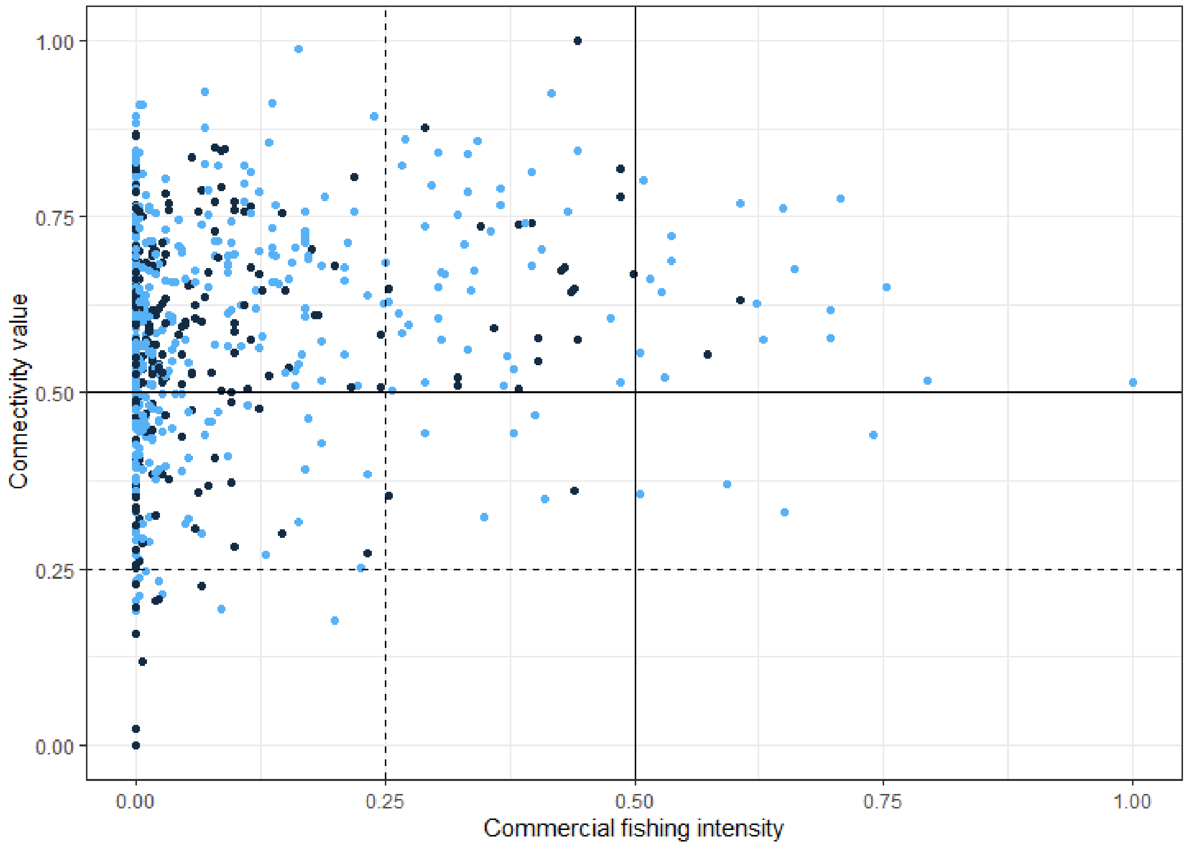


Figure 3.1: The relationship between standardised commercial fishing intensity and standardised connectivity for each Key Source Reef (n=687). Light blue dots represent a reef that has majority of its area is in a zone where commercial fishing is permitted (General Use zone, Habitat Protection zone, Conservation Park zone). Dark blue dots represent a reef where majority of its area is in a zone where commercial fishing is not permitted (Marine National Park zone, Preservation zone, Scientific Research zone, Buffer zone).

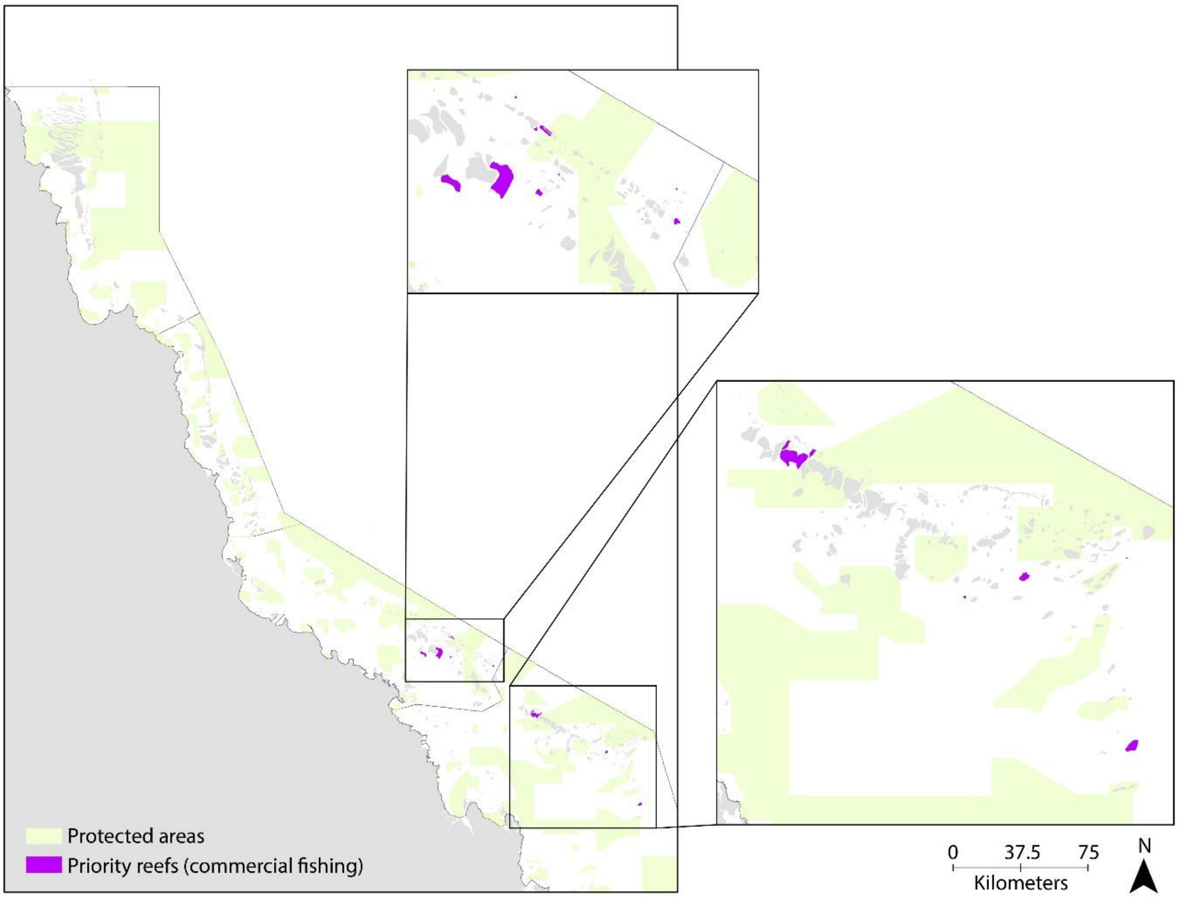


Figure 3.2: Priority reefs (*n*=20) that have high standardised commercial fishing intensity (>0.5) and a high standardised larval connectivity value (>0.5). Green areas represent zones where commercial fishing is not permitted (Marine National Park zone, Preservation zone, Scientific Research zone, Buffer zone).

Table 3.3: Priority reefs (*n*=20) that have high standardised commercial fishing intensity (>0.5) and a high standardised larval connectivity value (>0.5). Reefs marked with an asterisk are in areas protected from commercial fishing.

Reef ID	Reef Name	Management Area
19-134	'Circular Quay Reef'	Townsville Whitsunday
19-135	'Hardy Reef' *****	Townsville Whitsunday
19-223	'U/N Reef'	Townsville Whitsunday
19-225	'U/N Reef'	Townsville Whitsunday
19-230	'Blossom Bank (West)'	Townsville Whitsunday
19-241	'U/N Reef'	Townsville Whitsunday
19-244	'U/N Reef'	Townsville Whitsunday
19-246	'U/N Reef'	Townsville Whitsunday
19-250	'U/N Reef' *	Townsville Whitsunday
19-254	'U/N Reef'	Townsville Whitsunday
19-255	'U/N Reef'	Townsville Whitsunday
19-257	'U/N Reef'	Townsville Whitsunday
20-338	'U/N Reef'	Mackay Capricorn
20-366	'U/N Reef'	Mackay Capricorn
20-369a	'Cockatoo Reef (No 1)'	Mackay Capricorn
21-247	'U/N Reef'	Mackay Capricorn
21-660	'U/N Reef'	Mackay Capricorn
21-663	'U/N Reef'	Mackay Capricorn
21-667	'U/N Reef'	Mackay Capricorn
22-130	'Gater Reef'	Mackay Capricorn

3.3.2 Recreational fishing

There were 31 reefs which were classified as recreational fishing priority reefs as visualised in the top right quadrant of Fig 3.3 and listed in Table 3.4. Eleven of these were in protected areas: ‘U/N Reef’ (14-140), ‘Ribbon No 7 Reef’ (15-026), ‘Camel Head Reef’ (15-029), 'Agincourt Reefs (No 4) (15-096), 'Agincourt Reefs (No 3)’ (15-099a), 'Agincourt Reefs (No 1)’ (15-099c), ‘Norman Reef’ (16-030), ‘Saxon Reef’ (16-032), ‘Green Island Reef’ (16-049), ‘North West Reef’ (16-072) and ‘Hardy Reef (19-135) (Fig 3.3, Fig 3.4). Priority reefs were all located in the CCMA, except for ‘Hardy Reef’ in the TWMA.

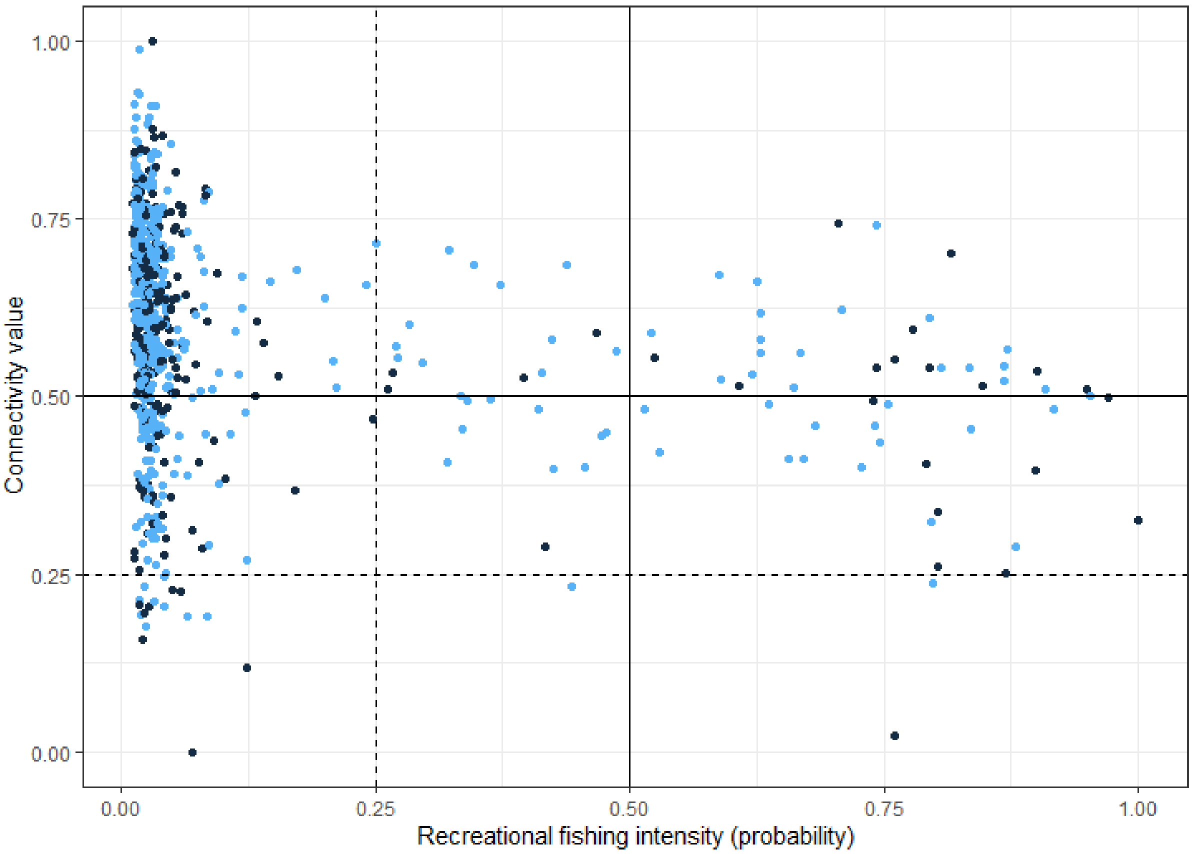


Figure 3.3: The relationship between standardised probability of recreational fishing intensity and standardised connectivity value for each Key Source Reef (*n*=687). Light blue dots represent a reef where majority of its area is in a zone where recreational fishing is permitted (General Use zone, Habitat Protection zone, Conservation Park zone, Buffer zone). Dark blue dots represent a reef where majority of its area is in a zone where recreational fishing is not permitted (Marine National Park zone, Preservation zone, Scientific Research zone).

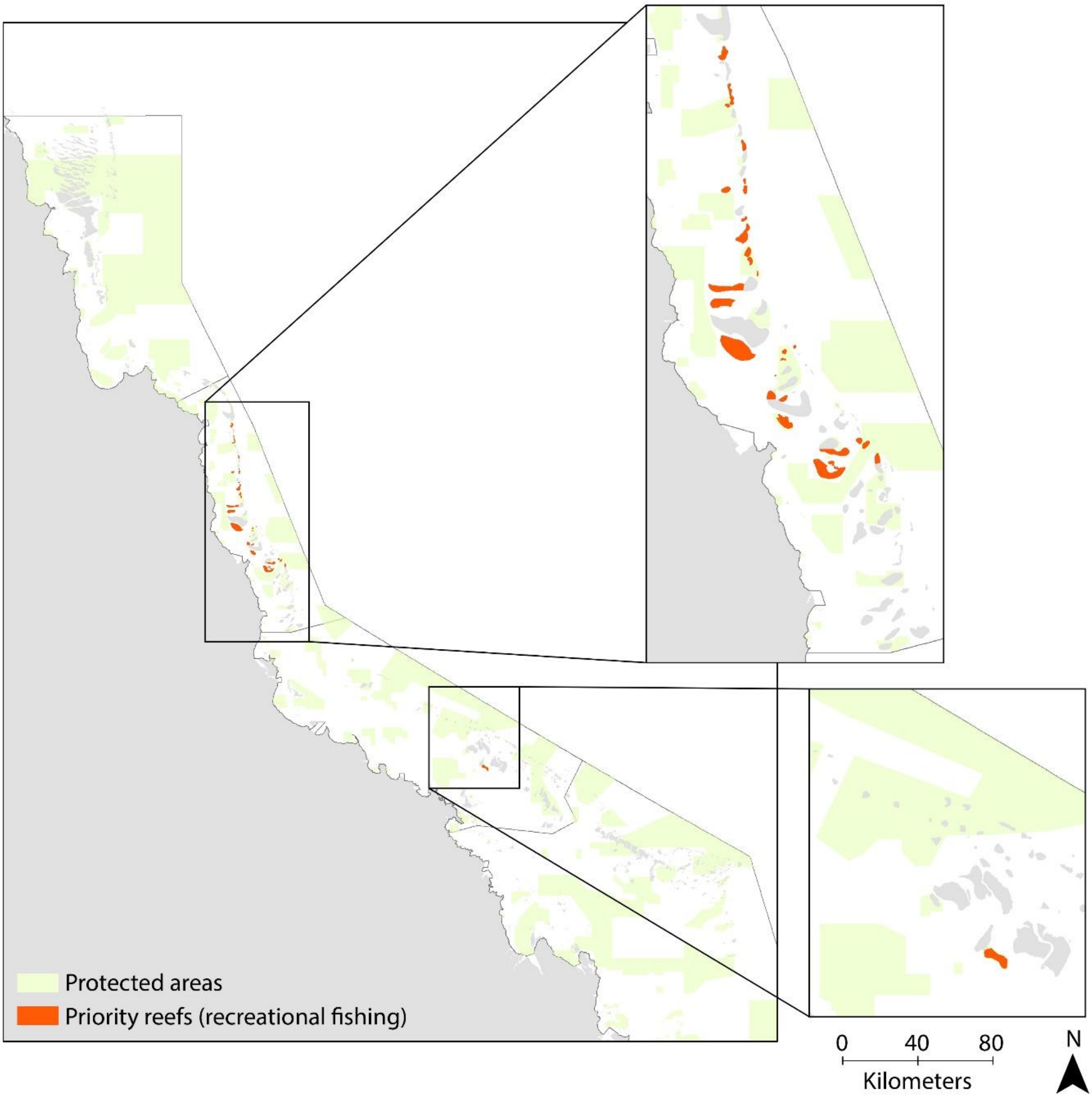


Figure 3.4: Priority reefs (*n*=31) that have high standardised probability of recreational fishing intensity (>0.5) and a high standardised larval connectivity value (>0.5). Green areas represent zones where recreational fishing is not permitted (Marine National Park zone, Preservation zone, Scientific Research zone).

Table 3.4: Priority reefs (*n*=31) that have high standardised probability of recreational fishing intensity (>0.5) and a high standardised larval connectivity value (>0.5).

Reef ID	Reef Name	Management Area
14-140	'U/N Reef' *	Cairns Cooktown
14-154	'Ribbon No 9 Reef'	Cairns Cooktown
15-026	'Ribbon No 7 Reef' *	Cairns Cooktown
15-029	'Camel Head Reef' *	Cairns Cooktown
15-046	'Ribbon No 4 Reef'	Cairns Cooktown
15-080	'Ribbon No 1 Reef'	Cairns Cooktown
15-084	'Irene Reef'	Cairns Cooktown
15-085	'Lena Reef'	Cairns Cooktown
15-090	'Andersen Reef'	Cairns Cooktown
15-092	'Rachel Carson Reef'	Cairns Cooktown
15-094	'Escape Reef'	Cairns Cooktown
15-096	'Agincourt Reefs (No 4)' *	Cairns Cooktown
15-099a	'Agincourt Reefs (No 3)' *	Cairns Cooktown
15-099c	'Agincourt Reefs (No 1)' *	Cairns Cooktown
16-020a	'Undine Reef (West)'	Cairns Cooktown
16-020b	'Undine Reef (East)'	Cairns Cooktown
16-023	'Rudder Reef'	Cairns Cooktown
16-029	'Batt Reef'	Cairns Cooktown
16-030	'Norman Reef' *	Cairns Cooktown
16-032	'Saxon Reef' *	Cairns Cooktown
16-034	'Spur Reef'	Cairns Cooktown
16-041	'Jorgensen Patch'	Cairns Cooktown
16-043a	'Oyster Reef'	Cairns Cooktown
16-044b	'Vlasoff Reef'	Cairns Cooktown
16-049	'Green Island Reef' *	Cairns Cooktown
16-070	'Pellowe Reef'	Cairns Cooktown
16-072	'North West Reef' *	Cairns Cooktown
16-073	'Elford Reef'	Cairns Cooktown
16-075	'Channel Reef'	Cairns Cooktown
17-001a	'Sudbury Reef (No 1)'	Cairns Cooktown
19-135	'Hardy Reef' *	Townsville Whitsunday

3.3.3 Overall fishing

There were 36 reefs which were classified as overall priority reefs as visualised in the top right quadrant of Fig 3.5 and listed in Table 3.5. Eleven of these were in protected areas: ‘Ribbon No 7 Reef’ (15-026), ‘Camel Head Reef’ (15-029), ‘Agincourt Reefs (No 4)’ (15-096), ‘Agincourt Reefs (No 3)’ (15-099a), ‘Agincourt Reefs (No 1)’ (15-099c), ‘Normal Reef’ (16-030), ‘Saxon Reef’ (16-032), ‘Green Island Reef’ (16-049), ‘North West Reef’ (16-072), ‘Elford Reef’ (16-073) and ‘Hardy Reef’ (19-135).

Each priority reef was also given a larval threat value which is the distance from each priority reef (represented as a dot) in Figure 3.5 to the top right corner of the top right quadrant

(Equation 1). This gives an indication of how the priority reefs rank in order of importance with each other. A smaller value indicates greater importance.

$$Larval\ threat = \sqrt{(1 - standardised\ overall\ fishing\ intensity)^2 + (1 - standardised\ larval\ connectivity)^2} \quad (1)$$

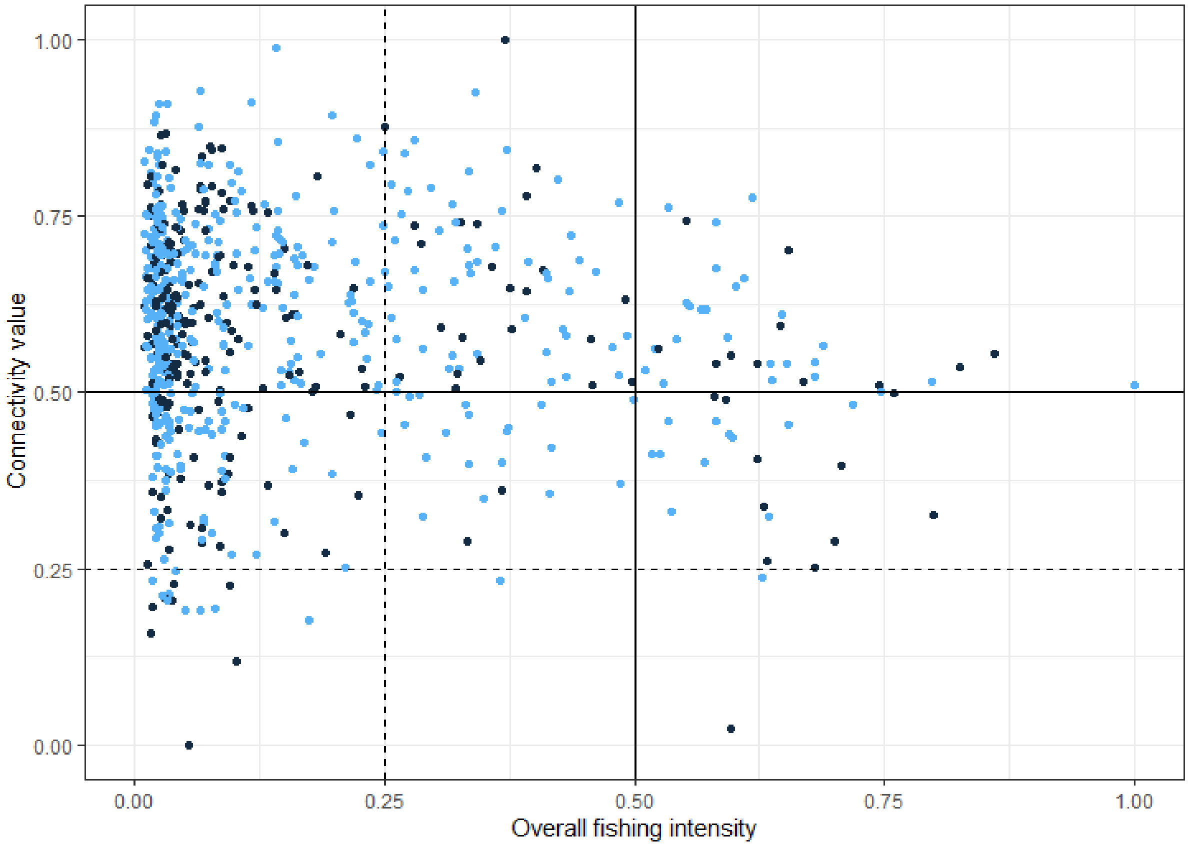


Figure 3.5: The relationship between standardised overall fishing intensity (commercial and recreational combined) and standardised connectivity value for each Key Source Reef (*n*=687). Dark blue dots represent a reef where majority of its area is in a zone where fishing is not permitted (Marine National Park zone, Preservation zone). Light blue dots represent a reef where the majority of its area is in any other zone.

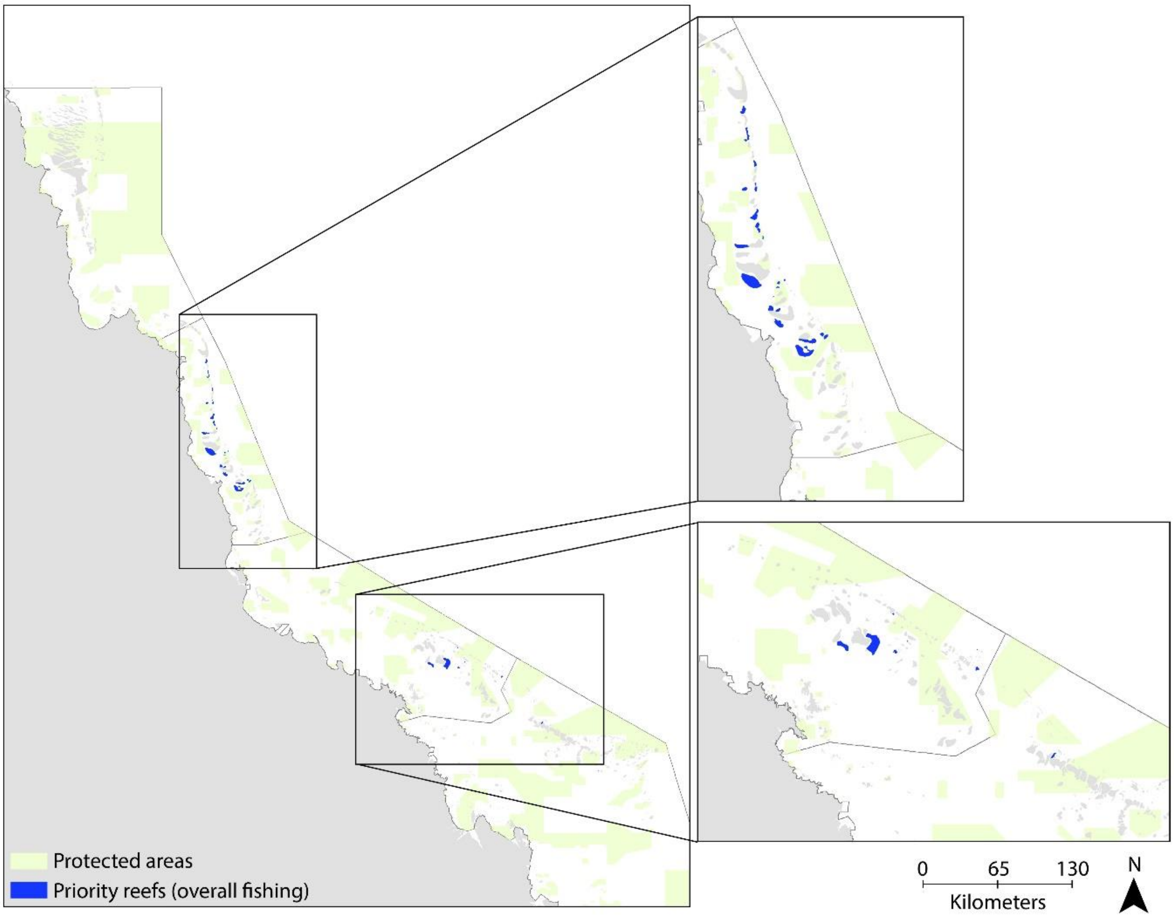


Figure 3.6: Priority reefs (*n*=36) that have high standardised overall fishing intensity (>0.5) and a high standardised larval connectivity value (>0.5). Green areas represent the main zones where fishing is not permitted (Marine National Park zone, Preservation zone).

Table 3.5: Priority reefs (*n*=36) that have high standardised overall fishing intensity (>0.5) and a high standardised larval connectivity value (>0.5).

Reef ID	Reef Name	Management Area	Larval threat
14-154	'Ribbon No 9 Reef'	Cairns Cooktown	0.822
15-026	'Ribbon No 7 Reef' *	Cairns Cooktown	0.764
15-029	'Camel Head Reef' *	Cairns Cooktown	0.718
15-046	'Ribbon No 4 Reef'	Cairns Cooktown	0.750
15-080	'Ribbon No 1 Reef'	Cairns Cooktown	0.704
15-084	'Irene Reef'	Cairns Cooktown	0.821
15-085	'Lena Reef'	Cairns Cooktown	0.743
15-092	'Rachel Carson Reef'	Cairns Cooktown	0.698
15-094	'Escape Reef'	Cairns Cooktown	0.799
15-096	'Agincourt Reefs (No 4)' *	Cairns Cooktown	0.750
15-099a	'Agincourt Reefs (No 3)' *	Cairns Cooktown	0.715
15-099c	'Agincourt Reefs (No 1)' *	Cairns Cooktown	0.663
16-020a	'Undine Reef (West)'	Cairns Cooktown	0.709
16-029	'Batt Reef'	Cairns Cooktown	0.680
16-030	'Norman Reef' *	Cairns Cooktown	0.654
16-032	'Saxon Reef' *	Cairns Cooktown	0.697
16-034	'Spur Reef'	Cairns Cooktown	0.748
16-041	'Jorgensen Patch'	Cairns Cooktown	0.742
16-043a	'Oyster Reef'	Cairns Cooktown	0.728
16-044b	'Vlasoff Reef'	Cairns Cooktown	0.724
16-049	'Green Island Reef' *	Cairns Cooktown	0.758
16-070	'Pellowe Reef'	Cairns Cooktown	0.740
16-072	'North West Reef' *	Cairns Cooktown	0.779
16-073	'Elford Reef' *	Cairns Cooktown	0.798
17-001a	'Sudbury Reef (No 1)'	Cairns Cooktown	0.608
19-134	'Circular Quay Reef'	Townsville Whitsunday	0.779
19-135	'Hardy Reef' *	Townsville Whitsunday	0.634
19-225	'U/N Reef'	Townsville Whitsunday	0.741
19-230	'Blossom Bank (West)'	Townsville Whitsunday	0.708
19-244	'U/N Reef'	Townsville Whitsunday	0.765
19-246	'U/N Reef'	Townsville Whitsunday	0.646
19-254	'U/N Reef'	Townsville Whitsunday	0.707
19-255	'U/N Reef'	Townsville Whitsunday	0.748
19-257	'U/N Reef'	Townsville Whitsunday	0.751
20-338	'U/N Reef'	Mackay Capricorn	0.701
21-667	'U/N Reef'	Mackay Capricorn	0.690

3.4 Discussion

Ensuring those undertaking fishing practices on the GBR are compliant with zoning regulations is one of the key priorities for marine park management, enabling enforcement of the legal protections granted to the GBR for the purposes of maintaining ecological integrity whilst providing for human use. This study exemplifies that the range of intensely fished reefs on the GBR vary in their ecological importance, and this should be addressed in the decision-making process for coral reef managers (Done, 1995). The ability to identify where highly-fished but reproductively-valuable reefs ('priority reefs') are in a vast area such as the GBRMP can assist with the distribution and allocation of limited resources when enforcing zoning regulations. The identification of priority reefs is a step towards implementing an optimal fisheries management strategy to best protect the reefs that are most important for coral recovery (GBRMPA & Queensland Gov, 2019).

This study highlighted that priority reefs were not evenly distributed across the GBR, but often clustered towards larger population centres. All the recreational fishing priority reefs were located throughout the Cairns Cooktown management area except for Hardy Reef in the Townsville Whitsunday management area. This is likely due to Cairns Cooktown residents having shorter travel distances to the GBR (Weekers et al., 2019). Proximity to boat ramps has been identified as a major contributing factor when identifying recreational poaching hotspots (Thiault et al., 2019) and may also explain the lack of priority reefs in the Far Northern Management Area.

The compliance-analysis developed in this study will improve in the future as more accurate field data becomes available. The commercial data may not have been completely accurate in determining which vessels were primaries or dories. It is likely that the patrol effort may have been skewed towards more populated areas such as Cairns, while also excluding the illegal flying zone around airports. Since January 1, 2019, vessel tracking has become mandatory for priority commercial fisheries in the World Heritage Area (Queensland Sustainable Fishing Strategy 2017-2027). This data could be used in future reanalyses of this study to enhance the accuracy of the commercial fishing information.

The outcomes of this research allow for resource-management with a strong ecological basis, and more targeted management strategies. The presence of large-scale extractive fishing practices within a World Heritage Area requires a delicate balance when satisfying the needs of all stakeholders. The approach developed here provides information that can inform compliance efforts in protected areas. It can also be useful when considering highly fished reefs in legal fishing zones as it informs which reefs would benefit the most from educational activities targeted towards fishers in the area. This includes campaigns educating reef users on anchoring and mooring best practice.

The approach used in this study to determine priority reefs is also a flexible one, with managers being able to choose what is considered an intensely fished reef and an ecologically important one. Our design assumed that both recreational and commercial fishing impacts were equally damaging to coral reefs, and while this is not the case in reality, there is much opportunity in future studies to tailor the values as soon as data on fishing intensity consequences becomes available. Therefore, identifying reefs that have a strong ecological importance is an important tool in facilitating a resilience-based management strategy for the GBR and can offer great insight into effective fishing compliance and education strategies within the GBRMP.

4.0 DEVELOPING THE RBM PLANNING TOOL FOR THE GBR

4.1 Introduction

From a practical perspective, implementation of resilience-based management (RBM) requires information on the baseline ecosystem condition, the locations and levels of impact from disturbances, and the impact of management interventions. For an ecosystem as large as the GBR, expert/local knowledge is insufficiently comprehensive to cover the entire ecosystem. However, modelling and remote sensing sources have now matured such that water quality simulations are accessible through the eReefs biogeochemical model, and the extent of coral bleaching and cyclone events are predictable through remote sensing. Models of larval dispersal have allowed CoTS outbreaks to be predicted and disrupted through control efforts. Ecosystem modelling (ReefMod) allows baseline coral cover to be predicted and management intervention impacts to be predicted.

A decision support tool is a software that is designed to bring together pertinent data and allow exploration, knowledge synthesis and effective resolution of a decision problem. The wide variety of decision problems within RBM include questions such as: (i) following an acute disturbance, which intervention types/portfolios and spatial scales of delivery are most effective and practical to support recovery? (ii) given a particular ecosystem goal such as maintaining a certain level of coral cover, what management strategy will allow it to be achieved? This project aimed to develop a RBM Planning Tool for the GBR that would support decision making for RBM on the Great Barrier Reef, using coral cover as a metric of ecosystem condition. The tool we created is a windows desktop software that allows managers to interact with the entirety of the reef, select scenarios of climate change (RCP2.6, 4.5, 6.0, 8.5) from a range of climate models, select key ecological criteria (e.g., whether to switch of CoTS, cyclones, bleaching), and simulate a choice of management measures. The tool brings state-of-the-art spatial information on ecosystem condition, disturbances and intervention impacts on the Great Barrier Reef and provides an interface with the flexible scope to define and address a broad range of goals for RBM.

4.2 Methods

4.2.1 User engagement in design

The scope and content of a RBM Planning Tool for the GBR was explored in consultation with the end users of the tool, reef managers themselves. Workshops were held early on to help define the scope of the RBM Planning Tool. Through these early meetings the scope was defined such that the tool would be designed to provide the ability to explore management outcomes of interventions currently being implemented by GBRMPA, the Field Management Program, or Queensland Government. These include CoTS control, anchor damage prevention, and water quality improvement. The current version of the RBM Planning tool did not incorporate interventions in development but not yet implemented, such as restoration. After building an initial version of the tool, further consultation was performed with users to identify aspects of the tool that they liked / disliked and additions that they would like to be made. The following design components of the RBM Planning Tool were identified through the consultation sessions (Table 4.1).

Table 4.1: Design components of the RBM Planning Tool identified through consultation sessions with the Great Barrier Reef Marine Park Authority and Field Management Program.

Design feature	Implementation
Inclusion of a management zone effect.	a) Select which management zones to apply the effect b) Amount of improvement in units of additional percent coral cover per year – e.g., 2% pa c) Allocate that improvement to species as either evenly split among species (default) or specify the proportion of the zoning benefit per species (e.g., 0.1, 0.3, 0.6, 0,0,0).
Anchor damage	Two layers that can be incorporated as modifiable inputs: i) the number of commercial vessel sightings per reef ii) probability of risk of recreational fishing Both layers are reef specific attributes. The user should be able to select to use either or both types of fishing. User to adjust the threshold level of each fishing metric that switches anchor damage on. So at one extreme just about any fishing could be used to elicit anchor damage but much more conservative scenarios are possible. Allow anchor damage to be turned off/on as a function of management zone. So for example, fished areas (blue zones) could have anchoring switched on. Ideally enable functionality such that we first set the 'likely fishing intensity' and then switch it off in particular management zones (mostly pink and green).
Add a viewer for the key source reefs	This is just a visualisation and would be independent of any model run – they are the specified long-term key source reefs overall (circa 600). Ideally, when viewing the reef states using the time slider you could add an option that highlights which reefs are long-term key source reefs (maybe a white border). Unlike the reef recovery algorithm which changes the key sources dynamically according to the states of reefs, the fundamental list of the 'top 600' doesn't change at all.
Optimisation – that is, allowing the user to set objectives and the software to identify solutions	Examples of optimisation tasks include: i) Find management options that deliver an average coral cover (for region of interest) by given time horizon, likely using a running mean of say 11 years for average coral cover. ii) Allow user to specify region of interest, the target reef state (which is probably best defined using the reef state categories E, VG, Good etc.) and allocate the max number of times each intervention type can be

	used (where the maximum is all reefs in the GBR). In principle, someone could select a single reef of interest but the software might have to look into a wider range of actions to include neighbouring reefs in order to secure larval supply.
Visualisation of results	An option to specify the numbers and percentages of reefs that have switched between state categories between the start and end of the simulation.
Export of results	Allow export of all output full model runs, and settings, as a .csv file. Allow export of the graphs from within the interface as a .csv file.
Ability for the user to update the spatial data layers	Ability for the user to update the cyclone and DHW layers by importing a csv file of key value per reef per year, in order to keep the projections "current".

A final design point was that the RBM planning tool must be able to operate on a desktop computer and produce results in a matter of seconds. However, ecosystem modelling typically requires a high-spec desktop computer or computing cluster and tens of minutes to days to produce a result. To ensure rapid processing whilst maintaining most of the power of an ecosystem model, the RBM planning tool was built around a table that contained the results of millions of ecosystem model simulations performed during the RBM planning tool's development. This allowed the RBM planning tool to operate by the rapid approach of interpolating the results of the ecosystem simulations as opposed to running these simulations from scratch.

4.2.2 Data sources

Water quality layers were obtained from the eReefs biogeochemical model. The layers included present day ("baseline") water quality and three layers corresponding to progressive improvements on baseline water quality, which were (i) Best Practice Land Management, (ii) meeting the water quality targets of the Reef 2050 Water Quality Improvement Plan, and (iii) implementing "Innovative management", an aspiration plan to achieve ambitious water quality improvements through implementing technologically-advanced land management approaches. Water quality layers were then transformed to ecological effects of water quality using relationships between suspended sediments and coral early life history parameters (Bozec et al. 2020). If water quality deteriorates or improves in the future, this will be reflected in contemporary biogeochemical predictions of baseline water quality of eReefs, and therefore in the spatial layers the RBM Planning Tool (after applying an update). Scenarios of future long-term declines in water quality on the Great Barrier Reef are currently beyond the scope of the RBM Planning tool. Details of additional spatial layers used in the RBM Planning Tool are presented in Table 4.2. As new disturbances such as cyclones, bleaching events, and runoff events occur, the spatial layers of starting coral cover, CoTS densities and rubble will require updating, which will be facilitated through dedicated upload functions in the tool interface.

Table 4.2: Spatial layers and their corresponding sources used in the RBM tool.

Spatial layer	Source	Reference
Larval connectivity between reefs	Hydrodynamic models of current flow throughout the Great Barrier Reef for multiple spawning seasons	Hock et al. (2017)
Timeseries of Cyclone disturbance	Synthetic cyclone tracks for the 20th century, used under the assumption that cyclone frequency and intensity will not change over the 21st century compared to 20th century guidelines	Wolff et al. (2016)
Future predictions of sea-surface temperatures,	CMIP5 initiative of the World Climate Research Program. Obtained for: - RCPs: 2.6, 4.5, 6.0, 8.5 - AOGCMs: HadGEM2-ES GFDL-ESM2M CCSM4 CESM1-CAM5 MIROC5 GISS-E2-R Rates of coral mortality due to bleaching were determined from temperature-mortality relationships established by Hughes et al. (2018).	
Baseline coral cover and baseline crown-of-thorns densities	Obtained from simulations of Reefmod-GBR (described below) for the 2008-2018 period, which were initialised using surveys of coral cover and CoTS densities conducted by AIMS and the Field Management Program (GBRMPA / QPWS).	Bozec et al. (2020)
Baseline water quality and water quality under three progressively-improving catchment management scenarios	Obtained from simulations of the eReefs biogeochemical and hydrodynamic model of the Great Barrier Reef.	Baird et al. (2020)

4.2.3 Ecosystem modelling

ReefMod-GBR is a coral reef ecosystem model that uses an individual-based modelling approach that has been parameterised for the Great Barrier Reef. A patch of reef 20 × 20 metres in size is represented as a grid, with each grid cell containing colonies of six coral types (Branching *Acropora*, Tabular *Acropora*, Corymbose *Acropora*, *Pocilloporids*, small massives and large massives) and two algal types. The size and identity of each individual colony of each coral type is tracked through time. The size structure and density of coral and algae colonies are initialised according to coral cover surveys from the Great Barrier Reef performed under the Australian Institute of Marine Science Long Term Monitoring Program. Coral and algae colonies are updated at 6 month intervals to account for growth, partial mortality, and reproduction, the rates of which are parameterised from experimentally measured values.

To construct the lookup tables described in the next section, simulations of ReefMod-GBR were performed across a range of starting values for each input variable (a total of 2,592,000 simulations):

Table 4.3: Input simulation values for Reefmod-GBR simulations that were used to build the lookup table.

Variable name	Variable units	Used Values
Starting coral cover (target species)	Percent of benthic area	0.1%, 2%, 6%, 10%, 18%
Starting coral cover (non-target species)	Percent of benthic area	5%, 10%, 20%, 35%, 50%
Lobophora algal cover	Percent of unoccupied substrate	0.01, 0.25, 0.65
SSC	mg/L	0.1, 0.5, 1, 10, 100
CoTS density	Density per reef grid ($400m^2$)	0, 0.12, 0.25, 1.08
Coral larvae	Larval output per reef grid	0, 10^5, 10^6, 10^7, 10^8, 10^9
CoTS larvae	Larval output per reef grid	0, 10^5, 10^7, 10^9
Rubble cover	Percent of benthic area	0, 20%, 60%
Parrotfish herbivory	Grazing efficiency	15%, 100%
Anchor damage	Anchor strikes	0, 50

For each individual Reefmod run, the change in each output variable (Table 4.5) was averaged over the first three years of the simulation to obtain the final output values for the RBM tool lookup tables.

4.2.4 RBM planning tool computational design

The RBM planning tool was designed as a lookup-table approach to ecosystem modelling, with changes to coral cover, CoTS densities, larval export (of coral and CoTS), rubble and algae recalculated every year, over a period determined by the user (from 2020 up to 2099). The RBM planning tool operates by:

1. Disturbance effects (bleaching, cyclones) are applied to initial coral covers, algae cover and rubble cover by applying the disturbance-mortality relationships from ReefMod. This step does not require a lookup table nor require input covers to be discretised and provides coral, algae and rubble covers post-disturbance that are fed into the next step.

2. For calculating change in coral covers in the year post-disturbance, there are lookup tables (one for each of the 6 coral species) that each take the following inputs. Each lookup table has specific coral cover input/output for one of the 6 species, and then a second coral cover level for all 5 other species combined. The entire table is interpolated over such that it can accept any input values within the maximum and

minimum values of each input variable, and output a corresponding value on a continuous scale for each of the output variables.

Table 4.4: Inputs (per lookup table, where one lookup table has been created for each of six species of coral (individually referred to as the "Target Species").

Coral larval input
Coral larval input
Crown of Thorns larval input
Starting coral cover of the target coral species
Starting coral cover (summed over the other five coral species)
Starting Rubble level
Suspended sediment concentration
Lobophora cover
Crown of Thorns starting density
Crown of Thorns control
Herbivory level
Anchor damage level

Table 4.5: Outputs (of each lookup table)

Crown of Thorns density
Crown of Thorns larvae output
Lobophora cover
Rubble level
Coral cover of the target coral species
Coral larval production

4.2.5 Software architecture

The RBM planning tool was coded in C++. The software package was wrapped by a graphical user interface that allows the user to specify the intervention types, timing, locations, and future threats, and initialise the simulation. The RBM planning tool then looks up initial (2020) starting conditions (e.g. coral cover, CoTS) from spatial layers, and feeds these as input values into the lookup table to obtain an annual update to coral cover, larval output etc. Disturbances (Cyclones, bleaching) and some interventions (CoTS starfish control) are then applied to the updated values to achieve final updated values that are fed into the next lookup table step. This process is repeated for every year in the selected time window. Spatial layers of starting conditions, projected disturbances, connectivity, and all other data required, including the lookup tables themselves, are held as tables within the software package. Results can be displayed in the GUI in a number of formats, including as trajectories over time for any output variable, or spatially (via an embedded mapping application) as maps of reef state over time.

The RBM planning tool was designed as a standalone package for use on any Windows 10 PC. The package is able to be distributed on demand to selected users through a Google drive link (~110 Mb download size) and is run simply by opening the executable file, with no additional installation needed.

4.3 Results

4.3.1 Overview of the RBM planning tool

The RBM planning tool is designed with two planning objectives in mind. The first is to predict feasible trajectories of reefs under different stressors and management. The second is to quantify management benefit of an intervention against a counterfactual scenario (in which the intervention is not run. It is important to emphasise that under both aims, we are not concerned about predicting the correct coral cover in future (which is impossible) but rather the improvement that management can make across feasible trajectories of disturbance and recovery.

The aim of this section is to provide a broad overview of the functionality of the tool. From the open screen (Figure 4.1), the set of reefs at which the user desires to run the simulation can be selected (Point 1, Figure 4.1). Standard reef sets are provided (e.g. all GBR reefs, reefs in each sector of the GBR) however the user can also create a set of reefs by selecting in a checkbox list (Figure 4.2) or uploading a reef list as an xml file. The time period of the simulation can be set as any years from 2020 to 2100 (Point 2, Figure 4.1), and the number of replicate simulations can be selected at this box. The ability to perform replicate simulations allows different time series of some variables to be utilised at each replicate (cyclones, water quality and connectivity) as these variables are extrapolated into the future by repeating a sequence of observed (water quality and connectivity) or synthetic (cyclones) events from the past. The simulation outputs are then averaged over replicates to obtain one final trajectory.

The representative concentration pathway (RCP) and Atmosphere-Ocean General Circulation Model (AOGCM) used to generate the future sea-surface temperatures are definable by the user (Point 3, Figure 4.1). The choice of RCP enables exploration of the difference between meeting the emissions reductions of the Paris goals (i.e. RCP 2.6) versus moderately, substantially, or severely underperforming against the Paris goals (RCP 4.5, 6.0 and 8.5, respectively). Choice of AOGCM is important if the user intends to make a serious exploration of climate futures, as AOGCMs have represent different levels of climate sensitivity to greenhouse gas emissions, and thus vary in their degree of pessimism for future SSTs on the GBR. Our recommendation is to choose at least one AOGCM from each of the following levels (pessimistic: HadGEM2-ES and CCSM4; optimistic: GFDL-ESM2M and GISS-E2-R; in-between: CESM1-CAM5 and MIROC5), run simulations with the same settings under the ensemble of chosen AOGCMs, and examine the mean of the simulations over all AOGCMs within the one RCP, with the spread of simulations also providing information on what the expected the best and worst case might be. The “best practice” approach is to perform the above with all six AOGCMs.

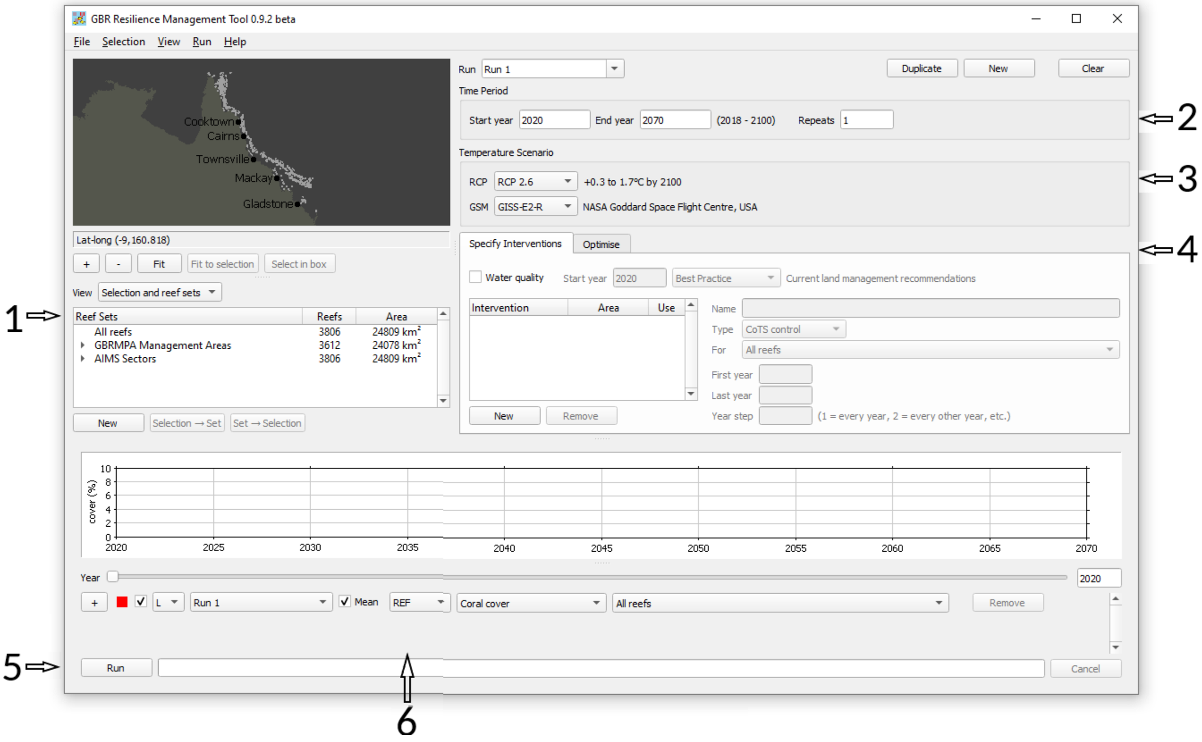


Figure 4.1: GBR Resilience Management Tool main window. Numbers refer to program functions allowing the: (1) selection of subset of the GBR to run simulation at; (2) choice of start year and end year of simulation and number of repetitions of simulation; (3) choice of emissions scenario (RCP) and climate model; (4) selection of management intervention(s) to apply, the set of reefs to apply at and the years to apply over; (5) simulation to be initiated with selected configuration of options; (6) exploration of output trajectories (reference, intervention, and their difference) of a range of output variables.

Management interventions including the prevention of anchoring damage, the choice to protect functionally important herbivorous fish, and the improvement of water quality, can be specified by the user (Point 4, Figure 4.1). Additional run setting choices made available for diagnostic purposes (e.g. for isolating the relative impact of different drivers on simulation outcomes) can be specified in the options menu (Figure 4.3). Some key options here include the choice to turn off cyclone damage or bleaching damage. These (particularly cyclone damage) are important from the user's point of view if the RBM planning tool is being used to explore the benefit of making interventions to the reef. Running of simulations with cyclones and without cyclones could be important for interpreting the intervention benefit, as it's possible that cyclone damage can obscure the signal of interventions even if present.

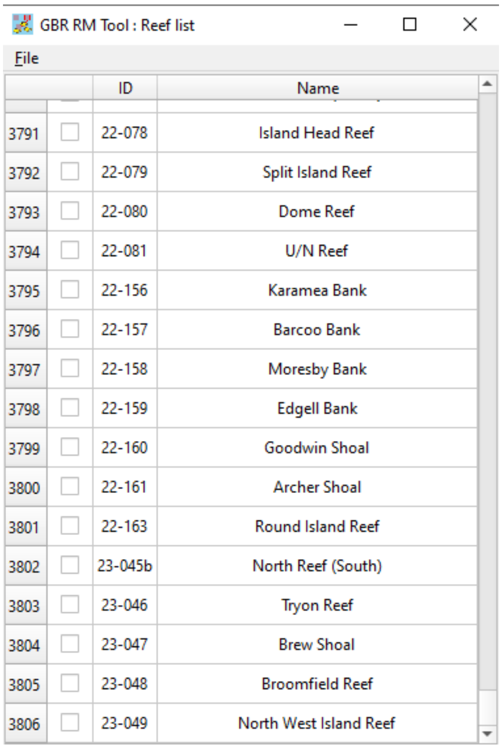


Figure 4.2: Reef list window enabling the user to define their own set of reefs to run a simulation at.

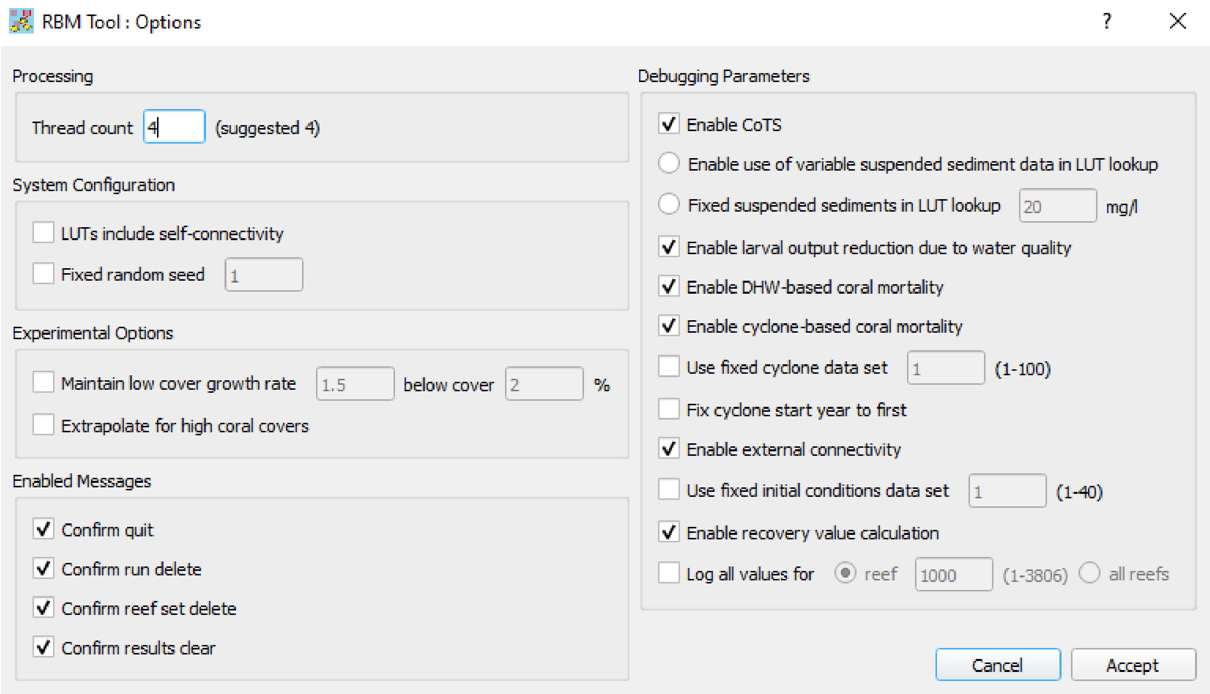


Figure 4.3: Diagnostic options for RBM planning tool simulations.

When the reef selection, time period, temperature scenario, interventions and diagnostic options are completely specified, the simulation is then performed by hitting the run button (Point 5, Figure 4.1). Total simulation time is typically <10 seconds though this will depend on the time period and number of repeats selected. The results can then be viewed as trajectories of any available output value, such as coral cover, using the trajectory pane (Point 6, Figure

4.1). An alternate view is the reef health class view, which shows the reef health class for each reef in the map pane using a colour coded display (Figure 4.4). Reef health is represented as five classes of total coral cover; the software allows the user to define these classes but the default classes are ≥ 30% coral cover, ≥ 20% to 30%, ≥ 15% to 20%, ≥ 10% to 15%, and < 10%. The user can display a map of reef health at any year of the trajectory by using the slider below the trajectory pane.

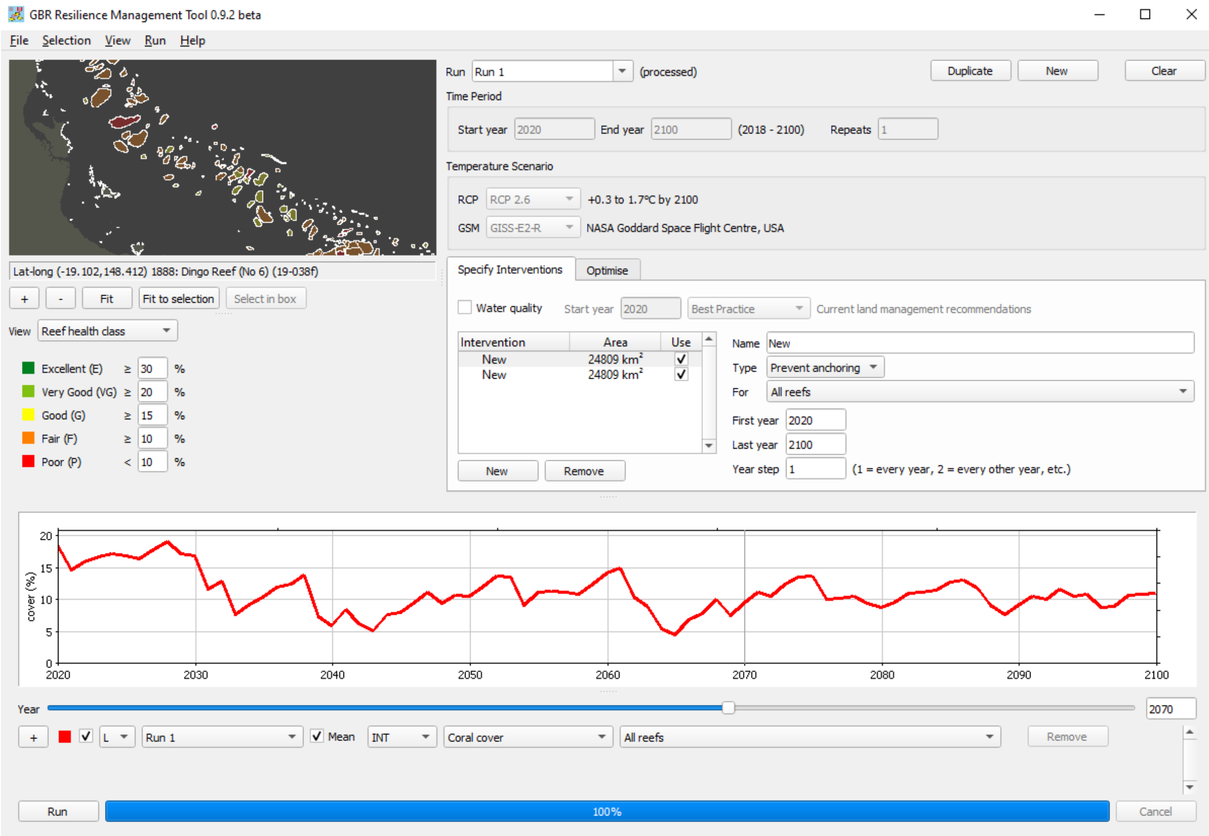


Figure 4.4: Reef health class view.

A third method of viewing reef cover is reef recovery value (Figure 4.5). A separate component of the NESP TWQ Hub Project 4.5 developed the concept of reef recovery value as a means to identify specific reefs with high value to support GBR resilience, based on connectivity and GBR reef state. Reef recovery value is the value of a reef given its capacity to supply larvae, the degree of connectivity it has to other reefs, and the neediness of the connected reefs for larvae to support recruitment (see section 2.2.1). In other words, reefs with high recovery value are those that supply the most larvae to the reefs that are the least able to self-recruit due to low coral cover. In the RBM Planning Tool, reef recovery value is displayed in the map pane. The user can toggle between the different views – selection and reef sets, reef health class or reef recovery value – by using the drop down menu below the map pane.

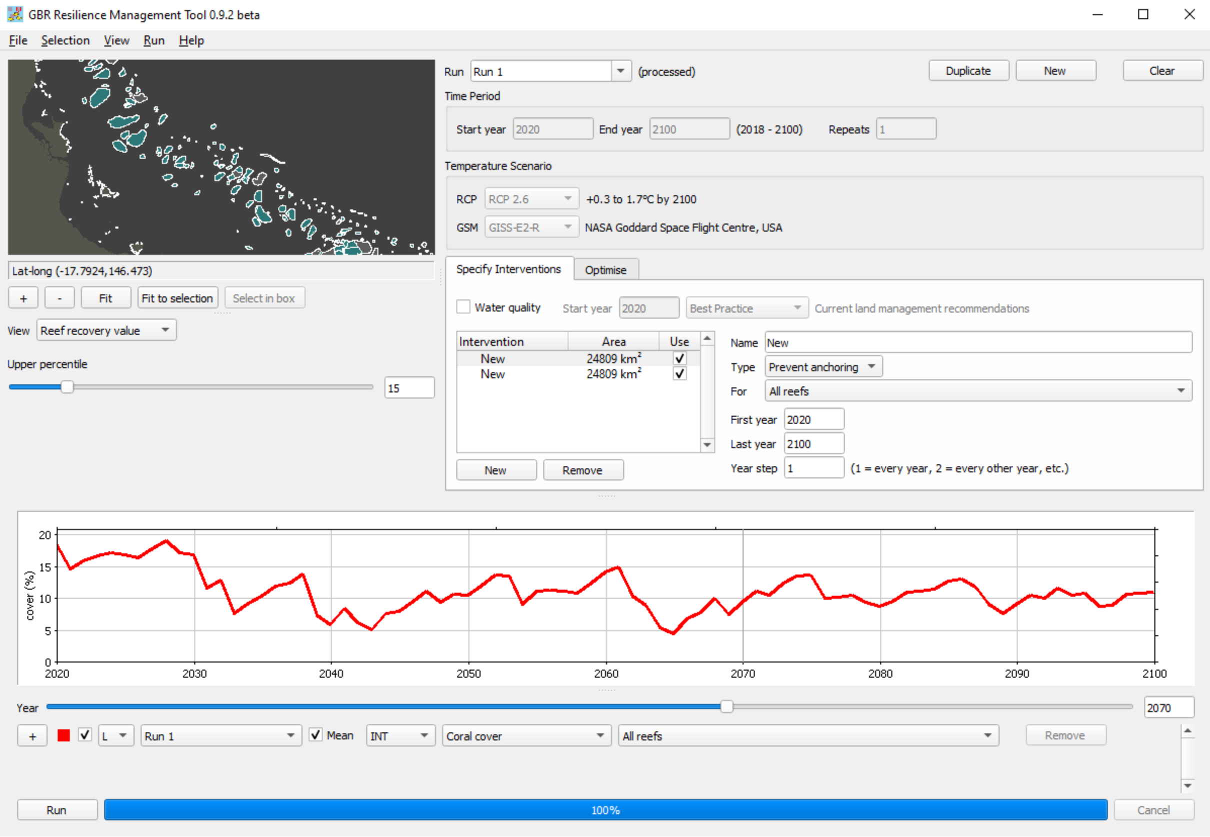


Figure 4.5: Reef recovery value view.

4.3.2 Visualising outputs

In this section, examples of some simulation runs will be presented. One basic way to use the tool is for the prediction of a trajectory for the entire GBR, with no specialised management in any localised area. Figure 4.6 depicts a simulation over 2020-2100 where water quality has not been improved but CoTS control continues, and assuming Paris targets are met and that climate sensitivity is low (the AOGCM used was GISS-E2-R). The coral cover trajectory for the whole reef shows a moderate decrease in coral cover from present day levels by the early 2030s, but then maintenance of coral cover at a mean of around 10% for the remainder of the century (Figure 4.6 a). The reef health pane can be used to explore values of reef health at selected timepoints in the future, depicted here for a window of the reef centred near Cairns (Figure 4.6 b).

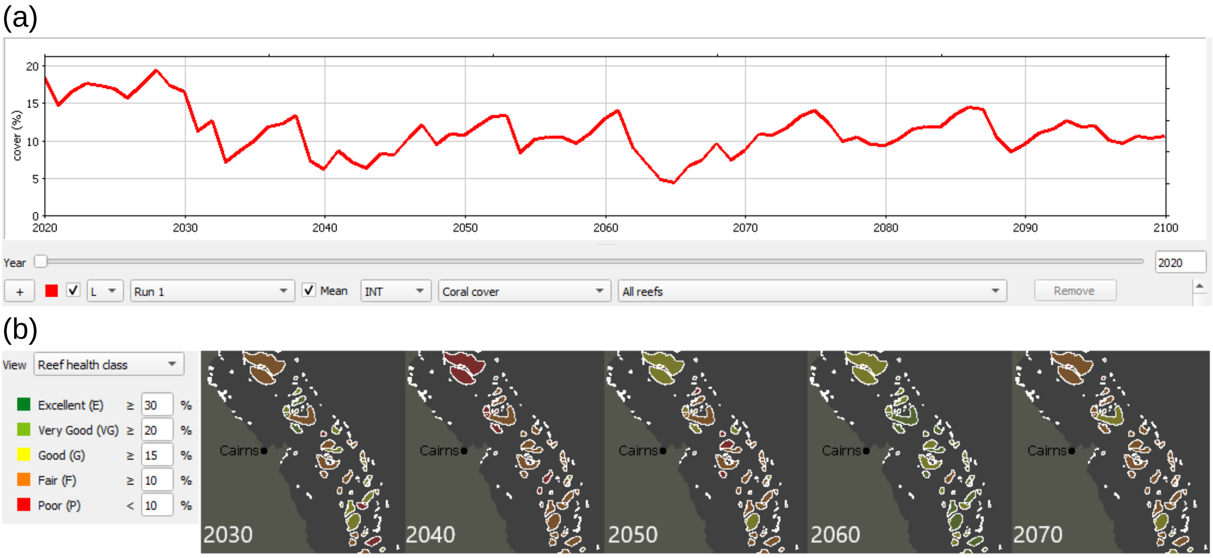


Figure 4.6: Simulation under RCP 2.6 (GISS-E2-R climate model) with CoTS control implemented. (a) Results are the average trajectory of coral cover over 3806 reefs on the GBR. (b) Maps of reef health class near the Cairns region, at decadal timepoints. These are presented here as a montage, as the GUI presents one map at a time.

A second method of using the tool is to run simulations only for reefs in a subsection of the entire GBR. This might be useful when an intervention is intended to be localised to one area, such as no anchoring areas for anchor damage protection, and the resulting effect of that intervention to the immediate area is of the most interest. In the next example, anchor damage prevention was simulated at fringing reefs around Hook Island and Hayman Island in the Whitsundays area (Figure 4.7a), using a simulation that included only those reefs. In one run of the RBM planning tool with anchor damage prevention chosen, the counterfactual scenario (i.e. anchoring allowed) (Figure 4.7b) and the intervention scenario (anchoring prohibited) (Figure 4.7c) are both run automatically. The trajectories view also allows the management benefit (the difference in coral cover, or any other available variable of interest, between the management and intervention scenarios) to be plotted (4.7d).

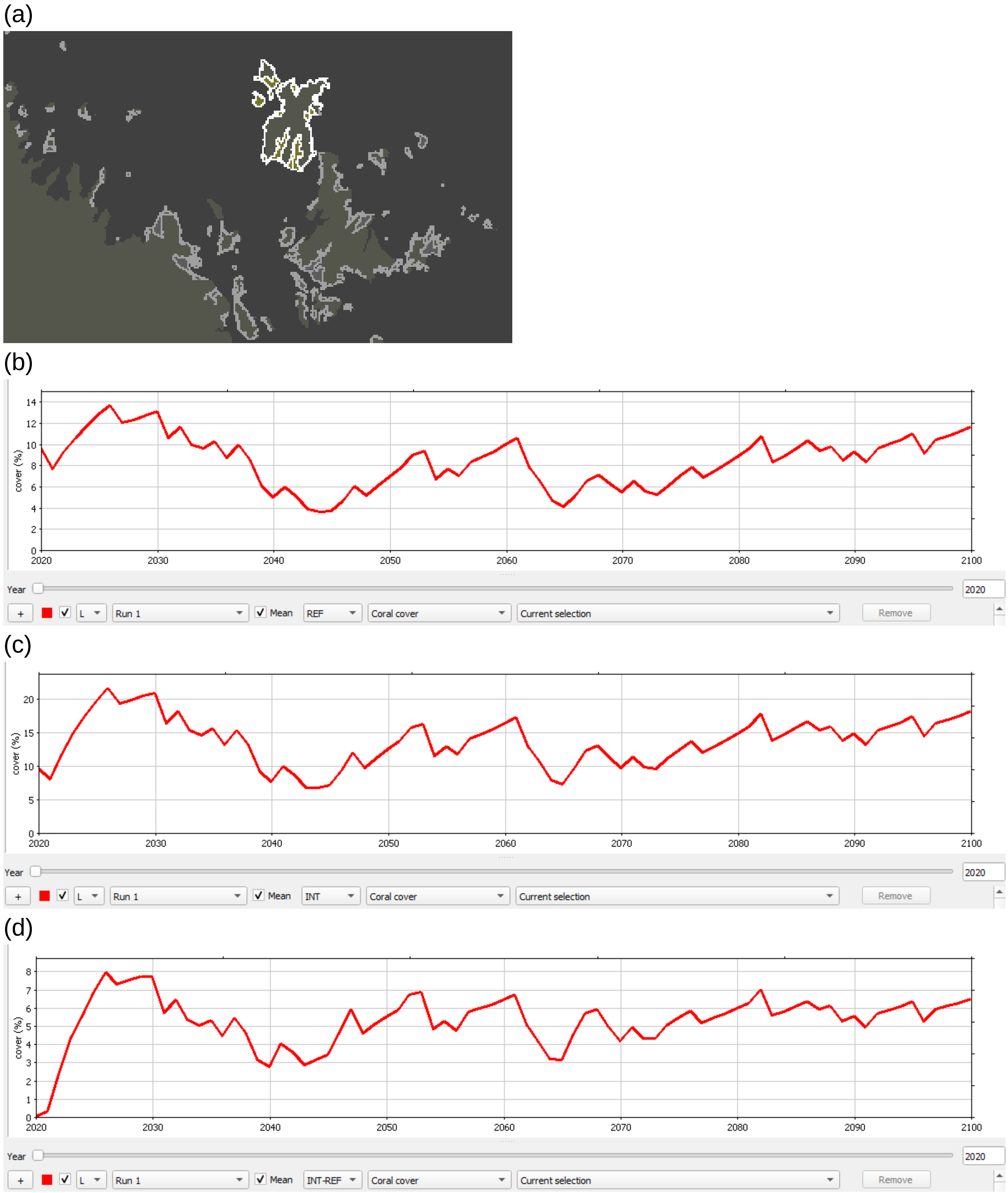
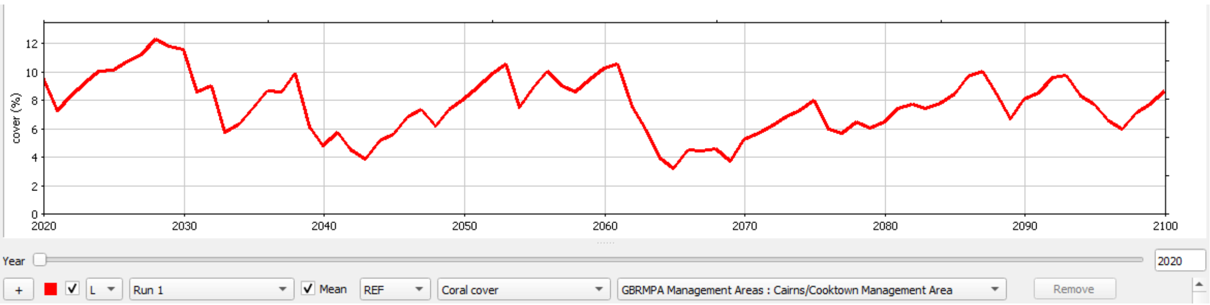


Figure 4.7: The impact of protection from anchoring was explored at a locality of the Great Barrier Reef that is vulnerable to anchoring impacts due to its role in as a popular tourist hotspot (a) Reef set used in simulation: the fringing reefs of Hayman Island and Hook Island in the Whitsundays region (outlined in white). (b) Coral cover trajectory when anchoring is allowed. (c) Coral cover trajectory when anchoring is prohibited. (d) Management benefit: the difference in coral cover between simulations with and without anchoring protection. All simulations used RCP 2.6 (GISS-E2-R climate model) without implementation of CoTS control.

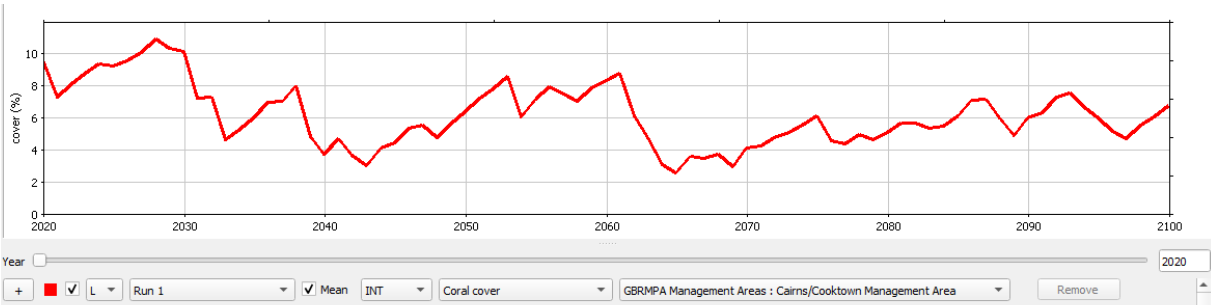
A third method of using the RBM planning tool is to run a simulation over a large set of reefs with an intervention specified at a subset of the larger set. This approach would apply if users were interested in how much the trajectory of coral cover over an entire region is affected by changes in coral cover at a smaller subset of reefs. In the following example, we simulated the impact of increased exploitation of herbivores at reefs close to Cairns, a feasible scenario that could occur if recreation fishing pressure increased due to population growth, boat ownership growth, or increased popularity of some types of fishing. All reefs within the Cairns-Cooktown management region were selected for a simulation in the decision software, but the herbivore exploitation option was enabled for only a select group of reefs near Cairns (Figure 4.8a). Herbivore exploitation at these reefs had a moderate effect (~2% loss) on total coral cover in the Cairns-Cooktown management area (Figure 4.8b [no exploitation allowed], Figure 4.8c [exploitation allowed near Cairns]). In contrast, the subset of reefs at which exploitation occurred saw a far higher drop in coral cover in relative terms (Figure 4.8d [no exploitation allowed], Figure 4.8e [exploitation allowed near Cairns]).

(a)

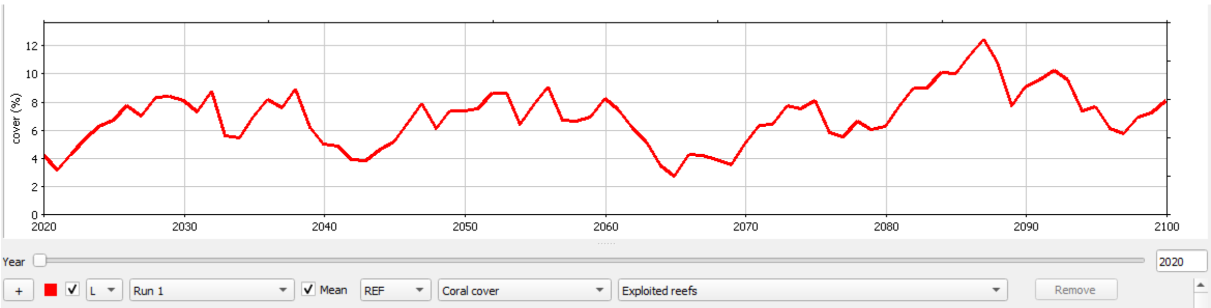
(b)



(c)



(d)



(e)

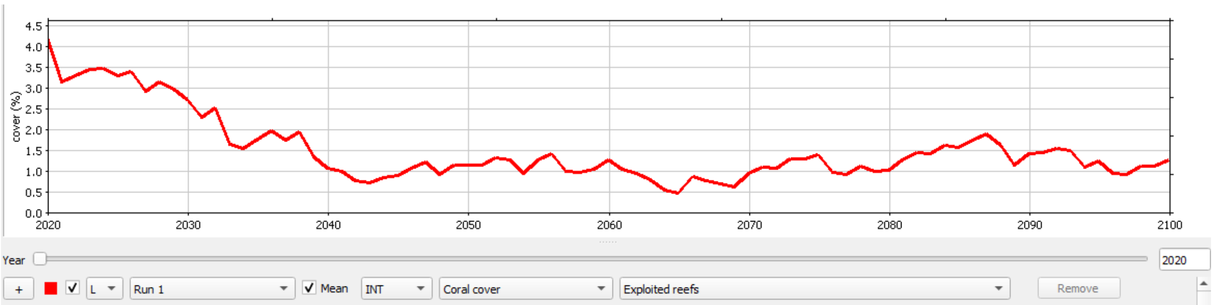


Figure 4.8: Simulation of fishing pressure on herbivorous fish that could feasibly occur due to increased recreational fishing pressure following population growth in a coastal urban area. (a) All reefs in the Cairns-Cooktown management area were simulated (red outlines); reefs that were easily accessible from the major urban area of Cairns were designed as a subset to experience increased fishing pressure (white outlines). (b) Coral cover trajectory for the entire Cairns-Cooktown region in the absence of increased fishing pressure. (c) Coral cover trajectory for the entire Cairns-Cooktown region when fishing has increased at the reefs closest to Cairns. (d) Coral cover trajectory at Cairns-adjacent reefs (white outlines in (a)), in the absence of increased fishing pressure. (e) Coral cover trajectory at Cairns-adjacent reefs when fishing pressure has increased. All simulations used RCP 2.6 (GISS-E2-R climate model) without implementation of CoTS control and anchor damage protection.

This approach – simulating a large region but with interventions at a smaller number of reefs – would also be of interest where the impact of an action within a localised area is expected to also affect surrounding reefs through impacts on larval supply. In the following example, we illustrate the application of CoTS control in the Swains region to CoTS levels in an adjacent section of the reef.

4.3.3 ReefMod-GBR simulations

Results from ReefMod-GBR simulations of management interventions on the GBR can give a sense of the level of management benefits that the RBM Planning tool is expected to produce. A comprehensive set of ReefMod-GBR simulations were performed under future climate change trajectories in a report prepared for the Office of the Great Barrier Reef (Mason et al. 2020). Figure 4.9 displays the results of water quality simulations for the next three decades for the most improved water quality scenario, "Innovative management", averaged over the six AOGCM models used in the RBM tool assuming that the Paris Climate targets are met (i.e., RCP 2.6). The results reveal widespread but mild improvements to coral cover, which diminishes through time likely as a result of increased warming.

In the OGBR research, anchor damage was also simulated, though for a smaller case study involving several reefs in the Keppel Bay area. Under RCP 2.6, when results were averaged across all AOGCMs, benefits of additional coral cover of up to 4% were detected up to 2030, with benefits diminishing after that time (Figure 4.10). CoTS control was also simulated, with very high benefits observed under some climate models up to 2030 (median values of up to ~25% additional cover) (Figure 4.11).

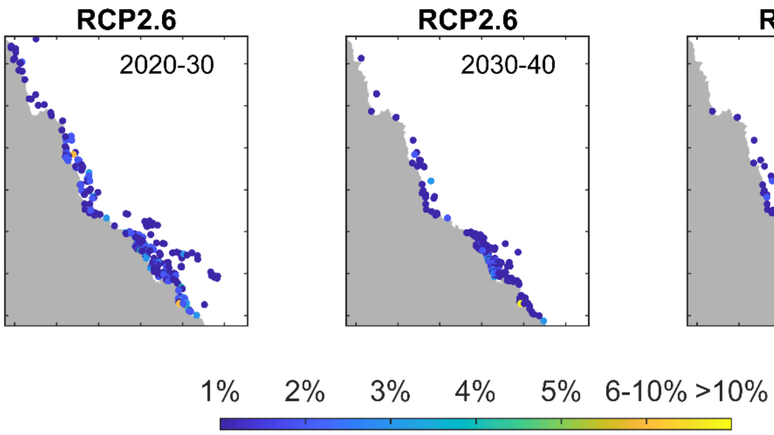


Figure 4.9: Map of mean management benefits of the Innovative management water quality scenario (determined for each year at each reef, and then averaged at each reef over all climate models and years within one decade). Benefits <1% were not mapped.

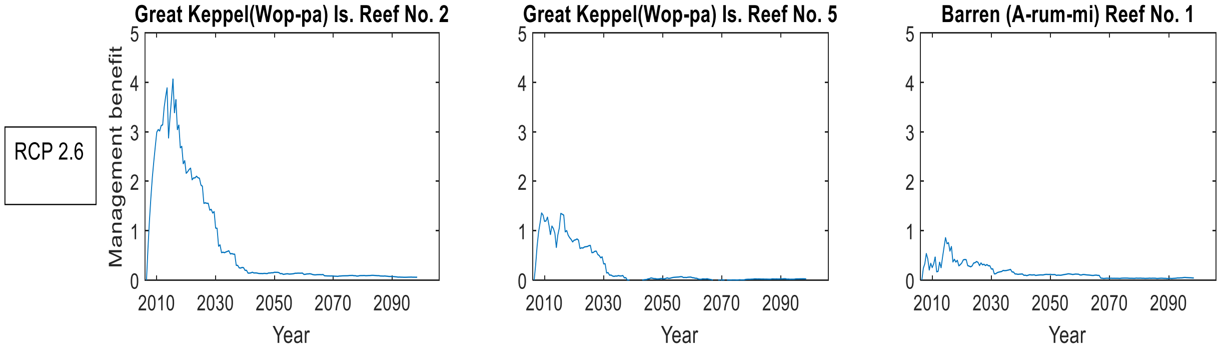


Figure 4.10: Trajectories of management benefit per year (managed scenario coral cover minus counterfactual) at three reefs under anchor vs no-anchor damage, averaged over 6 climate models and 10 replicate simulations.

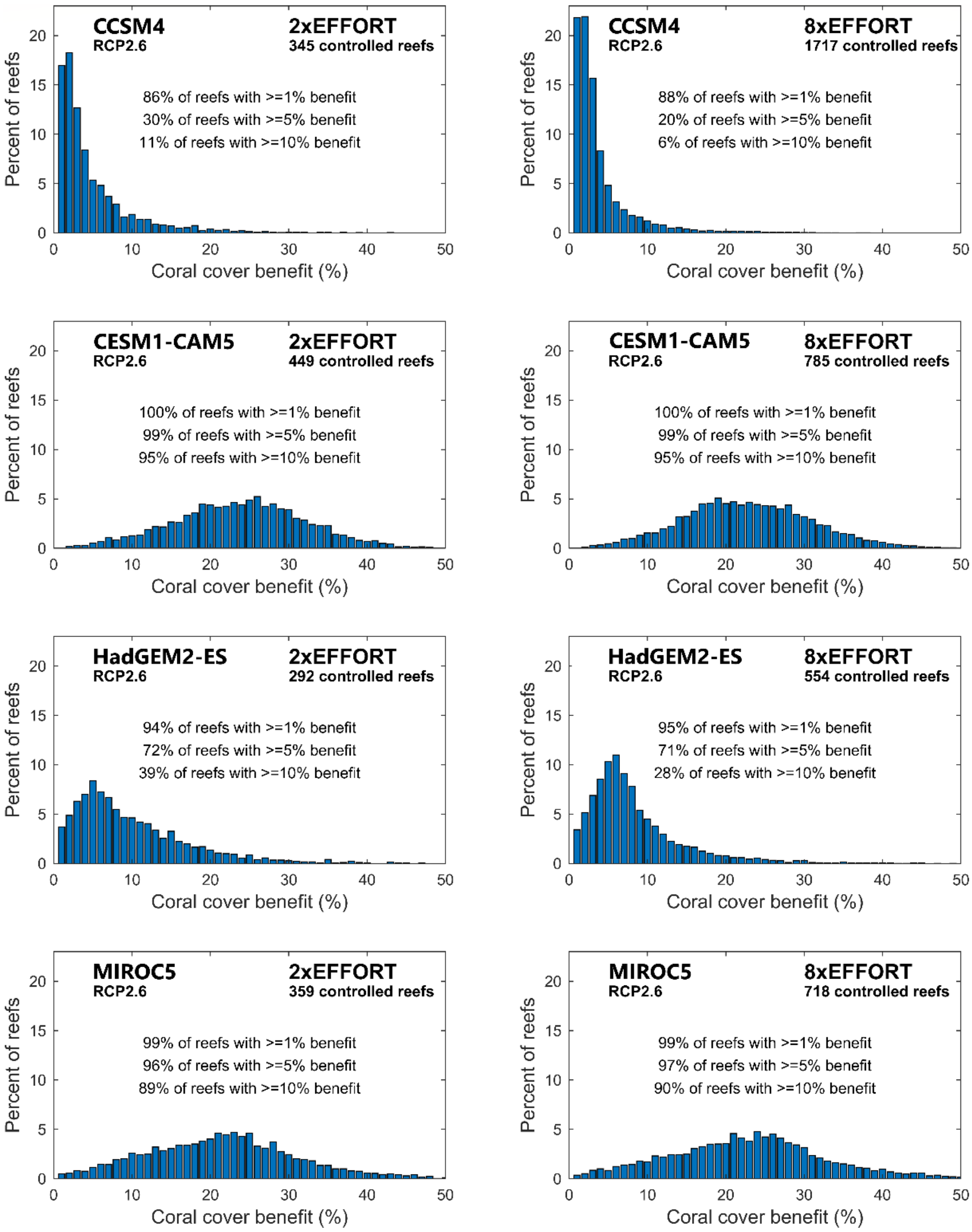


Figure 4.11: COTS control benefits at reefs where control occurred, for the decade 2020-2030 under the RCP2.6 emission scenario for the climate models CCSM4, CESM1-CAM5, HadGEM2-ES and MIROC5, when COTS control is targeting the COTS outbreaks based on abundance with the level of effort equivalent to two or eight control vessels. The number of controlled reefs refers to the number of unique reefs visited, and is an average over 10 replicate simulations. Management benefit (*x* axis) was calculated for each reef as the maximum of the annual differences in coral cover between the managed and counterfactual scenario over 2020-2030. The sample size of each histogram is the number of controlled reefs summed over 10 replicate simulations.

4.4 Discussion

The RBM planning tool is a first attempt to integrate stressors across a wide range of spatial and temporal scales, with models of the reef ecosystem, all within a flexible user interface that allows exploration of the ecological outcome of mitigating chosen stressors at particular times and places. A number of purposes to which the tool could be applied have been identified through research as well as consultation with potential users of the tool (Table 4.6).

Table 4.6: Management applications of the RBM Planning Tool, either in the current version or as a planned feature in the future version.

Application	Current feature or in development?
Visualise and compare feasible trajectories of the reef as a function of emissions policy, management choice, region of the reef, and time	Current
Effects of improving water quality on reef health in time and space	Current
Benefits of preventing anchor damage at particular locations	Current
Benefits of CoTS control as a function of location, time and number of reefs treated	Current
Benefits of combinations of management interventions (management “portfolios”)	Current
Identification of the present-day key source reefs	Current
Maintenance of projection accuracy following new cyclones and bleaching events by updating spatial layers within the tool (can be done by user)	In development
Explicit comparison of the size of management benefits to the size of climate impacts to explore strategies for reef persistence under climate change	Current
Effects of zoning (open, no take, no entry) on coral cover	In development
Optimisation procedures in which the user defines a management objective and the software finds solutions that deliver the objective	In development

An example of user input into the development of the tool emerged from a recent presentation of the initial version of the tool at GBRMPA in Townsville. Personnel from the Field Management Program identified complementarity between compliance efforts and anchor damage in terms of how the RBM planning tool could be used. Whilst compliance typically focuses on prevention of poaching and trespass into no-entry zones, the ability to predict anchor damage could assist the Field Management Program to better quantify the ecological impacts of these offences. Enforcement patrols collect data on the number of boats observed, enabling estimation of the recreational and commercial boat visitation pressure in different zones. The current version of the tool models anchor damage as an “on/off” stressor, but future versions will enable anchoring to be included on a sliding scale of severity, ideally through the use of maps of boat visitation pressure which is the best available proxy. The use of anchoring damage along with connectivity could also assist in planning of enforcement efforts. Compliance officers may choose to devote resources to reefs where illegal activities are generating substantial anchoring damage, and are either ecologically sensitive or important as key source reefs.

An important future application of the decision tool identified by users revolves around questions of optimisation. The ultimate goal of optimisation would be a form of “best practice” in which managers would define an environmental goal and allow the software to find the portfolio(s) of management actions that are capable of achieving that goal. For example, a goal may be to maintain coral cover at a level of 15% under a particular climate change trajectory.

Whilst the decision tool allows the user wide flexibility to set up simulations within the decision tool, it is possible that the user may never happen upon a portfolio of actions that allows the goal to be met. Performing a formal optimisation within the software would provide a solution more rapidly, if one exists, and if one doesn't it would provide confirmation that this is indeed the case. Knowledge that a solution *doesn't* exist is also valuable knowledge as it sets the boundaries of what management can feasibly achieve. A basic optimisation routine is being implemented in an upcoming version of the decision tool.

Additional sophistication in the exploration of management benefits against a background of rising sea surface temperatures could be included in the RBM Planning Tool. The question of coral reef climate refugia – whether particular areas should be protected based on their historical or predicted future climatology – is an active area of research. Reefs that possess different climatological features – possessing consistently cool, consistently warm, or predictably variable temperatures – have been identified, but there is no consensus on which of these should be prioritised for protection. Future development of the RBM Planning Tool could include spatial layers of GBR cool tendency, warm tendency and variability, which would allow the benefits of different strategies for selecting and protecting climate refugia to be compared.

Reef restoration activities are not yet widely implemented on the Great Barrier Reef, but are being investigated from ecological, economic and technological perspectives in the Reef Restoration and Adaptation Program (RRAP). The RBM Planning Tool (along with its underlying ecosystem model, ReefMod-GBR) will be the starting point for continued development of decision support capability under RRAP. Therefore, reef restoration options will be included in a future version of the RBM Planning Tool.

4.4.1 Summary

The building of the RBM Planning Tool was one of the core goals of the NESP 4.5 project. This software gives reef managers, for the first time, the ability to use a desktop environment to explore projections of reef state under different management decisions. Through the course of developing the ecosystem models and spatial data layers that were required for this software, several other products have been delivered to end users. Several products include some that involved improvements to spatial layers and reef predictions in ReefMod-GBR paid for by GBRMPA ("Resilient Reefs Project"), but which have played a role as key steps in the development of the final layers used in the RBM Planning Tool. These products have been incorporated into GBRMPA's Resilient Reefs Dashboard, and include an index of reef recovery that combines water quality and coral connectivity, and a map of cyclone risk across the GBR.

Other products developed alongside the RBM Planning Tool and incorporated into the Resilient Reefs Dashboard include a map of predicted reef state (coral cover) in 2020 through hindcasting the last decade of bleaching, cyclones, CoTS and water quality, and improved map of recovery potential, and a map of predicted present-day key source reefs in 2020 based on the state of reefs today and their connectivity to reefs in early stages of recovery. The Great Reef Census, described in section 2.4.1, is providing groundtruthing of the predicted coral cover, which is used as the starting reef state layer in both the RBM Planning Tool and in the connectivity-recovery algorithm. An analysis of benefits to future reef health of Water Quality Improvement, CoTS control, restoration, anchor protection and herbivore protection, was provided to (and funded by) Queensland and Commonwealth Governments. This ongoing program of research has culminated in the RBM Planning Tool, which has now been delivered to reef managers in GBRMPA and the Field Management Program.

5.0 DISCUSSION

Maintaining the ecosystem functioning of the Great Barrier-Reef is an imperative due to its outstanding global value, yet this is increasingly challenging under a warming and acidifying future. In 2017, GBRMPA reached a watershed moment in the history of the management of the GBR by embarking on a long-term strategy of resilience-based management. The implementation of RBM marks a departure from an equilibrial approach to management, towards one where spatio-temporal knowledge of current and future drivers of ecosystem function is utilized to adapt management actions and maximise their efficacy. RBM is well suited to application on the GBR due to the inherently dynamic natural disturbance context of the GBR, the variety and changeability of human pressures, and because the spatial data types required to pursue this strategy are beginning to reach maturity.

A natural starting point for RBM on the Great Barrier Reef is to build upon systemic-resilience management methods that are already integrated into management practice. One of these methods is the identification of key source reefs, developed by Hock et al. (2017). This method used hydrodynamic models and coral spawning data to identify reefs that have a disproportionately larger role in supplying other reefs with larvae of corals and pest species (crown of thorns starfish). Key-source reefs have been used by GBRMPA to prioritise reefs for CoTS control planning. This project built-upon the concept of long-term key source reefs by using a dynamic algorithm that identifies the present-moment key source reefs through ranking reefs on the basis of which reefs are most in need of recovery, and to which healthy reefs do they have the highest level of connectivity (Chapter 2). Our goal in this was to facilitate the timely identification of locations requiring management intervention in the months following a bleaching event. The algorithm was also used in subsequent work, including within the RBM Planning Tool.

As reefs important for larval replenishment and those experiencing high fishing intensity are both spatially heterogeneous on the GBR (Hock et al., 2017, 2019; Castro-Sanguino et al., 2017; Weekers et al., 2019; Thiault et al., 2019), a synthesis of where these locations align is an important tool to inform science and management. This is the primary outcome of the second part of this project, resulting in the identification of highly fished but reproductively valuable reefs as priority reefs. Analyses were undertaken separately for commercial fishing intensity and recreational fishing intensity as they differ in their spatial distribution and management requirements. This study also combined them into an overall fishing priority reef distribution map. Investigating where commercial fishing and recreational fishing overlap with key source reefs can inform compliance strategies in protected areas and identify reefs within fishing zones that require more education for commercial fisheries and recreational fishers regarding best practise of anchoring and mooring (GBRMPA & Queensland Gov., 2019).

This approach is an important step in integrating compliance with an ecological foundation to foster the reef resilience and recovery strategy currently in place for the GBR (Done, 1995). It also highlights the need for more complex analyses in the future with more meaningful measures of commercial and recreational fishing. Fishing compliance and education strategies can be guided by this approach to be more streamlined for effective management and resource-distribution. Fishing pressures predictions developed using the methodology of this project, along with zoning-effect spatial layers, will be incorporated into the next version of the

RBM Planning Tool, enabling (a) total fishing impacts, and (b) the benefits attainable through enforcement, to be explored.

Through its aim to adaptively inform management in response to both present and future drivers, resilience-based management requires the development of forecasting and visualisation methods. In the latter stage of this project, these methods were developed through several processes. Ongoing development of an ecosystem model for the Great Barrier Reef, ReefMod-GBR, was performed, producing a mature ecosystem model with good predictive ability of coral cover across the GBR (Bozec et al. 2020). Spatial data of numerous drivers were collated, including updated maps of water quality impact, cyclones, and sea warming predictions from a range of future climate models. Predictions of management benefits for reef interventions under climate change were performed using the improved ecosystem model and spatial layers (Mason et al. 2020). Building upon these efforts, the user-driven exploration of intervention efficacy within a dynamic disturbance and recovery context, which is required for adaptive management, was provided through the development of the RBM Planning Tool.

It is finally worth mentioning some areas for future development of the predictive capacity that underlies the RBM Planning Tool. Ocean acidification has not yet been explicitly incorporated into the ReefMod-GBR ecosystem model and the RBM Planning Tool. However, an additional activity under NESP 4.5 has been the development of the science that is required for the modelling of ocean acidification and its impacts upon coral cover. This activity has been led by Matt Adams (Queensland University of Technology), who has developed both a mechanistic and a statistical model to predict coral calcification (including uncertainty) in response to light, temperature, salinity, dissolved inorganic carbon and total alkalinity. Both models display a good match to empirical observations of coral calcification in three coral species (Figure 5.1a, b).

(a) (b)

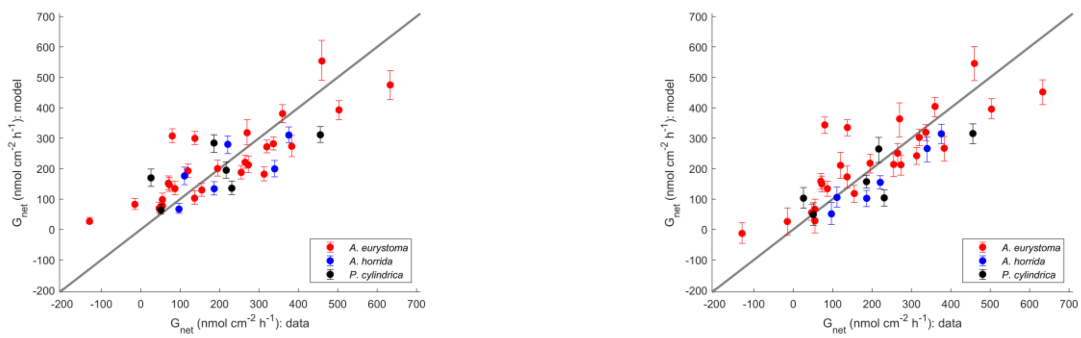


Figure 5.1: Newly developed methods enable the prediction of coral calcification from light, temperature, salinity, dissolved inorganic carbon and total alkalinity. Here, the predicted calcification rate (G_{net}) (on the y-axis) is compared to the empirically observed calcification rate using (a) a mechanistic model, or (b) a statistical model. Genus abbreviations are *A., Acropora; P., Porites*.

This development allows the implementation of ocean acidification impacts on coral calcification based on the eReefs biogeochemical model outputs, as eReefs already predicts the five abiotic parameters required. The approach is being considered for integration as an operational component of eReefs in the future, allowing present-day maps of coral calcification (including uncertainty) across the Great Barrier Reef to be produced and continually updated

(Figure 5.2). Application of the approach to predictions of ocean chemistry performed in Atmosphere-Ocean General Circulation models will enable future predictions of coral calcification to be incorporated into the RBM Planning Tool.

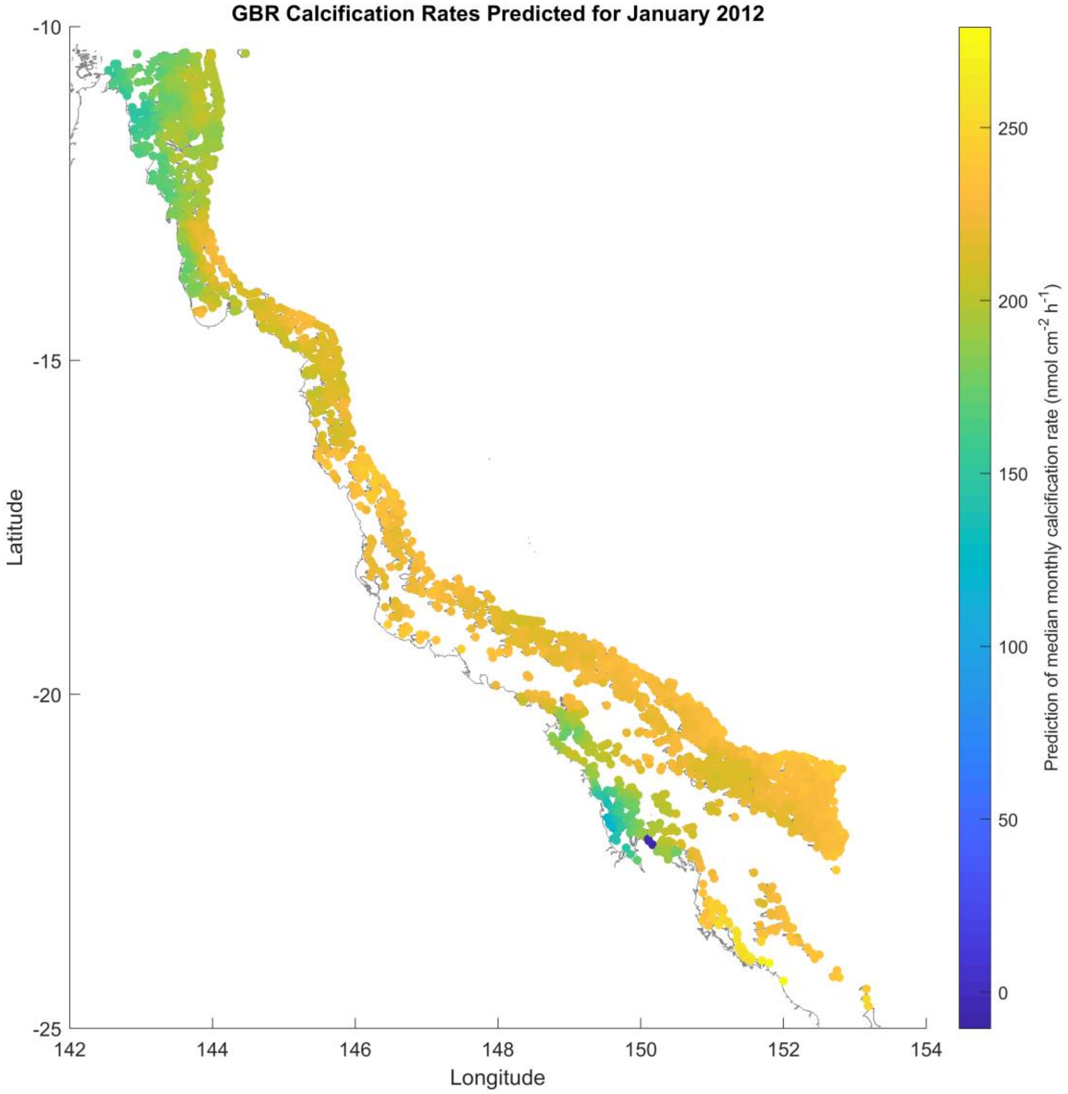


Figure 5.2: Prediction of calcification using the outputs of the eReefs biogeochemical model of the Great Barrier Reef. The statistical method of calcification prediction (e.g. Figure 5.2b) was used. Uncertainty in the predictions is of order ±100 nmol cm^{-2} h^{-1}.

6.0 RECOMMENDATIONS AND CONCLUSION

This project can further RBM on the GBR in three ways: through an algorithm to identify present-day key source reefs, through integration of field-based compliance with long-term key source reefs, and through development of a desktop software that enables a broad sweep of RBM exploration and planning activities. These tools are being made available to reef managers within Queensland to enable exploration of the capabilities, applications and areas for future development of these tools. Whilst it is not our role as scientists to proscribe how and why managers should go about the exploration and use of these tools, there are some points to which we believe attention should be paid:

- Whilst the prediction capability provided here is a powerful one, no tool can truly predict the exact future. However, it *is* possible to qualitatively understand the limits of certainty so that the predicted outputs can be appropriately interpreted and acted upon.

- The future projections provide a method to estimate potential impact of differing options, and thus make choices.

- This report has emphasised the scientific aspects of the development of predictive capability for RBM. In performing the science we have firmly kept in mind the way that managers could use the RBM Planning Tool, and have consulted managers about this during the project. However, a full exploration of the practice of using these new predictive capabilities in the process of management is warranted. This would include cognitive aspects such as the way that predicted information is synthesised and interpreted by users; field planning, such as whether more work needs to be done to integrate prediction outputs with the logistical constraints of field management to better identify practical solutions; the identification of barriers to utilising and applying the tool (e.g. lack of data, technical capacity, concerns around how to tackle multiple/synergistic stressors); financial aspects such as cost-benefit analysis of management options; and finally, incorporation of social components resilience that pertain to the GBR. We also note that managers also have a role to play in refining the science behind the tool, such as by identifying additional stressors, interventions and ecosystem processes that need to be captured with the tool.

- Challenges such as qualitatively classifying uncertainty of predictions, and exploration of the RBM Planning tool outputs within the practice of decision making and planning, could be advanced through ongoing collaboration between the scientific team behind the tool and the end users of the tool.

- Social components of resilience are important considerations in the resilience-based management. The mapping of social, economic and cultural values of the GBR has occurred through projects such as the Resilience Framework funded by the Great Barrier Reef Foundation, and NESP 5.5 (Measuring Aesthetic and Experience Values). It will be important to incorporate social, economic and cultural aspects into future development of the RBM Planning Tool to enable decision making from a linked social-ecological system perspective.

- Development of decision tools for coral reef management is now an incipient subfield of coral reef conservation (National Academies of Sciences, Engineering and Medicine, 2019). Efforts should be made to link the RBM Planning Tool to the international efforts in this area.

- Finally, the RBM Planning Tool is intended, in part, to act as a stimulus for further research and development of RBM decision science that will occur under the Reef Restoration and Adaptation Program.

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APPENDIX 1: COMPLIANCE ANALYSIS MAPS

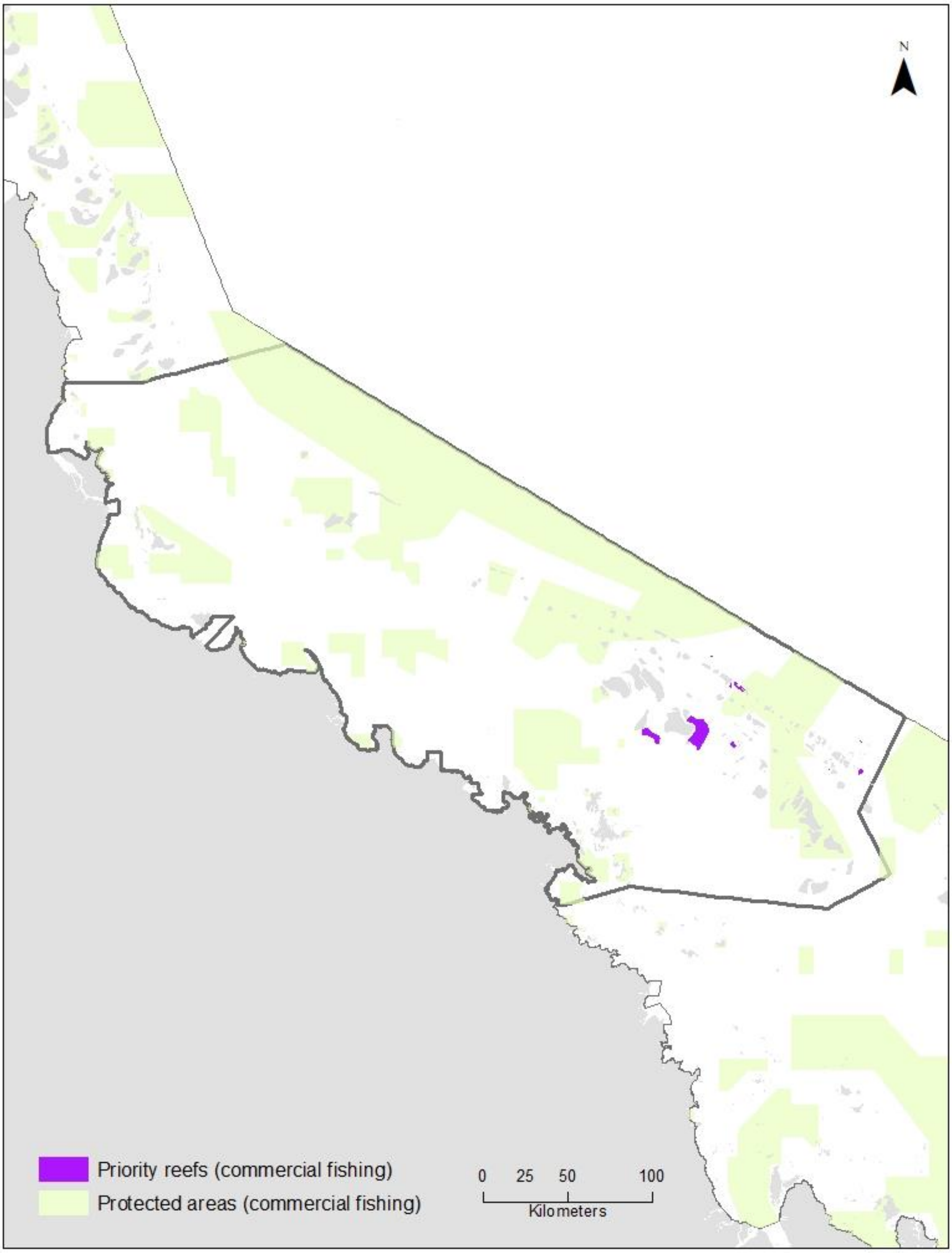


Figure A1.1: Priority commercial reefs in the TWMA that have high standardised commercial intensity (>0.5) and a high standardised larval connectivity value (>0.5). Green areas represent the main zones where commercial fishing is not permitted (Marine National Park zone, Preservation zone, Scientific Research zone, Buffer zone).

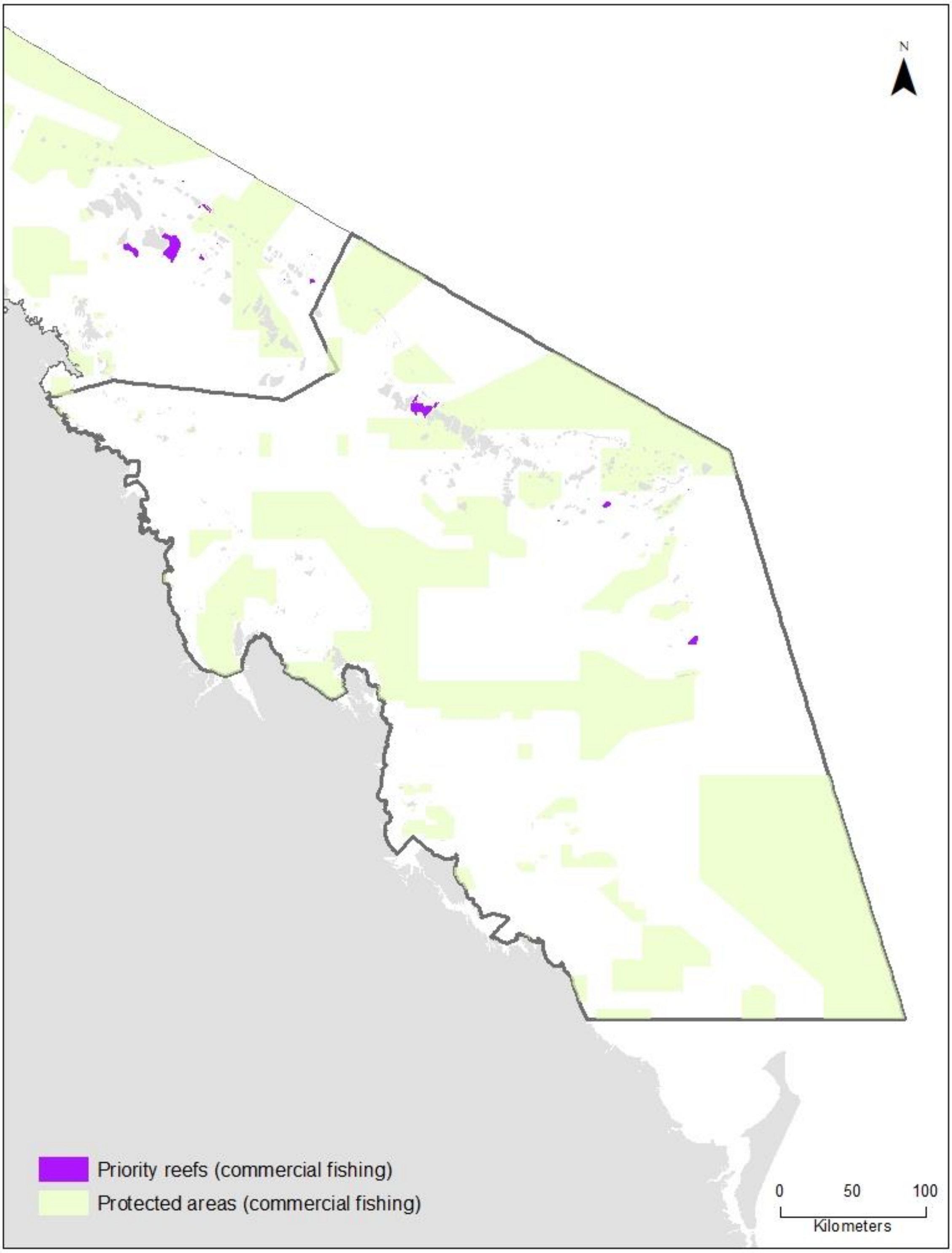


Figure A1.2: Priority commercial reefs in the MCMA that have high standardised commercial intensity (>0.5) and a high standardised larval connectivity value (>0.5). Green areas represent the main zones where commercial fishing is not permitted (Marine National Park zone, Preservation zone, Scientific Research zone, Buffer zone)

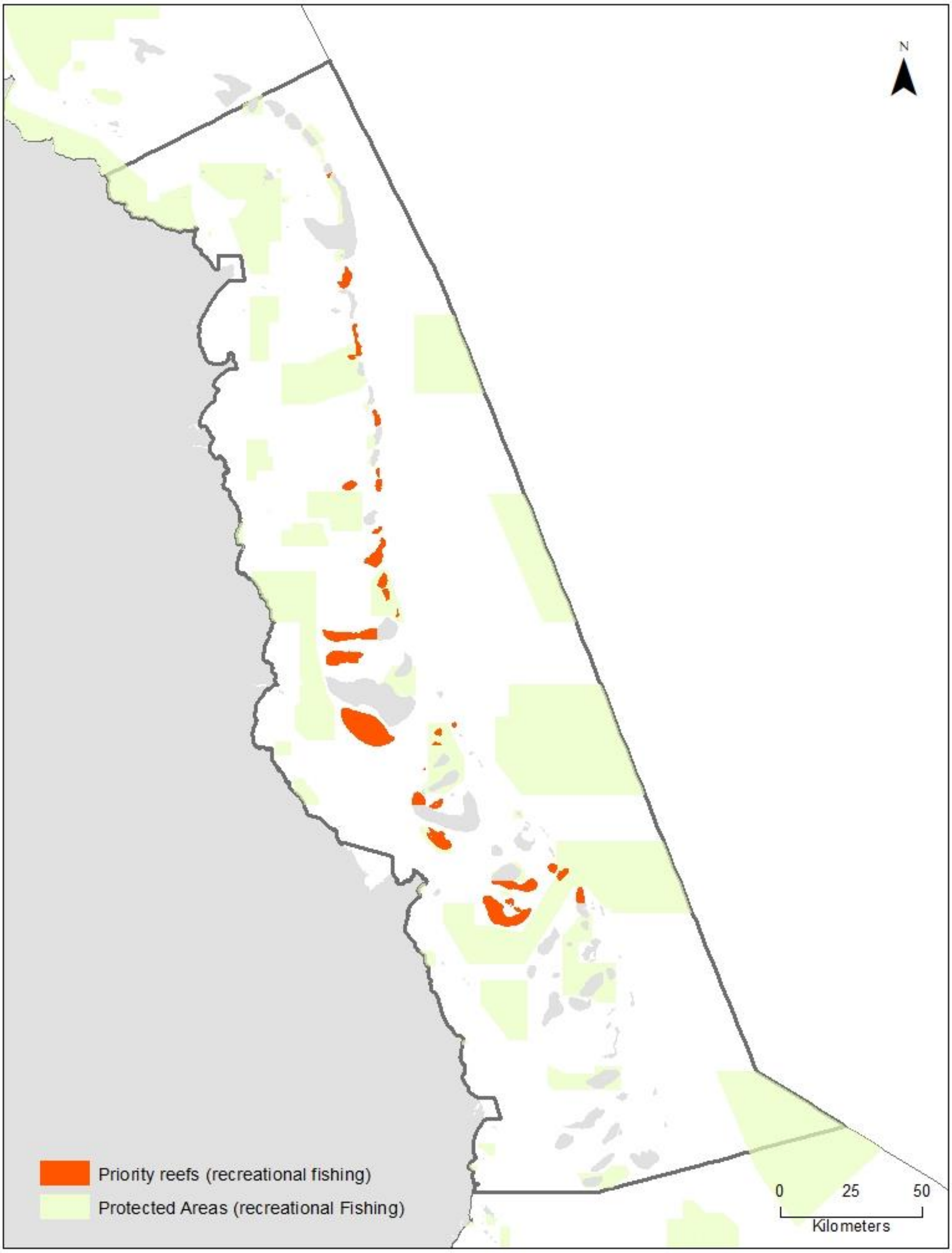


Figure A1.3: Priority recreational reefs in the CCMA that have high standardised recreational intensity (>0.5) and a high standardised larval connectivity value (>0.5). Green areas represent the main zones where recreational fishing is not permitted (Marine National Park zone, Preservation zone, Scientific Research zone)

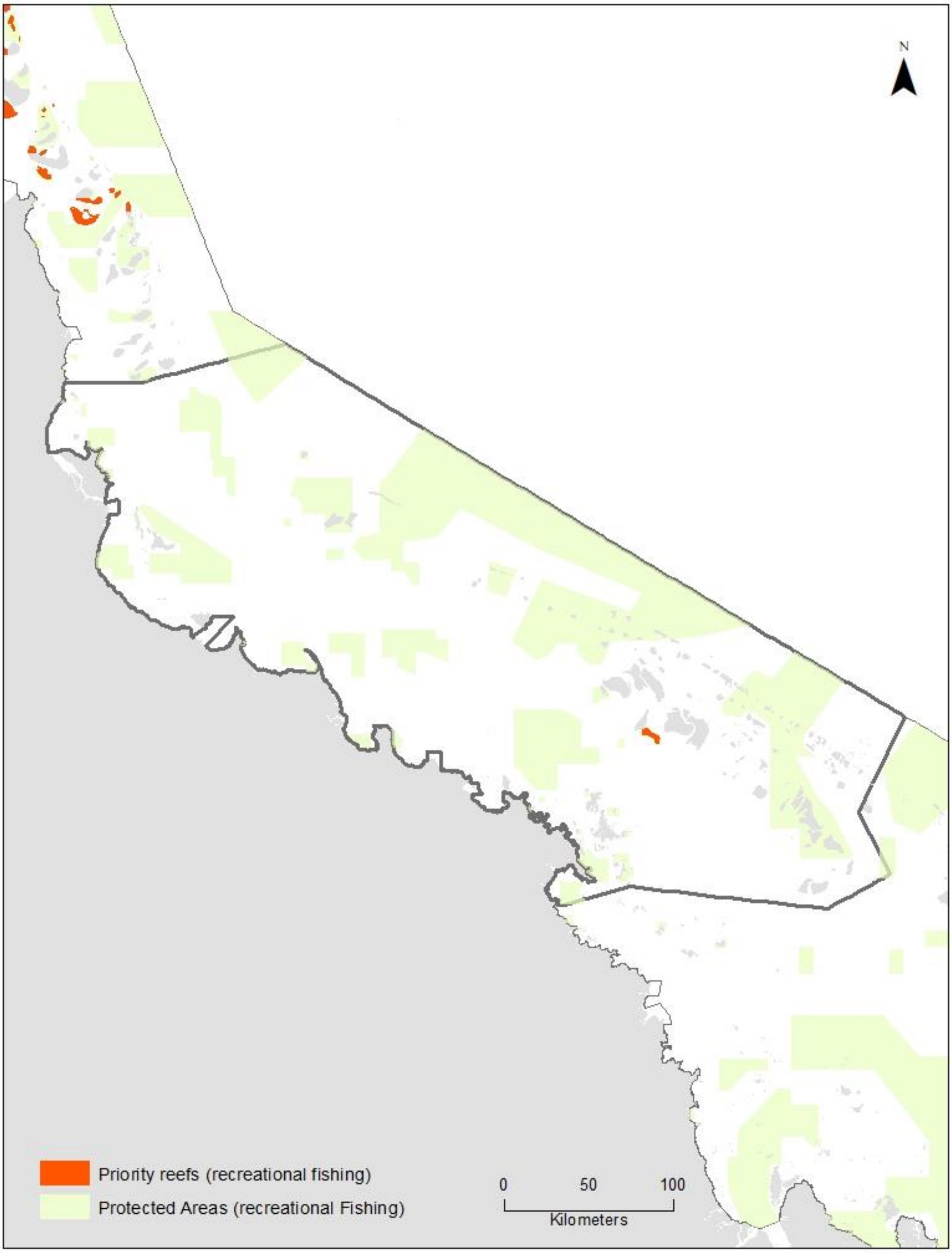


Figure A1.4: Priority recreational reefs in the TWMA that have high standardised recreational intensity (>0.5) and a high standardised larval connectivity value (>0.5). Green areas represent the main zones where recreational fishing is not permitted (Marine National Park zone, Preservation zone, Scientific Research zone)

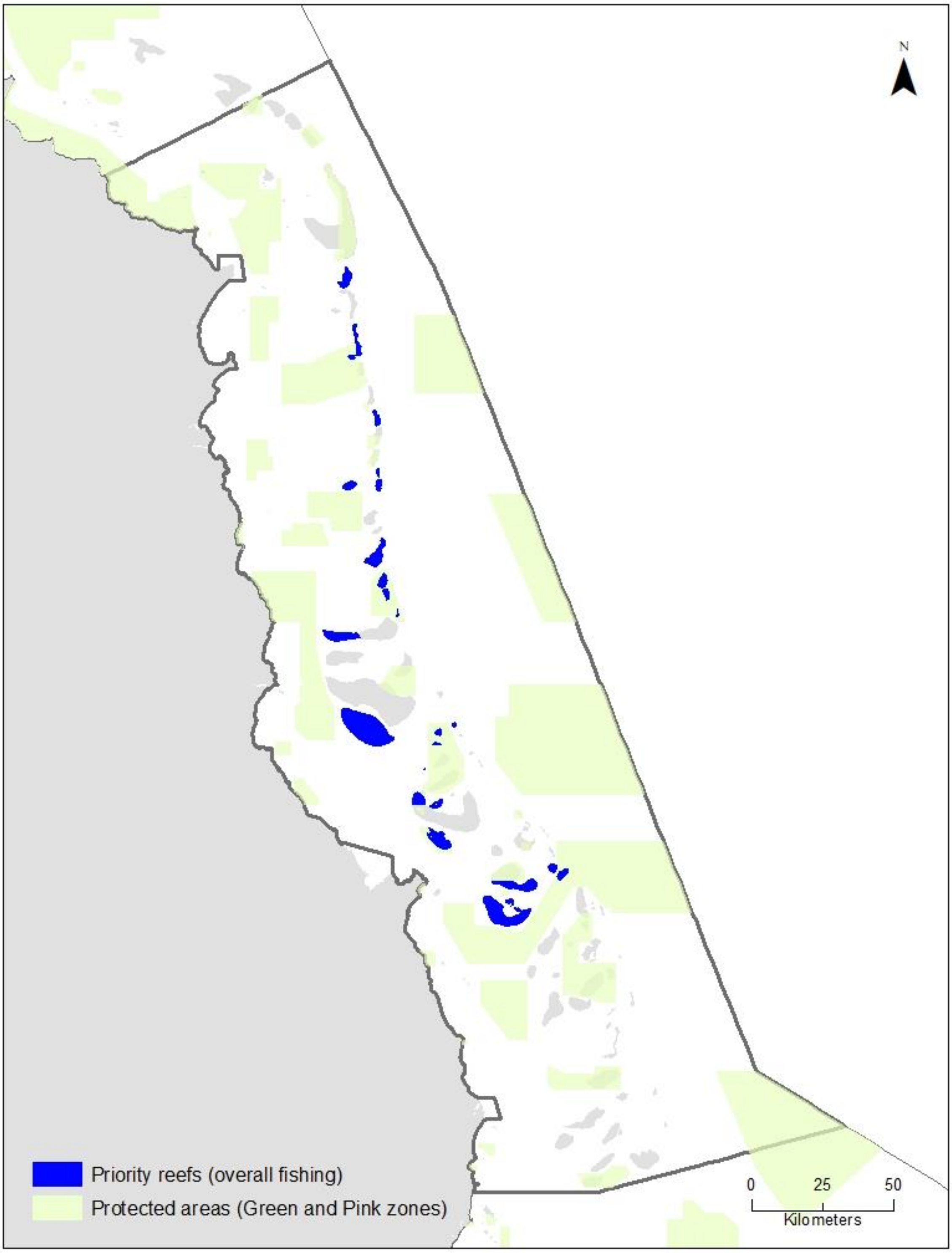


Figure A1.5: Priority overall reefs in the CCMA that have high standardised overall intensity (>0.5) and a high standardised larval connectivity value (>0.5). Green areas represent the main zones where fishing is not permitted (Marine National Park zone, Preservation zone)

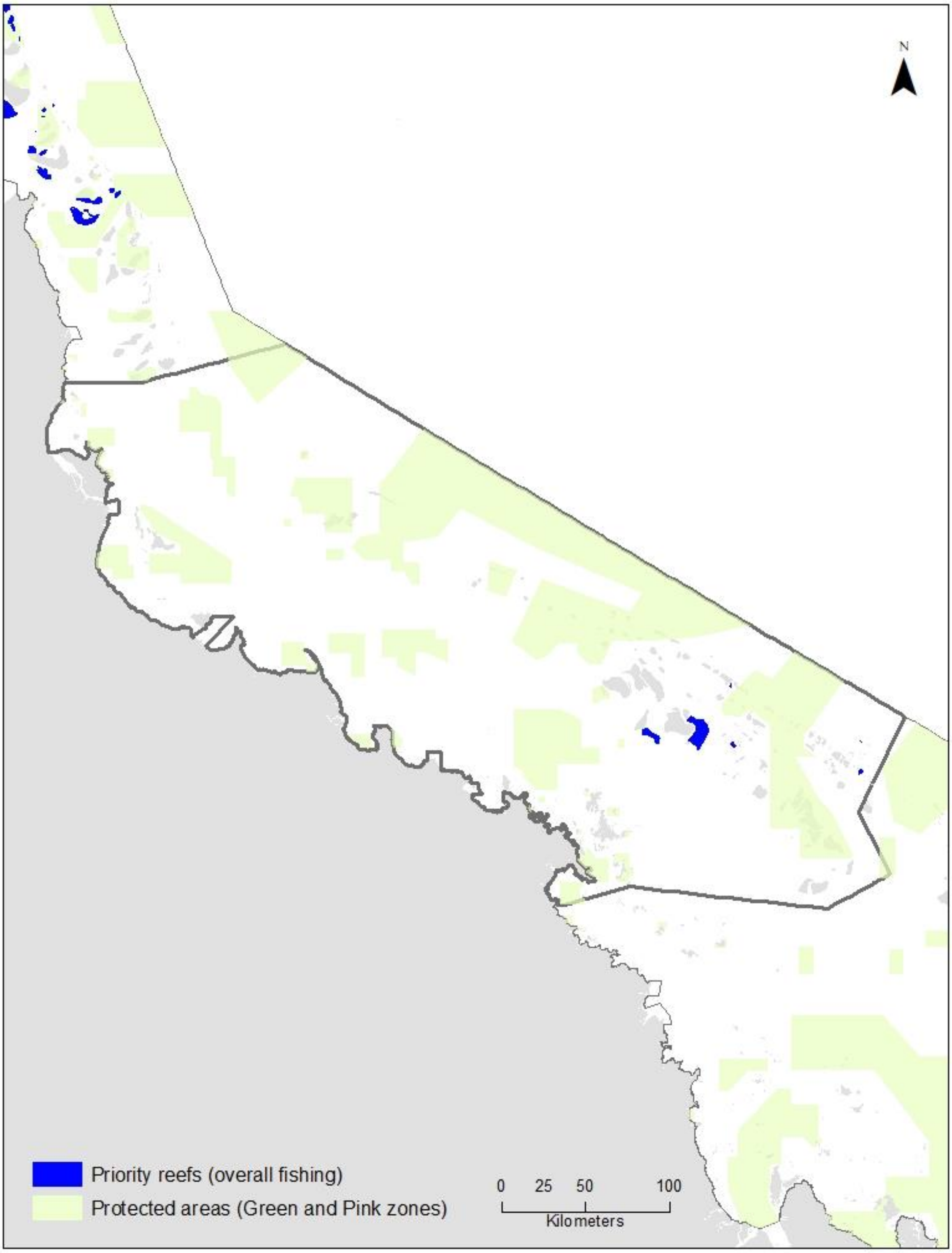


Figure A1.6: Priority overall reefs in the TWMA that have high standardised overall intensity (>0.5) and a high standardised larval connectivity value (>0.5). Green areas represent the main zones where fishing is not permitted (Marine National Park zone, Preservation zone)

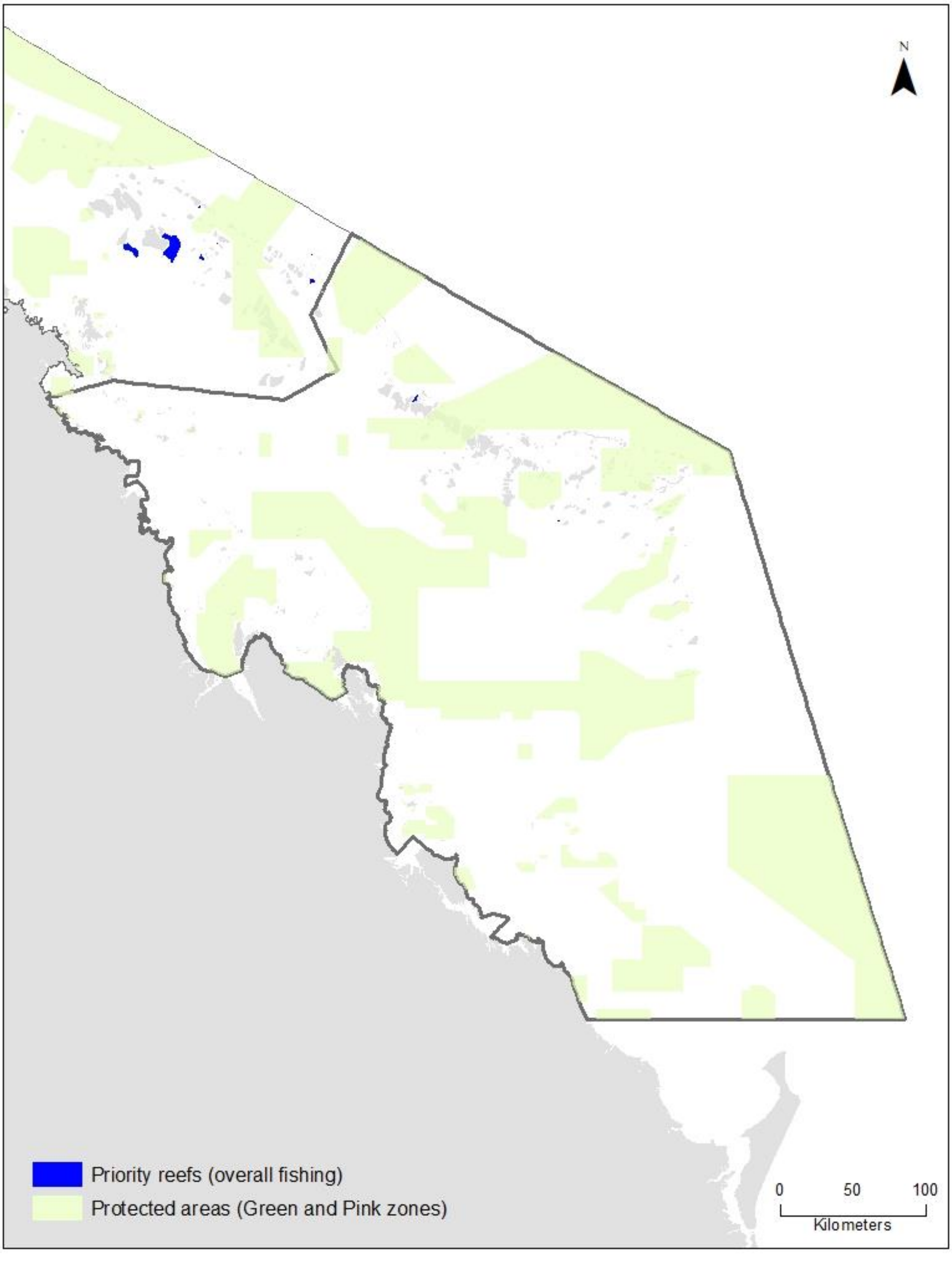


Figure A1.7: Priority overall reefs in the MCMA that have high standardised overall intensity (>0.5) and a high standardised larval connectivity value (>0.5). Green areas represent the main zones where fishing is not permitted (Marine National Park zone, Preservation zone)

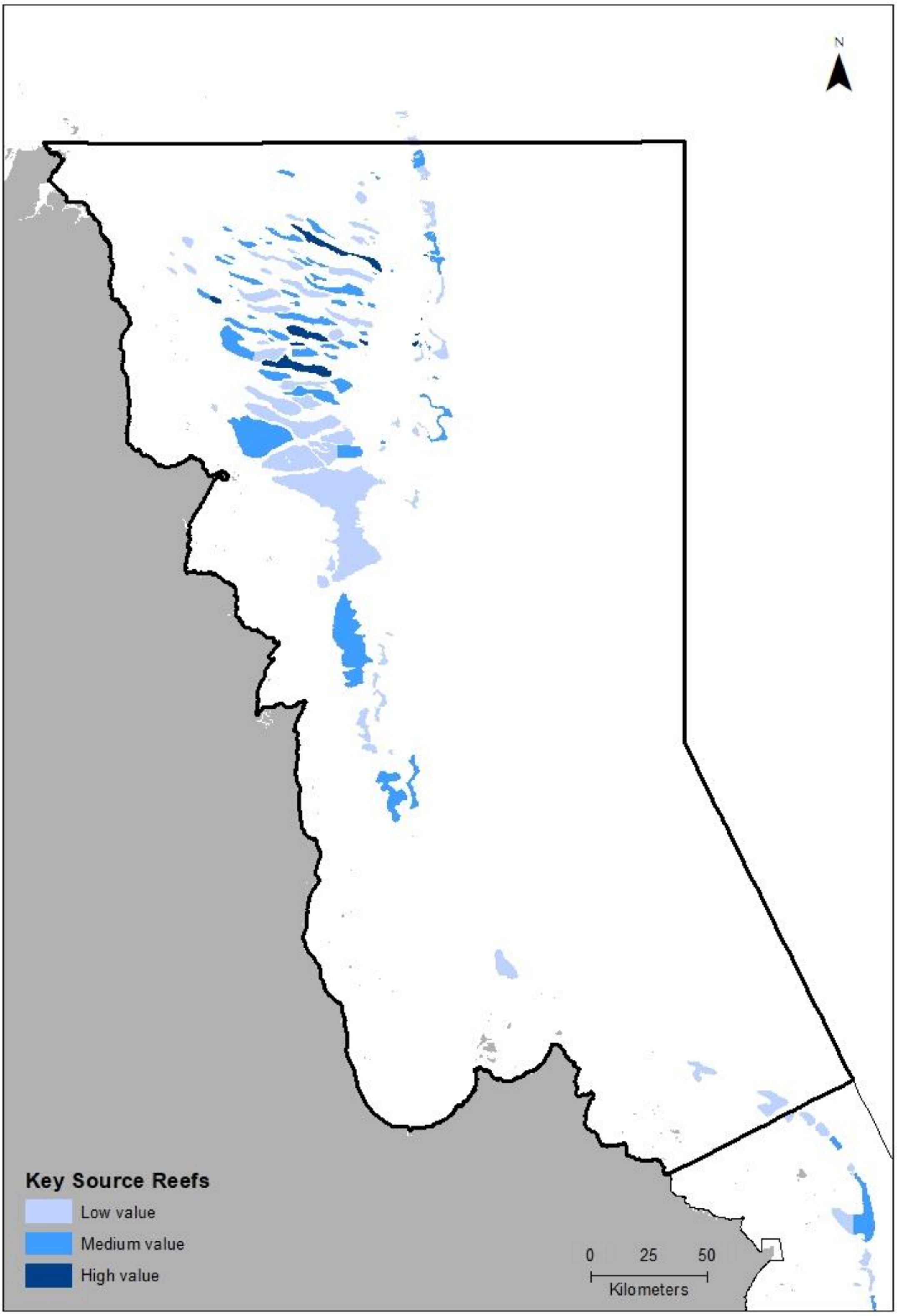


Figure A1.8: Long-term key source reefs in the FNMA (*n*=687). Reefs are divided into terciles according on their larval connectivity value: Low value: 0.012634 – 17.138794, Medium value: 17.138795-21.400569, High value: 21.400570-32.275990.

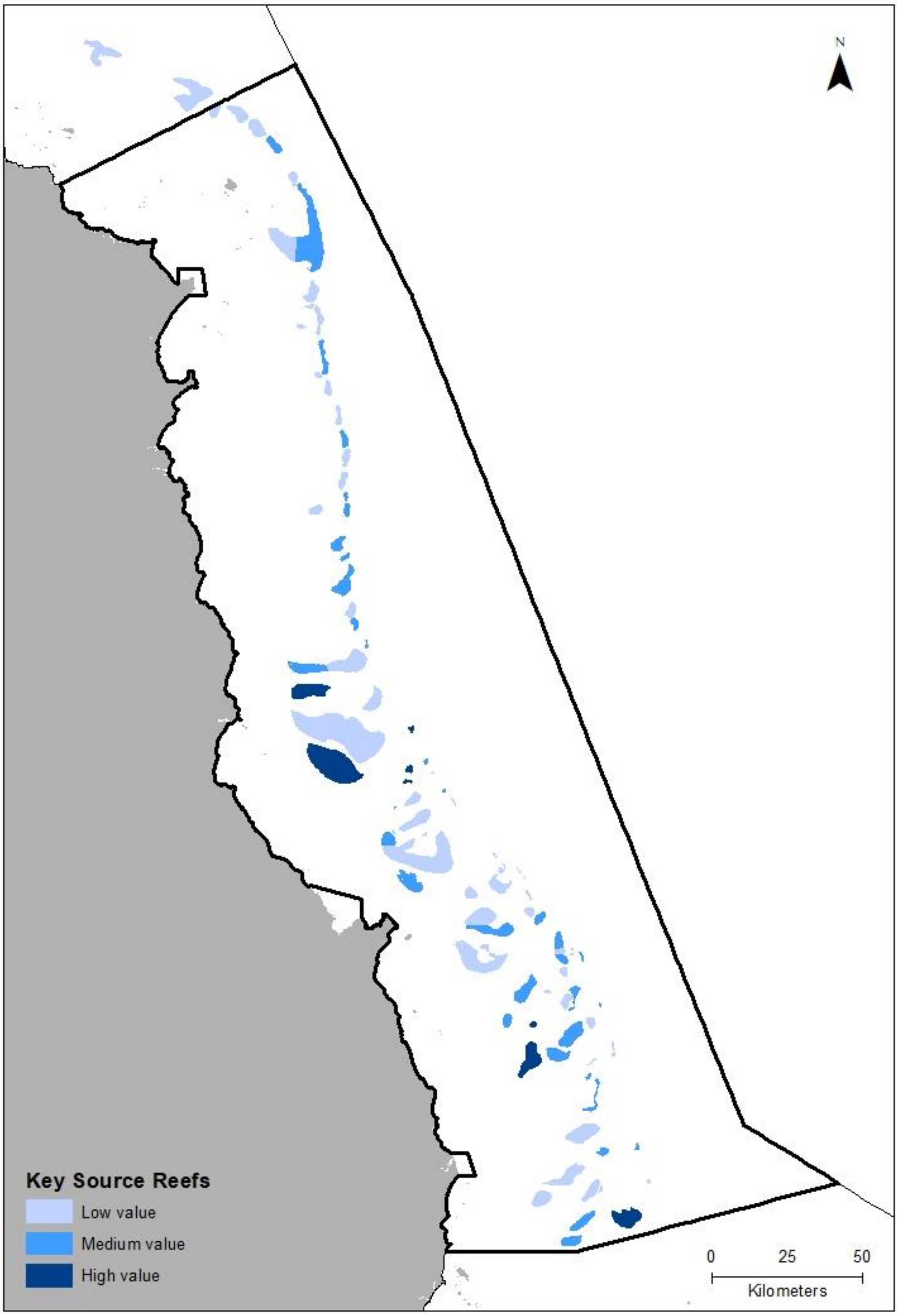


Figure A1.9: Long-term key source reefs in the FNMA (*n*=687). Reefs are divided into terciles according on their larval connectivity value: Low value: 0.012634 – 17.138794, Medium value: 17.138795-21.400569, High value: 21.400570-32.275990.

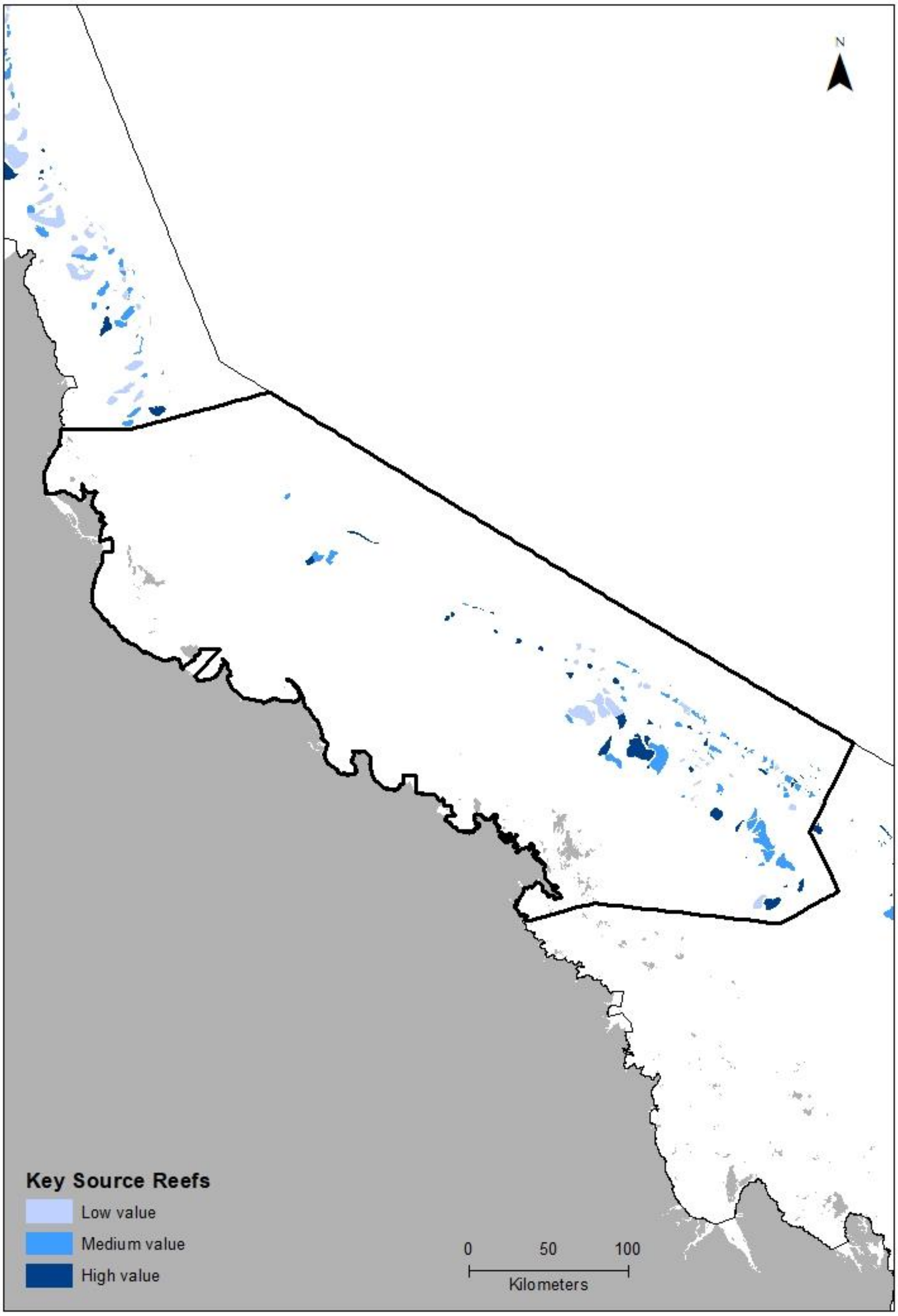


Figure A1.10: Long-term key source reefs in the FNMA (*n*=687). Reefs are divided into terciles according on their larval connectivity value: Low value: 0.012634 – 17.138794, Medium value: 17.138795-21.400569, High value: 21.400570-32.275990.

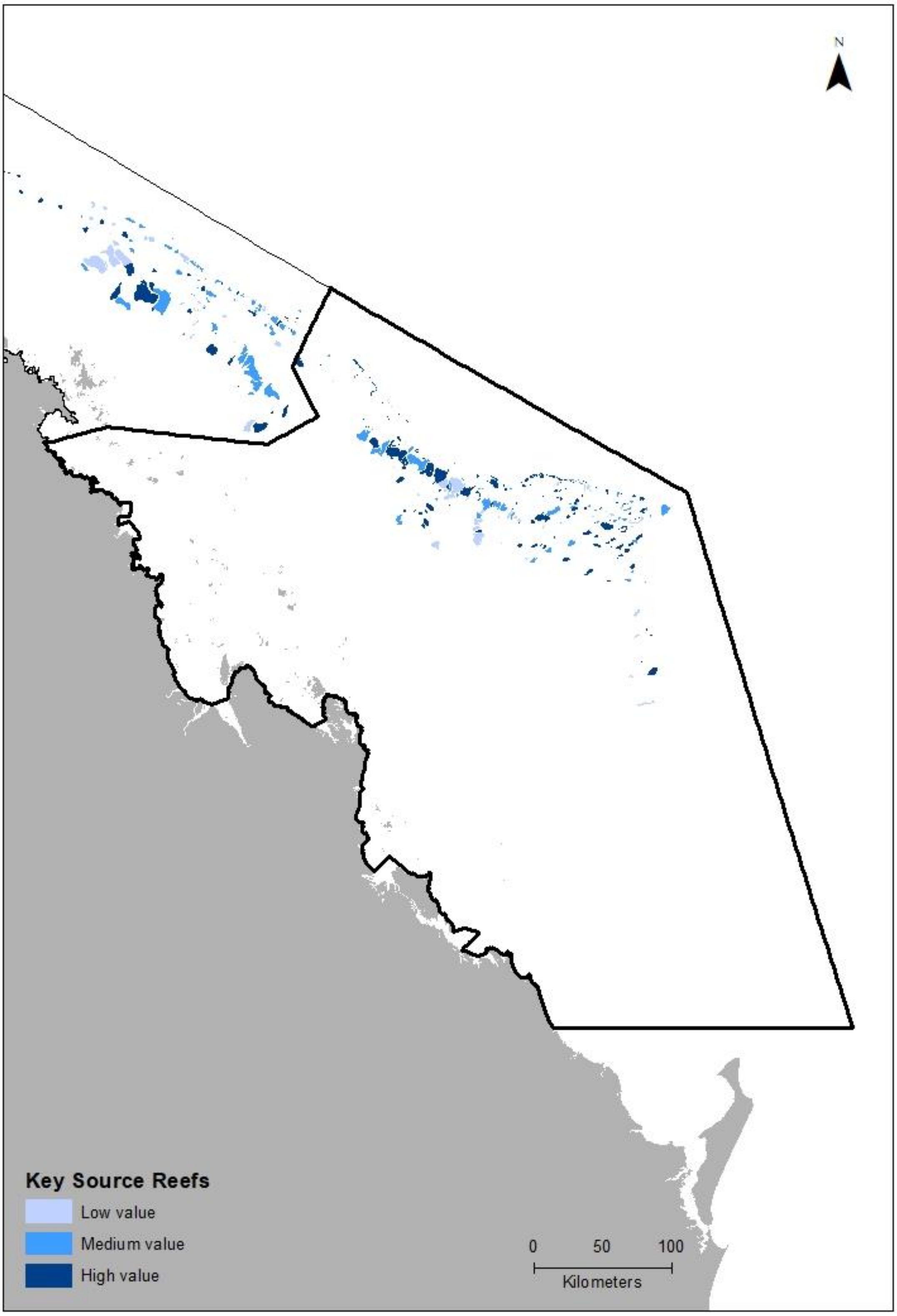
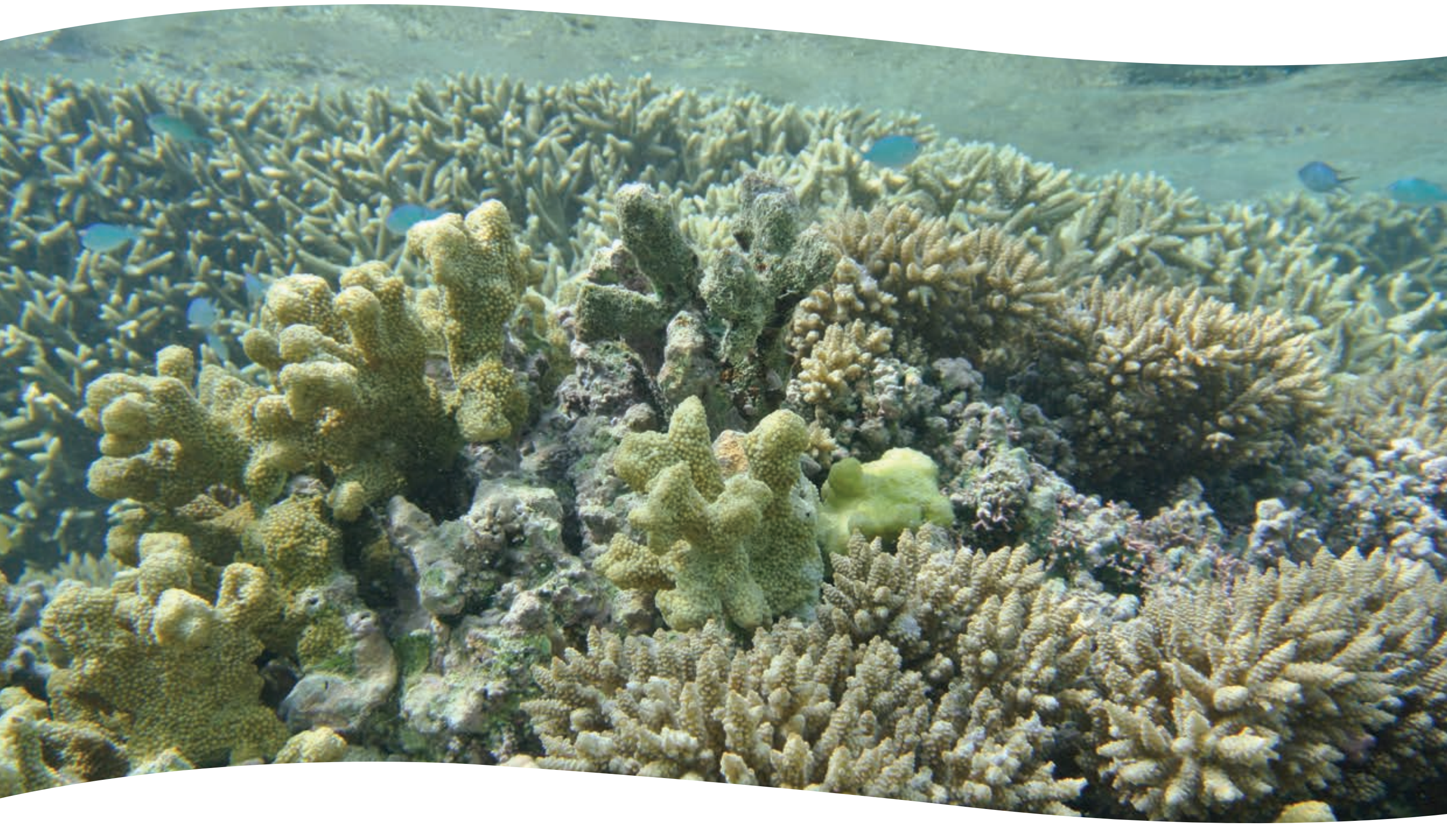


Figure A1.11: Long-term key source reefs in the FNMA (*n*=687). Reefs are divided into terciles according on their larval connectivity value: Low value: 0.012634 – 17.138794, Medium value: 17.138795-21.400569, High value: 21.400570-32.275990



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