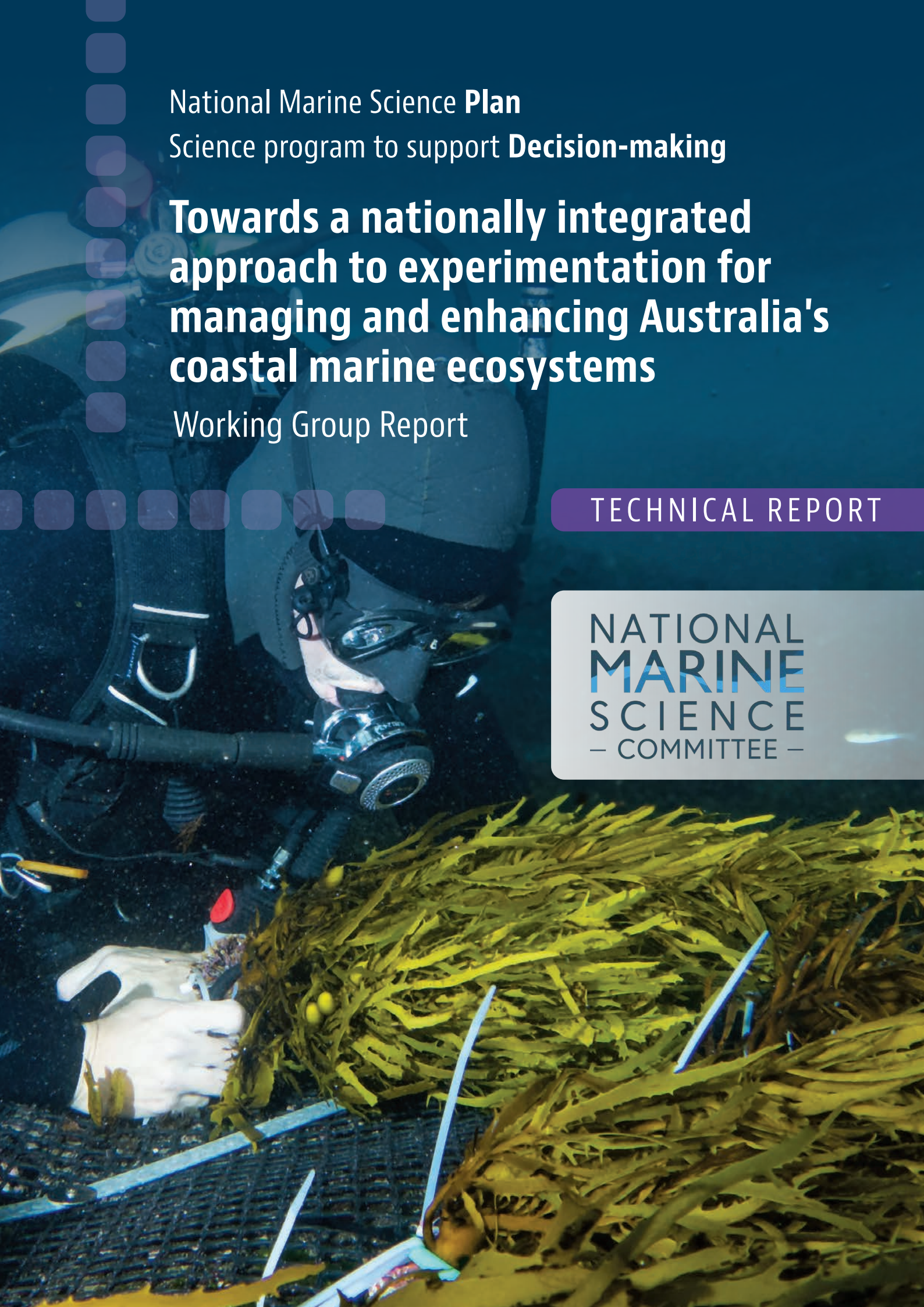
National Marine Science **Plan**

Science program to support **Decision-making**

# Towards a nationally integrated approach to experimentation for managing and enhancing Australia's coastal marine ecosystems

Working Group Report

TECHNICAL REPORT



NATIONAL MARINE SCIENCE – COMMITTEE –

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Front cover: Experimental testing of restoration in a temperate kelp (crayweed) forest. Experiments like these, in habitats where crayweed is now extinct, allow for large scale restoration of this foundational species to its former habitat. Front cover and above images: John Turnbull, www.marineexplorer.org

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## Acknowledgement of Country |

The National Marine Science Committee acknowledges the Traditional Custodians and Elders of the land and sea on which we work and observe, and recognises their unique connection to land and sea. We pay our respects to Aboriginal and Torres Strait Islander peoples past, present and future.

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# Summary


Australia's coastal marine ecosystems contain enormous economic, environmental and sociocultural value. They are a key part of Australia's marine natural capital, with assets and services valued at tens of billions of dollars.

They are, just as crucially, a core part of Australia's identity as a healthy and sustainable country. However, many of these coastal ecosystems are deteriorating, and with the prospect of continued climate change, greater urbanisation and increasing coastal development, ongoing decline and loss of key marine ecosystems remain a significant challenge. The consequence of this decline will be a loss of unique and valuable biodiversity, ecological functions and ecosystem services, including fisheries, tourism and coastal amenity.

The *National Marine Science Plan 2015–2025* (NMSP) was written in response to such challenges, and Recommendation 3 in the NMSP focused on a nationally integrated experimental approach for providing critical new knowledge on 'marine ecosystem processes and resilience to enable understanding of the impacts of development and climate change on our marine estate'. A national framework for a mechanistic – and thus experimental – understanding of our coastal ecosystems is urgently needed in order to develop new large-scale approaches for the effective management and rehabilitation of our coastal ecosystems. This framework would also provide a natural and necessary complement to other NMSP recommendations focused on coordinated long-term monitoring and modelling (Recommendations 2 and 4). These, together with Recommendation 3, provide the basis for decision support (Recommendation 5) and allow for the development of a resilience-building approach to coastal systems (Recommendation 11).

Here we develop the case for a coordinated national experimental approach for coastal marine and estuarine ecosystems, in order to provide a framework for: (i) understanding the impact of *drivers of change* for major coastal ecosystems; (ii) building the *resilience* of these ecosystems; and (iii) developing proactive *solutions* for these systems, including adaptive ecosystem management and active interventions via habitat restoration and rehabilitation. We describe the logic for such an approach, show that there is considerable latent infrastructure and capacity in Australia for national integration, and develop the framework in more detail for four key coastal ecosystems.

Potential solutions to the challenges faced by Australia's coastal ecosystems are emerging, but a national experimental approach is critical for testing and improving those solutions in a future where our oceans are rapidly changing. Investment into large-scale experimental approaches to the management and rehabilitation of one of our valuable coastal ecosystems – coral reefs – has already been made in the form of the Reef Restoration and Adaptation Program (RRAP).

Investment at a scale comparable to that of the RRAP is now critically needed to sustain the use of Australia's other equally important and iconic coastal systems, including kelp forests, oyster reefs, seagrass beds, mangrove forests, estuarine sediments and coastal wetlands. Developing solutions to sustain Australia's immensely valuable coastal ecosystems without an integrated experimental approach to inform those solutions is the equivalent of investing in a multi-billion dollar business without first testing the market, or releasing a new drug to market without conducting clinical trials. Without investment in experimental science, which enables us to directly test the impacts of rapidly changing conditions at a national scale, the management, restoration and rehabilitation of many of Australia's most sensitive and valuable marine ecosystems will be navigating uncharted territory.


> *"The focus on coastal ecosystems stems from the fact that Australians are a coastal people, with over 87 per cent of us living within 50 kilometres of the ocean.*

# **Introduction** and context |

The *National Marine Science Plan 2015–2025: Driving the development of Australia's blue economy* (NMSP) was written to guide the management and sustainable use of Australia's marine and coastal environment at a national level.

It is intended to 'focus investment on the biggest development and sustainability challenges facing Australia's marine estate, and [on] the highest priority science needed to tackle these challenges.'

The NMSP made eight high-level recommendations, four of which explicitly address national approaches to marine science that will underpin the use and management of our marine estate. In this report we outline an approach to address Recommendation 3 of the NMSP: 'Facilitate coordinated national studies of marine ecosystem processes and resilience to enable understanding of the impacts of development and climate change on our marine estate.' An integrated experimental approach is required to understand the processes that underpin marine ecosystem resilience and the drivers that may compromise it, and to understand how innovative technical management or policy solutions can enhance ecosystem resilience, bolster adaptation and rehabilitate existing damage. Here we present a framework and rationale for a national approach to experimental investigations of Australia's coastal ecosystems.

The focus on coastal ecosystems stems from the fact that Australians are a coastal people, with over 87 per cent (ABS 2020) of us living within 50 kilometres of the ocean. Our coastal environments are enormously valuable, with the Great Barrier Reef valued at over $6 billion annually (Deloitte 2013, 2017) and the Great Southern Reef, which spans 8000 kilometres of southern Australia's coastline, valued at over $10 billion annually (Bennett *et al*. 2016). Perhaps even more profoundly, a healthy and vibrant coastal marine environment is a core value for Australians. Our coastal ecosystems are a social good that can provide services and values in perpetuity (de Groot *et al*. 2013) and are places of belonging and custodianship for traditional owners in a way that does not easily translate to monetary value.

These coastal ecosystems and the values and assets they represent have been significantly diminished by climate change, pollution, coastal development, agriculture and urbanisation, and other anthropogenic stressors (Clark *et al*. 2021; Trebilco *et al*. 2021). Coral cover on the Great Barrier Reef decreased by an estimated 50 per cent in two years from mass bleaching events driven by ocean warming and marine heatwaves (Hughes *et al*. 2017, 2019a). We have lost tens to hundreds of kilometres of kelp forests from temperate Australian coasts in recent years (Wernberg *et al*. 2019b). Comparable declines have also been documented for other major 'habitat-forming' organisms, such as oyster reefs, mangrove forests and seagrasses (Gillies *et al*. 2018; Beck *et al*. 2011; Larkum *et al*. 2018). These organisms are the foundations of our coastal systems, but it is estimated that nearly half have already been impacted by climate change (Babcock *et al*. 2019). The challenges faced by these ecosystems will only grow in the future, given predicted increases in ocean warming and acidification, coastal population growth and development, and other stressors (IPCC 2019, 2022; Clark *et al*. 2021; Trebilco *et al*. 2021).

To maintain the value of our coasts to the blue economy and to the Australian people, we need to do science that informs effective management and provides active solutions to build resilience and sustain or restore value. This science needs to be done on a large scale. Australia's coastal ecosystems occur at scales ranging from regional to national, along thousands of kilometres of coastline. The key drivers that affect them occur at national (e.g. coastal development) and global (e.g. climate change) scales. For Australia to understand and address the challenges these systems face, and to mitigate and adapt to these changes, we need a nationally integrated approach to marine science. Multiple policy documents and government initiatives support just such a nationally coordinated approach (Australian Academy of Science 2022).

NMSP Recommendation 3 is built around an experimental approach to these challenges. Experimentation, in which the researcher or manager perturbs or manipulates the system and then measures its response, is a fundamental component of science-informed management for at least three reasons:

- Experimentation is the primary tool for determining causality, thus elucidating the mechanisms and the processes which drive change in a system (Underwood 1997).
- Experiments are the key means for testing, modelling and predicting the consequences of future conditions (Benedetti-Cecchi *et al*. 2018).
- Experimental insights into mechanisms and dynamics under future conditions inform adaptive management, including strategies for active rehabilitation and restoration of ecosystems (Underwood 1995; Hobbs *et al*. 2011).

An integrated experimental approach is both itself a key component of the overall approach to marine science proposed by the NMSP and a critical link between Recommendations 2 and 4, which focus on the need for national approaches to long-term monitoring and modelling, respectively. Without such integrated and coordinated experimentation to test the consequences of future ocean conditions, management plans for Australia's coastal ecosystems will be navigating uncharted territory.

Figure 1 outlines a conceptual framework for a nationally integrated approach to experimentation for Australia's coastal ecosystems. We focus on the use of experiments to characterise the *drivers of change* in these systems, to understand the scope and limits of ecosystem *resilience*, and to develop *solutions* that help sustain or remediate these ecosystems:

- ***Drivers of change*** include ocean warming and acidification (including marine heat waves), natural disasters (e.g. floods, bushfires), coastal development, extractive industries, phenomena intrinsic to the system (such as species interactions), and other social, economic and environmental factors that result in pressures that affect these systems.
- ***Resilience*** includes processes that facilitate tolerance or resistance to pressures, recovery from impacts and increased adaptive capacity.
- ***Solutions*** are interventions that influence drivers, alleviate pressures or promote resilience, such that ecosystem services, uses and values can be sustained or improved. Solutions range from global mitigation of stressors (e.g. reduction of carbon emissions), to traditional environmental management (e.g. zoning and marine protected areas), to targeted restoration and rehabilitation of coastal ecosystems (an increasing focus for scientists and managers), to adaptive management more broadly. These different approaches were highlighted in the recent report from the Intergovernmental Panel on Climate Change, where both reactive and preventive measures were proposed as highly viable response options for strengthening and enhancing ecosystems (IPCC 2019).

National approaches for experiments based on this framework will allow us to manage and optimise the value of our marine estate, now and into the future. We develop this rationale for Australia's coastal ecosystems generally, and specifically exemplify the approach for several critical coastal habitats – coral reefs, kelp forests and other marine macrophytes, oyster reefs and estuarine sediments.

We use these systems to illustrate how a nationally integrated experimental approach can inform effective resilience-based management and policy into the future. We also show that a considerable amount of underlying infrastructure and capacity for supporting a national experimental approach is already present. This presents opportunities for synergy and cost efficiency associated with coordinating these resources.

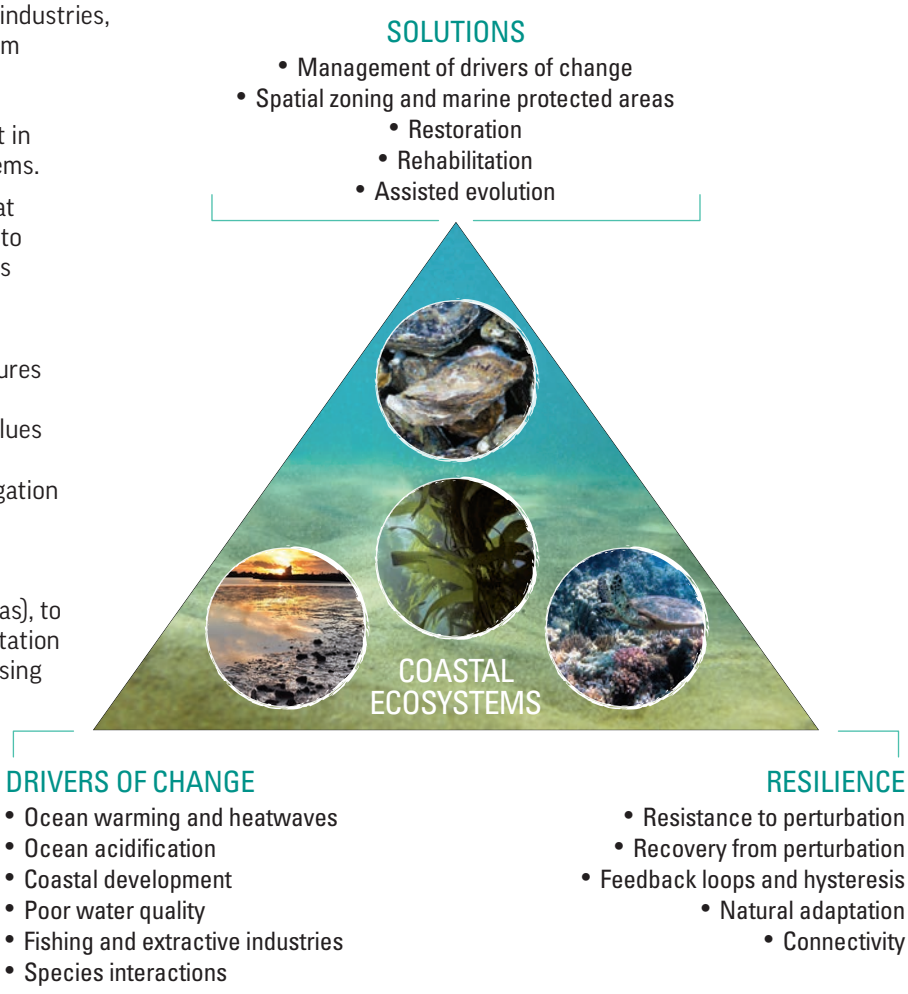



**Figure 1**: Conceptual framework underpinning a nationally integrated approach to experimentation to inform effective management strategies for enhancing Australia's coastal ecosystems.

# Australia's coastal ecosystems: **valuable and vulnerable** |

Our framework for the implementation of NMSP Recommendation 3 focuses on coastal ecosystems. The reasons for this focus are threefold:

1. Our coastal ecosystems are enormously valuable and indeed iconic to Australia as a nation.
2. Our coasts are at the confluence of all the factors – climate change, pollution, development and others – which impact our marine environments.
3. Coastal systems are cost-efficient and logistically feasible options for an experimental approach towards understanding the dynamics, resilience, management and rehabilitation of marine ecosystems.

## Value

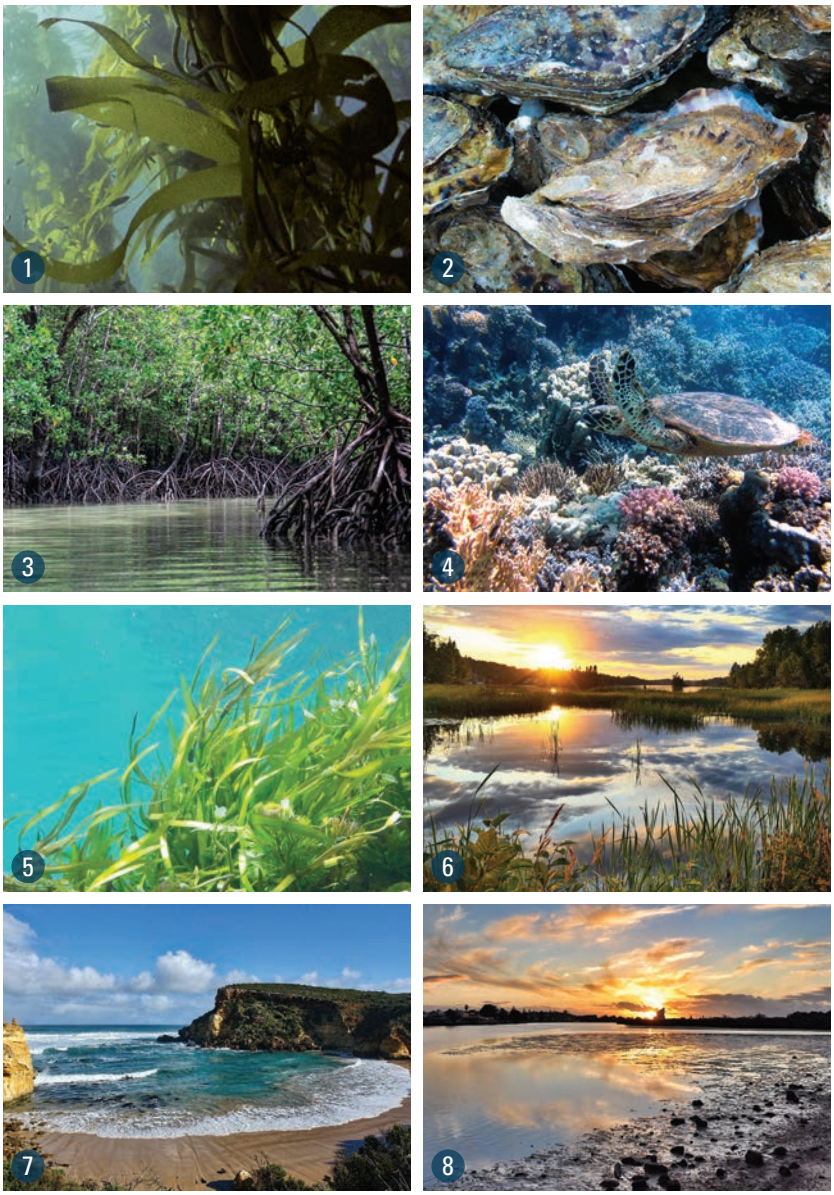
Australia's coastal ecosystems, such as those shown Figure 2, have immense social, economic and environmental value and include some of the most iconic marine habitats in the world. Communities adjacent to our coasts or estuaries comprise over 85 per cent of Australia's population (ABS 2016) and our coasts and nearshore waters are used intensively by Australians for building residences and commercial infrastructure, fishing, tourism and recreational activities, and industries such as aquaculture or agriculture (Bennett *et al*. 2016; Clark *et al*. 2021; Trebilco *et al*. 2021; GBRMPA 2019).

Our beaches are renowned globally and are a physical representation of the deeply held view of Australians that our country is clean and healthy. Coastal communities consistently rank 'clean and healthy water and ecosystems for coastal and estuarine environments' as a high-priority community value (Stoeckl *et al*. 2014). Our marine and estuarine environment is front and centre to Australia's presentation to the world; the Sydney Opera House is one of the most famous buildings in the world due in no small part to its location on Sydney Harbour. The health and wellbeing of coastal and estuarine ecosystems are intrinsic to the core values of our 'sunburnt country' and our coasts are places of belonging and custodianship for traditional owners. Our coastal ecosystems are a social good that can provide services and values in perpetuity (de Groot *et al*. 2013).

The economic value of coastal ecosystems is enormous and almost certainly underestimated. These systems, when healthy and functioning, provide ecosystem services – tourism, recreation, fishing, water filtration, carbon sequestration, and sites for industries such as aquaculture – which comprise a substantial component of Australia's $75 billion blue economy.

The annual value from ecosystem services provided by the Great Barrier Reef is estimated at $6.4 billion (Deloitte 2017). Estimates of the value of the kelp forest–dominated Great Southern Reef are even higher at $10 billion annually, even when only a few ecosystem services such as tourism and fishing are included (Bennett *et al*. 2016). These valuations include support to Australia's most valuable wild-caught fisheries, rock lobsters and abalone, which by themselves contribute more than $850 million to our economy (https://www.agriculture.gov.au/abares/research-topics/fisheries/fisheries-economics/fisheries-forecasts). In the gulfs of South Australia alone, seagrasses are estimated to contribute $114 million per year to the fisheries economy (Blandon and zu Ermgassen 2014). Marine macrophyte systems (mangroves, seagrasses, saltmarsh, seaweed forests) also represent a globally significant component of carbon sequestration, or Blue Carbon (Serrano *et al*. 2019, Macreadie *et al*. 2019, Filbee-Dexter and Wernberg 2020). Ecosystem accounting has shown that restoring lost tidal marshes, mangroves and seagrasses in two metropolitan areas in south-east Australia (Port Phillip Bay and Western Port Bay) would result in an investment–benefit ratio of 10.5, with an investment of A$8.5 million yielding ecosystem services of A$100 million (Carnell *et al*. 2022).

Moreover, these (substantial) monetary values are only a snapshot and arguably an underestimate of the true value of these systems. Economic valuations of Australia's ecosystems generally apply short time horizons, underestimating their true value several-fold. In a recent study where longer time frames were used, using only a subset of the ecosystem services provided by coral reefs, the present value of the Great Barrier Reef was estimated at $56 billion (Deloitte 2017). The net present value over 20 years of Sydney Harbour, a single estuary, was estimated at $40 billion by Hoisington (2015).



> *The economic value of coastal ecosystems is enormous and almost certainly underestimated.*

**Figure 2**: Common coastal marine and estuarine ecosystems of Australia. Eighty-five per cent of Australians live near these habitats, and they contain enormous economic, social and environmental value to the country. In many instances they are dominated by one or a few taxa of foundational, habitat forming organisms:

1. Kelp forests
2. Oyster reefs
3. Mangrove forests
4. Coral reefs
5. Seagrass meadows
6. Wetlands and saltmarshes
7. Beaches
8. Estuarine sediments

The environmental value of these systems matches their socio-economic worth. The Great Southern Reef, largely dominated by a single species of habitat-forming kelp (*Ecklonia radiata*), stretches along 8000 kilometres of coast from northern New South Wales to the middle of Western Australia (Bennett *et al*. 2016; Wernberg *et al*. 2019a), and is the longest contiguous coastal habitat on Earth. It is home to the greatest regional diversity of seaweeds on the planet (Phillips 2001), as well as being a hotspot for many other types of biodiversity (Poore and O'Hara 2007; Bennett *et al*. 2016). Our coasts are also host to some of the largest and most diverse seagrass meadows in the world (Larkum *et al*. 2018), including many key endemic species, and provide habitat for iconic species such as dugongs. The Great Barrier Reef is the world's largest coral reef system, a natural World Heritage Area, and home to over 12,000 macroscopic marine species (GBRMPA 2012). Ningaloo Reef in Western Australia, also a World Heritage Area, is one of the longest fringing reef systems in the world. Our extensive and diverse estuarine systems provide critical nurseries for fishes and other biota and play a key role in excess nitrogen removal (Eyre and McKee 2002; Eyre *et al*. 2016). Even one of our most urbanised estuaries, Sydney Harbour, has a greater diversity of fishes than the entire United Kingdom (Johnston *et al*. 2015).

## Vulnerability

The second reason for focusing Recommendation 3 on our coasts is that these systems, and the value we derive from them, are some of the most threatened of our marine estate (Clark *et al*. 2021). In their global analyses of cumulative stressors on marine systems, Halpern *et al*. (2008, 2015) showed that coastal marine ecosystems are the most impacted. This is because all the drivers of change that affect natural environments coalesce on our coasts. These include climate change, coastal development and agriculture, extractive industries, multiple-use conflicts, and the suite of impacts associated with population growth and urban sprawl of our coastal cities. These phenomena are affecting our coastal systems now (Clark *et al*. 2021), and the trajectories for climate change, coastal development and other drivers all suggest increasing impacts from the cumulative effects of local and global pressures (Brown *et al*. 2013; Anthony 2016; Harley *et al*. 2006; IPCC 2019).

We have already lost substantial value from our coastal ecosystems. Following a long period of decline since the 1980s (De'ath *et al*. 2012; IPCC 2014), coral cover on the Great Barrier Reef has been significantly affected by four mass bleaching events since 2016. This includes the first ever bleaching event resulting from a marine heatwave during a La Niña period, in 2022, the impacts of which are still being assessed (AIMS 2022; Hughes *et al*. 2017, 2019a). Oyster beds in estuaries throughout Australia have decreased by an estimated 95 per cent from historical levels, most likely due to overharvesting (Gillies *et al*. 2018). This represents an enormous direct economic loss, as well as the loss of key ecosystem services such as water filtration or sediment denitrification (Eyre and McKee 2002; Eyre *et al*. 2016), which kept our estuarine waters clean. The lowering of water pH resulting from acid sulfate soils and land clearing threatens oyster farming (Dove and Sammut 2007; Sammut *et al*. 1995; Fitzer *et al*. 2018), and ocean acidification more generally is causing upwelled water along the east coast of Australia to cross a number of geochemical and biological thresholds, which will impact on coastal ecosystems (Schulz *et al*. 2019).

In recent years, we have measured the loss of tens to hundreds of kilometres of kelp forests from New South Wales to Western Australia, due to the direct and indirect effects of changing water quality, fishing, urbanisation and climate change (Connell *et al*. 2008; Coleman *et al*. 2008; Johnson *et al*. 2011; Smale and Wernberg 2013; Vergés *et al*. 2016; Wernberg *et al*. 2016; Carnell and Keough 2019). The magnificent giant kelp forests of Tasmania are now nearly gone, and in 2012 they were listed under the *Environment Protection and Biodiversity Conservation Act 1999* as a threatened ecological community – the first such listing for a marine community in Australia. Seagrasses have declined by over 90 per cent in Sydney Harbour and Cockburn Sound, Western Australia, and are declining at a rate of around 7 per cent per year globally (Waycott *et al*. 2009). Thirty-six per cent of Shark Bay's seagrasses were lost to a single heatwave in 2011 (Arias-Ortiz *et al*. 2018). Extensive die-offs of mangroves, linked to extreme weather events, have occurred in the Gulf of Carpenteria (Duke *et al*. 2017). Environmental conditions in iconic coastal lagoons like the Coorong in South Australia are declining (Brookes *et al*. 2018), and flooding reduces the carbon storage capacity of intertidal sediments (Oakes and Eyre 2014) and potentially causes loss of shellfish reefs and other habitats (Benthotage *et al*. 2022).

Predicted future trajectories for most of the main drivers of change and their impacts add to the urgency of our need to understand the dynamics of these systems and to enhance their resilience and rehabilitation. Models of ocean warming predict both increased water temperature overall and extreme temperature events (marine heatwaves) over the coming decades (IPCC 2014, 2022; Frölicher *et al*. 2018; Oliver *et al*. 2018, 2019). Australia's population is projected to grow to over 37 million by 2050, with most of this growth along the coasts. The impacts and consequences of these drivers now being felt by coastal ecosystems will only increase into the future.

## Accessibility

The third reason that Recommendation 3 of the NMSP focuses on coastal systems is that they are logistically suitable for experimental approaches. They are generally accessible, shallow-water habitats, for which the foundational organisms are large and usually immobile (e.g. corals, kelp, oysters, seagrasses or mangroves) and thus amenable to the kinds of experimental approaches described here. This contrasts with oceanic systems, where experimentation, particularly *in situ*, is more challenging due to the open nature of these systems. There is also a long and well-established history of experimentation on benthic (bottom-dwelling) organisms such as kelp, corals, seagrasses and oysters in marine environmental science (e.g. Dayton 1971; Heck and Thoman 1981; Sale 1984; Dame *et al*. 1984; Kennelly 1987; Underwood and Barrett 1990; Ferguson *et al*. 2020). Indeed, these studies have had a profound influence more generally on the development of ecology as a science (Connell and Gillanders 2007; Bertness *et al*. 2014).

# **A national experimental approach** to enhancing the value of our coastal marine ecosystems |

The challenges faced by Australia's coastal systems and the value they contain are significant, but there are positive and proactive approaches to solving them. One critical component of that path should be coordinated national experimental studies.

In the previous sections, we have highlighted both the value of our coastal ecosystems to Australia's economy and the wellbeing of Australians, and the fact that they are experiencing significant change. To understand, in a mechanistic fashion, the drivers of these changes and to develop solutions to mitigate their impacts, we need an integrated experimental approach.

## Why experiments?

Like science more broadly, marine science is built on three methodological pillars: observations, experiments and modelling. Within this trinity, experimentation – in which the researcher or manager perturbs or manipulates the system – plays a crucial role as the primary tool for:

- determining causality
- elucidating mechanisms
- testing the impact of both current and future conditions and the viability of solutions (e.g. Underwood 1997).

This fundamental role of experiments in science can be seen through a medical analogy. Epidemiological studies (observations, modelling) reveal patterns, associations and risk factors. Clinical trials (experiments) determine whether a specific factor or drug is a therapeutic agent with a demonstrable effect and are the basis for whether a new drug is approved. Experiments are the clinical trials of marine science, and without them our ability to understand, manage or remediate our marine environment is severely constrained.

As in medicine, experiments in marine systems involve perturbations or manipulations of the system in a planned and controlled manner, followed by subsequent measurement of the response of the system to those perturbations. Experiments may be manipulations of single drivers; for example, how do oysters respond when the acidity of their surrounding waters is increased? Alternatively, they may perturb multiple factors simultaneously; for example, how do kelp forests respond to both removal of grazing sea urchins and the addition of nutrients from stormwater runoff? Experiments can be done in the laboratory or in the field (*in situ*) (Figure 3).

**Figure 3**: Examples of (left) a field (or *in situ*) experiment, testing approaches to kelp restoration, and (right) a laboratory experiment, testing the effects of ocean warming on corals. Image credits: (left) John Turnbull, www.marineexplorer.org; (right) Australian Institute of Marine Science.

Experimental manipulations enable a mechanistic understanding of the dynamics and resilience of ecosystems, provide fundamental insights into these systems at both small and large scales, and enable tests of specific management or rehabilitation interventions. They increase the resolution of predictive models and the quality of environmental decision-making, both now and into the future, and allow us to understand the three key features of coastal ecosystems introduced above (Figure 1):

1. What are the *drivers of change*, and by what mechanisms do they act?
2. What is the *resilience* of ecosystems to those impacts, including both their resistance to threats and their recovery following an impact?
3. What are the *solutions* whereby we can minimise impact, enhance resilience or rehabilitate degraded systems?

In the context of NMSP Recommendation 3, the impact of all the drivers of change commonly associated with climate change and development – ocean warming and acidification, increased pollution, extractive industries, coastal development, habitat degradation and many others – can be directly tested via experimentation to understand the processes shaping these ecosystems. Experimentation can test both the effects of one-off (i.e. acute) events, such as marine heatwaves, or more persistent (i.e. chronic) effects, such as estuarine eutrophication, through what are known respectively as 'pulse' versus 'press' experiments (Bender *et al*. 1984). The drivers tested may be physical or chemical (e.g. temperature, pollution) or biological (e.g. predation), or a combination of the two. They may be natural processes (e.g. changing salinities along an estuarine gradient), anthropogenic drivers, such as ocean warming or the influence of heavy metal pollution, or a combination of these. Marine ecosystems are now subject to a multiplicity of interacting drivers and uses, and this further highlights the role of experiments in understanding complex ecosystem dynamics in the Anthropocene. Carefully designed experiments allow for the effects of these multiple, often correlated, drivers to be disentangled in a way that cannot easily be done by monitoring alone (Boyd *et al*. 2018).

A second critical role for a national experimental approach is to understand the resilience of marine ecosystems to drivers of change. Resilience of marine ecosystems encompasses both their resistance to impact and their ability to recover to the previous condition following an impact (Holling 1973). Resilience is increasingly a focus for both managers and scientists and is precisely what appropriately designed experiments are able to detect.

Well-designed experiments can, for example, identify thresholds or tipping points for marine systems, where the resilience of the system breaks down. This is crucial information for informing management strategies (Folke *et al*. 2004), and identifying thresholds of collapse has now become a major feature of ecosystem assessments (e.g. IUCN Red List; Bland *et al*. 2017). The response of ecosystems to environmental change is usually not linear, both due to the intrinsic dynamics of the organisms themselves and because of the multiplicity of the factors to which they are exposed. For example, experiments in Australia and globally have shown that established kelp forests are resistant to grazing by relatively high densities of sea urchins. But when urchin densities exceed a threshold, the kelp forests rapidly decline and do not recover even when urchin densities are reduced to levels well below those present prior to the decline (Andrew and Underwood 1993; Flukes *et al*. 2012). Such 'regime (or phase) shifts' (e.g. Folke *et al*. 1998; Scheffer *et al*. 2001; Mumby *et al*. 2007; Anthony *et al*. 2015; Filbee-Dexter and Scheibling 2014) can result in severe consequences for Australia's coastal ecosystems. Well-designed experiments can help inform interventions that avoid regime shifts that would otherwise require expensive repair of the degraded systems.

Critically, the resilience of systems to the combined effects of multiple impacts is often not easily explained by observing only the individual effects of those factors (Crain *et al*. 2008; Przeslawski *et al*. 2015; Boyd *et al*. 2018). Here again, the ability of experiments to test different combinations and levels of multiple factors is critical for understanding not just the drivers of change, but also the resilience of systems to multiple interacting drivers. New guidelines for experimental approaches to understanding the impacts of multiple drivers are emerging, for example in the area of climate change (Wake 2019; Boyd *et al*. 2018.).

The third role for experiments in our coastal marine estate is for direct tests of the efficacy and impact of potential solutions for arresting, remediating or preventing the decline of coastal habitats. For environmental management strategies and policies to be effective in sustaining the services and values of Australia's coastal ecosystems, management and policy decisions need to be scientifically informed. Decision-making needs to navigate the uncertainty associated with future ecosystem states and benefits and do this both in the presence and absence of management decisions and interventions. Current predictions of ecosystem trajectories under environmental change, and associated management decisions, are strongly constrained by high uncertainty from multiple sources, most critically from biological and ecological processes and their interactions (Runge *et al*. 2011; Game *et al*. 2014; Condie *et al*. 2018; Holbrook *et al*. 2019; Ainsworth *et al*. 2020; Scanes *et al*. 2020).

A nationally integrated and coordinated experimental strategy could help reduce or resolve such uncertainty, increasing the resolution of predictive models and the quality of environmental decision-making.

The utility and logic of experimentation apply broadly to adaptive management solutions for marine coastal ecosystems, but they are particularly applicable for solutions that include ecosystem restoration and rehabilitation. Active restoration and rehabilitation of coastal habitats is increasing globally and in Australia (Box 1; McLeod *et al*. 2018), and it is imperative that such interventions be tested experimentally for their efficacy (e.g. Campbell *et al*. 2014; Fredriksen *et al*. 2020), underlying causality and cost effectiveness before being implemented at larger scales.

The results of these experiments can then be used to directly inform emerging decision-making frameworks for large-scale restoration (e.g. Layton *et al*. 2020), including guiding the prioritisation of efforts and resources into interventions. For example, under current climate scenarios (Rogelj *et al*. 2016), the resilience of large parts of Australia's coastal ecosystems could be overwhelmed by heatwaves or warming (Martínez *et al*. 2018; Lough *et al*. 2018; Smale *et al*. 2019; Davis *et al*. 2021). Understanding which areas, which species and which ecosystem functions can be sustained using particular interventions is a critical and urgent task for a coordinated experimental effort.

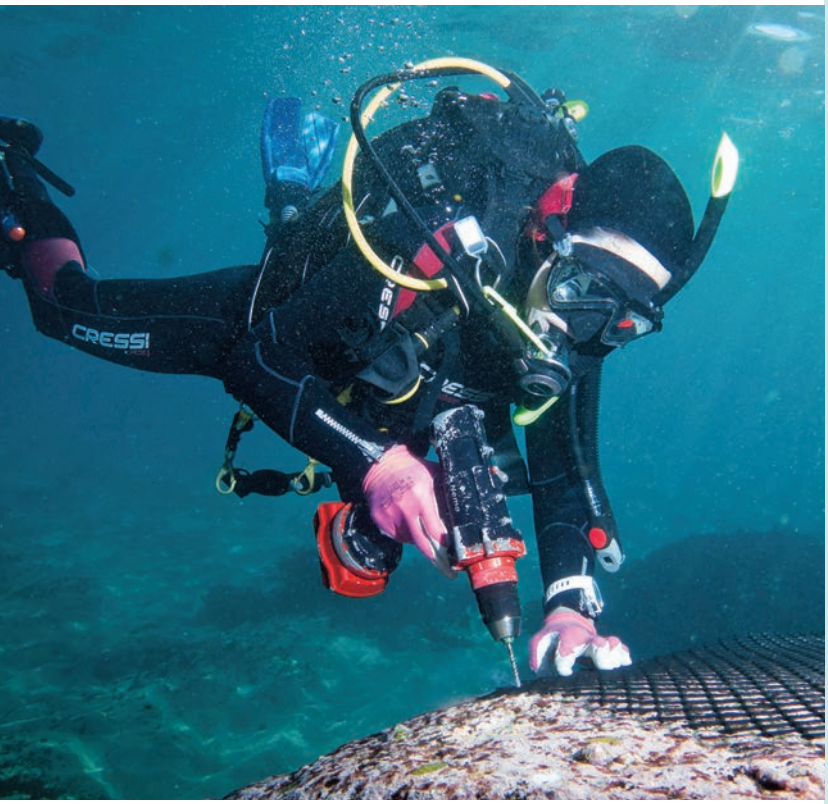



Image: John Turnbull, www.marineexplorer.org

## A solution-focused role for experiments: **restoration and rehabilitation of coastal marine ecosystems**

**The period from 2021 to 2030 is the UN Decade on Ecosystem Restoration. There are now efforts across Australia to restore many of the major habitat-forming organisms of coastal zones, including seagrasses, kelps, corals, oysters and mangroves (McLeod *et al*. 2018). Restoration or rehabilitation of habitats is, by definition, a manipulation, and thus well suited to an experimental approach (Underwood 1996).**

**Most current marine restoration efforts in Australia are small scale, with experiments focused on understanding the efficacy of restoration techniques, the consequences of re-establishment to the broader biodiversity and functioning of the system, and the response of restored species to specific drivers such as climate change or coastal development. However, for some systems, these experiments are beginning to lead to larger-scale efforts. For example, the Reef Restoration and Adaptation Program (RRAP), one of the most substantial investments in marine science made in Australia in the last decade, is substantially built around experiments aimed at developing methods for large-scale restoration or rehabilitation of coral reefs.**

**Operation Crayweed (www.operationcrayweed.com) in New South Wales, which began with small-scale experimentation (Campbell *et al*. 2014), has become one of Australia's most successful kelp restoration projects (Layton *et al*. 2020), with restoration of hectares of the habitat-forming seaweed *Phyllospora comosa* along the coast of Sydney underway. Restoration of oyster reefs is growing worldwide, and in South Australia has reached the hectare scale (https://theconversation.com/huge-restored-reef-aims-to-bring-south-australias-oysters-back-from-the-brink-77405?sa=pg1&sq=oys).**

**Similarly, following experimental testing of methodologies (e.g. https://www.seagrassresearch.net/restoration), seagrasses are now being restored at scale in Cockburn Sound, Western Australia, and the benefits of restoring ('repairing') saltmarsh has been demonstrated at sites across Australia (Creighton *et al*. 2019). Experimental testing of methods for the enhancement of coastal habitats can also extend to the marine built environment via eco-engineering of structures such as seawalls, jetties and breakwaters (Morris *et al*. 2019; Bishop *et al*. 2022).**

For all three components – drivers of change, resilience and solutions – experimental approaches allow us to test both the effects of current conditions and also, critically, *the effect of new or future pressures or conditions that lie outside current environmental envelopes*. Monitoring (observations) tells us what has happened, and modelling can make predictions about what will happen, but experiments are required to directly test the consequences of future conditions and to inform and refine predictive models (Benedetti-Cecchi *et al*. 2018). The future impacts of climate change are an ideal example. Conditions expected in future oceans under climate change represent uncharted territory for the biology and ecology of marine ecosystems. To understand how species and ecosystems will respond to climate change requires experimental manipulation of conditions that simulate likely future conditions. The outcomes of these experiments can then be used to calibrate predictive models, which can project the ecological, social and economic consequences of different climate change scenarios, guiding the choice and effectiveness of different management strategies.

## Types of experiments

Experiments on marine organisms and ecosystems can be done in both the laboratory and the field and at a variety of scales. Laboratory experiments have the advantage of being able to manipulate variables that are challenging to manipulate in the natural world (e.g. temperature, ocean acidification) and allow for close control of potentially confounding factors. They are enormously useful in allowing closer insight into specific physiological or molecular mechanisms, for example of thermal tolerance, and for testing future environmental conditions (e.g. Wernberg *et al*. 2012; Britton *et al*. 2020). They are arguably best suited for studies of individual organisms or species, or for model systems which are simplified representations of natural communities and interactions (e.g. 'mesocosm' studies; Dworjanyn and Byrne 2018; Colossi Brustolin *et al*. 2019).

Laboratory experiments are constrained by the fact that they are not done in 'the real world', where the complexity and interaction of multiple factors influences outcomes. Thus, where possible, the dynamics and resilience of marine ecosystems, their response to specific drivers, and the management of impacts should be tested in the field. However, it is also important to note that the coastal environment can be a dynamic and rigorous environment. In some instances, the manipulations required by an experimental approach are not logistically feasible *in situ*, and laboratory experiments or observational approaches may then be more appropriate.

Many coastal experiments include both laboratory and field components, thereby allowing for more ecologically realistic interpretation of results (e.g. Przeslawski 2005). This highlights a central point of the NMSP, namely that a multiplicity of approaches will be required to understand and manage our marine ecosystems.

A second key consideration for experimental approaches is the spatial or temporal scale at which they are done (Dayton and Tegner 1984; Underwood 2000; Denny and Benedetti-Cecchi 2012). Ideally, experiments should be done at the scale relevant to the system, which includes both the scale at which the driver operates and the scale at which ecosystems respond. While examples exist of large-scale experiments in marine environments (e.g. Smetacek *et al*. 2012), most field experiments are done at relatively small spatial scales of metres or tens of metres, and it is sometimes for this reason that the approach is often not properly integrated into management thinking (Dayton and Tegner 1984).

There are, however, well-established solutions to this challenge of scale. First, small-scale experiments can be replicated in many places or times on a regional, national or even global basis (Coleman *et al*. 2006; Wernberg *et al*. 2010; Borer *et al*. 2014; Duffy *et al*. 2015). Properly designed, such a program can provide fundamental insights and reveal differences or similarities in the dynamics of particular coastal habitats on a national scale, thereby informing appropriate management practices implemented at large scales. Second, where appropriate resources are available, experiments can be done at large scales (Smetacek *et al*. 2012). The main constraint on either approach, and the reason why large-scale experiments are relatively rare in marine systems, is that they usually lack the coordinated governance and resources necessary to implement them (Threlfall *et al*. 2021). *A key goal of this report is to highlight the need for integrated governance and resources for an effective large-scale experimental approach.*

Finally, although they are perhaps not typically considered as such, marine spatial planning instruments and programs such as the establishment of marine reserves, when properly designed, are in fact examples of large-scale experiments (e.g. Kelaher *et al*. 2014; Coleman *et al*. 2015). Rather than being experiments to test ecological hypotheses *per se*, they test management hypotheses, often in an adaptive management framework (e.g. McCook *et al*. 2010; Hoskin *et al*. 2011). Ideally, a national experimental approach would combine ecological experiments with adaptive management to ensure science and management strategies for Australia's coastal ecosystems are aligned and synergistic at large scales.

# **Why a coordinated national approach** for Australia? |

The scope and scale of experimentation proposed here under the framework of NMSP Recommendation 3 is a novel and much needed addition to the toolkit of any national approach to the science of managing our marine environment.

This is true for both Australia and internationally. While Australian scientists have participated in experimental approaches at national or even global scales, such studies are rare and are usually motivated by individual research programs rather than being driven by national coordinated initiatives (e.g. Duffy *et al*. 2015; Steinberg *et al*. 2016), and thus do not necessarily align with national goals and priorities.

Most national programs for understanding and managing marine ecosystems focus on observational or modelling approaches. Australia has an outstanding example of a national observing system in the Integrated Marine Observing System, and approaches to a national framework for oceanographic modelling are being considered. However, a national coordinated approach to experiments is lacking.

One reason for this is that experimentation has often been perceived to be more of a science tool than a decision-support tool for environmental management and policy. However, active adaptive management (McCook *et al*. 2010; Williams *et al*. 2011) by its very nature includes experimentation to narrow in on an optimal management strategy. Ecological and biological experimentation employed in a national strategic context could serve a similar purpose: to provide critical information that currently limits our capacity to sustain coastal ecosystems into the future. Given the value of the systems at stake, the value of information from a nationally integrated and coordinated experimental approach would be substantial indeed.

The ecological and geographical scale of the focal systems (i.e. kelp forests, coral reefs, estuaries and others) and the increasing scale at which drivers such as climate change operate dictate the need for a large-scale, and ideally national, approach to their management. Kelp forests occur along 8000 kilometres of southern Australia's coast, and coral reefs occur along thousands of kilometres of our northern coastlines. We know that there is often genetic exchange – connectivity – among key organisms over much of the length of these systems (Banks *et al*. 2007; Hughes *et al*. 2019b; Coleman *et al*. 2011; Woodings *et al*. 2018). Thus, they fundamentally function as single interconnected systems.

The same is often true for estuarine systems (Baker *et al*. 2019), even though many estuaries are physically separated by stretches of open coast (Coleman *et al*. 2019). Estuarine habitats such as seagrass meadows and oyster reefs can have similar species and a similar structure across thousands of kilometres of coastline in Australia.

In an analogous fashion, the critical processes – the drivers of change – affecting our coasts also occur at regional, national or even global scales. To understand how species and ecosystems will respond to these drivers will require experimental manipulation across matching scales. National-scale experimentation to inform management and policy can then be integrated appropriately with national-scale modelling and monitoring.

Australia is well placed to lead the world in establishing the first national framework for experimental studies of marine ecosystems for a number of reasons:

1. In the 1980s and 90s we played a critical role in helping to evolve marine science from a largely observational discipline to an experimental one (Fairweather and Quinn 2007). Thus experimental marine science is in the DNA of Australian marine scientists.
2. We have in the Integrated Marine Observing System a well-established template for national approaches to marine science and a marine science community that is coherent and integrated.
3. Australia is unique in having very long, geographically distinct east and west coastlines, with both tropical and temperate communities, which function as 'replicates' at the scale of thousands of kilometres.
4. Australian environmental management agencies and government departments are increasingly adopting active adaptive management, which incorporates an 'experimental' approach to management. Multi-scale experimentation, formally integrated into a national science program, flows naturally from such an adaptive management approach.
5. Australia has the capacity and expertise for such an approach, and unusually for most countries, this capacity spans a large range of climatic conditions in both temperate and tropical regions.

An audit of coastal infrastructure and programs shows that Australia has extensive infrastructure that could support a national experimental approach on the dynamics, resilience and rehabilitation of coastal ecosystems (Table 1). Running seawater or substantial recirculating aquaria systems suitable for laboratory experiments done under near natural (or future) conditions are distributed widely across the country, occurring in many of the major coastal universities and government agencies responsible for marine activities. The facilities at many of these institutions allow for controlled manipulation of environmental conditions, thus allowing tests of future environmental scenarios.

Australian capacity for nearshore field experimentation is also extensive, with many of these organisations and agencies also having nearshore research vessels, scuba diving activity and associated field programs (Table 1), though some of these core enabling activities (e.g. scuba diving) are increasingly challenged by onerous regulatory frameworks.

The audit of these facilities also showed that some of the experimental approaches envisioned in this report are underway at some of these facilities, although at relatively small scales and not in an integrated fashion. Strategic investments in these facilities nationally would see us well placed to take the next step towards a nationally integrated marine experimental capacity. Some integration of dispersed coastal facilities has been done elsewhere (e.g. the European Marine Biological Infrastructure Cluster, or EMBRIC; http://www.embric.eu) and could provide a template for facility networks and integration.

> *Many coastal experiments include both laboratory and field components, thereby allowing for more ecologically realistic interpretation of results.*

Image: Joanne Oakes

# **Exemplar** systems |

The sections above provide a general rationale and approach for NMSP Recommendation 3, a national experimental approach for understanding dynamics, processes and solutions in coastal ecosystems in the context of climate change and coastal development.

We believe that the most efficient way to implement such an approach is to focus on dedicated programs for key coastal ecosystems such as those in Figure 2. In principle, the approach could and should be rolled out for any of these ecosystems, but we have selected four different systems as exemplars to more explicitly illustrate the approach suggested in this report: coral reefs (Appendix A), marine macrophytes (e.g. kelp forests) (Appendix B), oyster reefs (Appendix C) and estuarine sediments (Appendix D). These four systems are (or were, historically, in the case of oysters) critical to the functioning of large areas of the Australian coastal marine environment, and they are foundational components of ecosystems along which 85 per cent of Australians live. They exemplify the social, economic and environmental values of coastal marine habitats.

Appendixes A to D show that regional or national-scale programs of experimental science for coastal ecosystems are very much possible. For one of these exemplar systems, coral reefs of the Great Barrier Reef, the need for a nationally integrated approach is being met and the approach is already being implemented as a core component of the RRAP, based on an initial investment of approximately $100 million. The *Reef 2050 Long-term Sustainability Plan* aimed to improve the Great Barrier Reef decade by decade (Commonwealth of Australia 2015). However, several recent mass-bleaching events (2016, 2017, 2020 and 2022) have made it clear that new management strategies will be needed for the plan to deliver on its promise (together with more global solutions such as emission reductions). Adaptation solutions are now coming from the RRAP, which is built around strategic experimentation to inform proactive decision-making around the development and potential deployment of new, effective and safe restoration interventions (https://www.gbrrestoration.org).

The RRAP provides the template for how we could roll out similar programs for other coastal ecosystems. It has also been a catalyst for the National Collaborative Research Infrastructure Strategy to invest in a new national facility for experimental research. Individual smaller-scale programs on both experimental kelp ecology and kelp restoration are underway in New South Wales, Tasmania, Victoria, South Australia and Western Australia, and a workflow for restoration at a national scale has recently been developed (Layton *et al*. 2020). Similarly, oyster reef restoration and supporting experimental research is occurring across Australia, but it needs integration, coordination and expansion (Gillies *et al*. 2018; also see https://www.shellfishrestoration.org.au). This has been scoped through a National Environmental Science Programme Marine and Coastal Hub project (McDougall *et al*. 2022), which yielded the guidelines for a universal approach to marine and coastal restoration monitoring in Australia (Cole *et al*. 2022).

Analogous programs for other systems are also possible. For example, seagrass researchers are connected through the national Seagrass Restoration Network (https://seagrassrestorationnetwork.com), facilitating the development of a national experimental seagrass program.

However, aside from the RRAP, there are no current experimental programs for coastal ecosystems explicitly coordinated at the regional scale or above *and* supported with resources at the level necessary for national implementation. A high-level approach similar to that of the RRAP, based on strategic and nationally integrated experimentation is needed for coastal ecosystems other than coral reefs if we are to keep these systems resilient, and in some cases even existent, under future pressures from climate change and development.

# Conclusion and **recommendations** |

## Australia needs a national experimental approach for enhancing the value of our coastal ecosystems.

The purpose of the integrated, strategic experimental approach proposed here is to produce critical information needed to better manage Australia's coastal ecosystems, including their restoration and rehabilitation. As we move further into uncharted territory imposed by rapid environmental change and increasing levels of urbanisation and development, the biological and ecological understanding derived from experiments will provide critical foresight to inform and underpin environmental management and policy. Without a plan for strategic experimentation, environmental management and decision-making will rely on monitoring data, which is primarily retrospective (Lindenmayer and Likens 2018) and cannot tell us how biological and ecological processes will respond to drivers outside their historical envelope.

Biological and ecological experimentation provides insight into drivers, pressures and processes that impact on coastal systems and their dynamics. In turn, this can help inform which management levers can be pulled or adjusted such that the ecosystem can be sustained in the face of climate change and development. From the perspective of managers and policymakers needing to be informed about effective management plans and policies, an experimental strategy guides more than just local actions to sustain habitats. It provides evidence-based insight into what management actions, at multiple scales, will be possible, effective and advisable as our coastal environments change.

This will tell us, for example, whether it will be possible to support an ecosystem's resilience sufficiently in the face of projected environmental change (Anthony *et al*. 2015; McLeod *et al*. 2019), and thus what degree of active intervention will be needed. Controlled experiments that emulate future environmental conditions will be able to establish whether key species, ecosystem functions and services that we currently value can be sustained, and for how long.

How might Australia develop such a broad-scale national or regional approach? For one large-scale regional system, the coral reefs of the Great Barrier Reef, we have addressed this question by investing over $100 million in the explicitly experimental RRAP. The other coastal systems presented here (Figure 1) are comparable in value (e.g. Bennett *et al*. 2016) and equally under threat. We suggest that investment in the management and rehabilitation of coastal ecosystems other than coral reefs – kelp forests, oysters reefs, seagrass beds, mangrove forests, estuarine sediments, coastal wetlands and others – at a scale comparable to that of the RRAP investment is critically needed to sustain the value and use of these coastal systems. Such an investment – built on the collaborative structural and governance templates that have been developed for other national marine programs, and using the extensive coastal research infrastructure present across Australia as a core – would result in a manyfold return.

**Table 1**: Coastal marine and estuarine facilities in Australia and their capacity.

| Name | Does your institution have a flowing seawater facility? | What is its (approximate) maximum capacity measured as (a) flow rate and/or (b) total tank volume? | Does it have the capacity to manipulate environmental variables in a controlled and prolonged fashion, (e.g. temperature, pH, nutrients)? | Does your research own or have access to research vessels? | Do you have a currently active research diving program? | Do you have active experimental research programs that make use of these facilities in (a) responses of marine or estuarine systems to climate change; (b) habitat restoration/ rehabilitation or eco-engineering; (c) for each of these, are the experiments lab-based, field-based or both? | Additional comments |
|---|---|---|---|---|---|---|---|
| **Australian Institute of Marine Science (AIMS), including Arafura Timor Research Facility (ATRF), Darwin, NT** | Yes | **AIMS**:<br>(b) SeaSim has a max. capacity of 3 million litres per day and 3.65 million litres of bulk seawater storage. This will soon double as the SeaSim is developed into a National Facility<br>**ATRF**:<br>(a) approx. 350 L/min<br>(b) approx. 9000 L | **AIMS**: $pCO_2$, light, water flow, temperature, carbonate chemistry, salinity, nutrients, sediments, pesticides, hydrocarbons/ condensates<br>**ATRF**: temperatures for the entire facility to ±0.5 °C. Individual tanks are not able to be independently controlled. Light duration adjustable over the entire facility, intensity controllable for individual tanks | 5 vessels | Yes | (a) Yes<br>(b) Yes<br>(c) Both | www.aims.gov.au/seasim<br>www.aims.gov.au/research-vessels |
| **Australian National University, Research Schools of Biology and Earth Sciences** | Recirculating only | (b) 14,000 L tank volume | No | No | Biology: Yes<br>Earth Sciences: No | (a) Yes<br>(b) Yes<br>(c) Yes | Mostly field-based projects but redeveloping capacity for small-scale lab-based experiments using tanks of several-hundred-litre and smaller capacity |

Table 1 continues on next page >

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Australian Museum Lizard Island Research Station** | Yes | (a) Approx. 20,000 L/h | Light, temperature, suspended particles and pH | Yes | Yes | (a) Yes<br>(b) Yes<br>(c) Both | |
| **Charles Darwin University, Research Institute for the Environment and Livelihoods (RIEL)** | No | N/A | Temperature, pH | Yes | No | (a) Yes<br>(b) Yes<br>(c) Both | Microbiology unit within RIEL has relevant analytical facilities (ICPMS) and has assisted AIMS with thousands of seawater analyses from their experiments |
| **CSIRO Oceans and Atmosphere Business Unit, facilities at Cleveland** | Yes | (a) 34,000 L/h | Aquaria tanks allow for all these factors to be manipulated | Yes | Yes | (a) Yes<br>(b) Yes<br>(c) Both | |
| **Deakin University, School of Life and Environmental Sciences** | Yes | (a) 320,000 L flow-through<br>(b) 100,000 L tank volume | Temperature, $pCO_2$ (pH) and oxygen levels. Systems can be set up to manipulate nutrients, turbidity and other treatments | 4 vessels | Yes, run from Queenscliff Marine Station | (a) Yes<br>(b) Yes<br>(c) Both | |
| **Edith Cowan University** | No, but large reservoir tank (5000 L) with recirculating system through filters. Truck in freshwater to reservoir | N/A | Temperature and pH | 2 vessels | Yes | (a) Yes<br>(b) No<br>(c) Both | |
| **Flinders University, College of Science and Engineering** | Yes (via refillable tank) | (b) 2 x 20,000 L holding tanks | Temperature, pH, nutrients, salinity (at tank level) | 2 vessels | Yes | (a) Yes<br>(b) Yes<br>(c) Mostly field based | |

| Name | Does your institution have a flowing seawater facility? | What is its (approximate) maximum capacity measured as (a) flow rate and/or (b) total tank volume? | Does it have the capacity to manipulate environmental variables in a controlled and prolonged fashion, (e.g. temperature, pH, nutrients)? | Does your research own or have access to research vessels? | Do you have a currently active research diving program? | Do you have active experimental research programs that make use of these facilities in (a) responses of marine or estuarine systems to climate change; (b) habitat restoration/ rehabilitation or eco-engineering; (c) for each of these, are the experiments lab-based, field-based or both? | Additional comments |
|---|---|---|---|---|---|---|---|
| **Griffith University, School of Environment and Science** | Yes | (a) Gold Coast lab: unlimited filtered continuous seawater supply at 10 L/s | Temperature, pH | 5 vessels | Yes | (a) Yes, both lab and field<br>(b) Yes, both lab and field | |
| **Heron Island Research Station, Faculty of Science, University of Queensland (UQ)** | Yes | (a) 12 L/s<br>(b) 100,000 L | No | 6 vessels | Yes, coordinated at the UQ St Lucia Campus | (a) Yes<br>(b) Yes<br>(c) Both | Heron Island Research Station also has significant teaching facilities<br>Further vessels are available at the St Lucia Campus |
| **James Cook University, ARC Centre of Excellence for Coral Reef Studies** | Flowthrough facility at Orpheus Island and recirculating system at the Marine and Aquaculture Research Facility Unit (MARFU) on campus | **MARFU**:<br>(a) Flow rate dictated by pumps<br>(b) 1.3 million litres<br>**Orpheus Island**:<br>(a) Approx. 650,000 L/day<br>(b) Individual tank volume unlimited | Both facilities have capacity to manipulate almost anything (temperature, pH, nutrients etc). | Yes | Yes | (a) Yes<br>(b) Yes<br>(c) Both. Research investigating the effects of climate change is using both field and lab-based approaches; most of the restoration activities are using field-based approaches | |

Table 1 continues on next page >

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Macquarie University, Faculty of Science and Engineering** | Yes | (b) 30,000 L recirculating seawater system | Temperature, $pCO_2$ (pH) | 2 vessels | Yes | (a) Yes<br>(b) Yes<br>(c) Both | |
| **Minderoo Exmouth Research Laboratory** | Yes | (a) 6 L/s (510 kL/day)<br>(b) 35,000 L | Temperature control to within 0.2 °C in 27 tanks (3 temperatures x 3 treatments x 3 replicates, multifactorial setup). Temperature control to within 0.5 °C in 3 x 1200 L tanks. Other tanks and aquaria at ambient temperature | 2 vessels (7.5 m) | No, we provide laboratory, field equipment and accomodation for researchers through an expression of interest process | (a) Yes<br>(b) Yes<br>(c) Yes | |
| **Murdoch University, Environmental and Conservation Sciences** | No | N/A | N/A | 6 small vessels for use in estuaries and coastal waters and 2 coastal vessels (7 m) | Yes | (a) Yes<br>(b) Yes<br>(c) Both | |
| **NSW Department of Primary Industries, Port Stephens Fisheries Institute** | Yes | Combined tank volume: 3 ML/day<br>Culture tanks: approx. 1 ML<br>Seawater storage tanks: approx. 0.5 ML<br>Lined ponds: >8 ML | Temperature, salinity, pH, nutrients, contaminants | Yes | Yes | (a) Yes<br>(b) Yes<br>(c) Both | |
| **Primary Industry and Regions South Australia – South Australian Research and Development Institute (PIRSA-SARDI)** | Yes | (a) Approx. 1400 L/min<br>(b) 240,000 L | Temperature, dissolved oxygen, pH | Yes, large offshore research vessel and fleet of smaller vessels | Yes | (a) No<br>(b) Yes<br>(c) Both | |

| Name | Does your institution have a flowing seawater facility? | What is its (approximate) maximum capacity measured as (a) flow rate and/or (b) total tank volume? | Does it have the capacity to manipulate environmental variables in a controlled and prolonged fashion, (e.g. temperature, pH, nutrients)? | Does your research own or have access to research vessels? | Do you have a currently active research diving program? | Do you have active experimental research programs that make use of these facilities in (a) responses of marine or estuarine systems to climate change; (b) habitat restoration/ rehabilitation or eco-engineering; (c) for each of these, are the experiments lab-based, field-based or both? | Additional comments |
|---|---|---|---|---|---|---|---|
| **Southern Cross University, National Marine Science Centre** | Yes | (a) Up to 500 L/min | Temperature and pH in some parts of the system, nutrients manually | 2 vessels | Yes | (a) Yes<br>(b) Yes<br>(c) Both | |
| **Sydney Institute of Marine Science (SIMS)** | Yes | (a) Approx. 50,000 L/h | Temperature, light, pH, other variables manually at tank level in some instances | 3 vessels | Yes | (a) Yes<br>(b) Yes<br>(c) Both | |
| **University of Adelaide, School of Biological Sciences** | Truck in seawater for experimental use | (b) Approx. 3000 L | Temperature and pH | Yes | Yes | (a) Yes<br>(b) Yes<br>(c) Yes | |
| **University of Melbourne, School of Biosciences** | Yes | (a) Flowrates are low<br>(b) Typically <100 L capacity tanks | Temperature (system wide) | 3 vessels | Yes | No | |
| **University of Newcastle (UoN), School of Life and Environmental Sciences** | Recirculating only | (a) Flow rate can be adjusted<br>(b) 28 tanks, 40 L each | Temperature but at room level only | 2 vessels | No | (a) Yes<br>(b) Yes<br>(c) both | The capacity of marine science at UoN is growing and will likely have a dive program by 2020 |

Table 1 continues on next page >

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **University of Sydney, One Tree Island Research Station (OTIRS)** | Yes | (b) System is gravity fed from 60 L storage tanks which are pumped from the lagoon as needed | Light and temperature | Yes. 12 m, 6 m, 3 x 4 m orca rigid pontoons, 2 x 3 m punts | The University does but OTIRS does not specifically manage diving | (a) Yes<br>(b) Yes<br>(c) Mostly field but chem lab and aquarium support projects | The station can accommodate 28 people<br>It now has high speed internet and a recently upgraded solar power system |
| **University of Sydney, School of Life and Environmental Sciences** | Recirculating only | (b) 6 x independent recirculating systems, each with 300 L sump<br>System is supplied by a 2000 L storage system | Temperature | 1 vessel plus access to SIMS vessels | Yes | (a) Yes, lab and field<br>(b) Yes, mainly field at this point | |
| **University of Tasmania (UTAS), Institute for Marine and Antarctic Studies** | No | N/A | Not built in; manipulated at level of individual aquaria in custom systems | Yes | Yes | (a) Yes<br>(b) Yes<br>(c) Mostly field but lab projects also done | There are some infrastructure funds from UTAS to go towards flowing seawater/ recirculating facilities in 2019 |
| **University of Western Australia (UWA), School of Biological Sciences and UWA Oceans Institute** | Yes | (a) 250 L/min | Not built in; manipulated at level of individual aquaria in custom systems | Yes | Yes | (a) Yes<br>(b) Yes<br>(c) Yes | Administration and compliance for field-based research is becoming onerous and limiting |

> *Coastal communities consistently rank 'clean and healthy water and ecosystems for coastal and estuarine environments' as a high-priority community value.*

Image: Peter M Kyne, Charles Darwin University

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APPENDIX A

# Experimentation to inform science and the effective management of coral reefs |

*Andrew Negri, Craig Humphrey, Carly J Randall, Line K Bay and Ken Anthony*

Tropical coral reefs are iconic ecosystems and are among the most biologically diverse and economically valuable ecosystems on the planet.

They are essential to many nations around the world, providing significant food and income, as well as coastal protection (Moberg and Folke 1999). Globally, reefs provide significant economic value through tourism, commercial fisheries, coastal protection and biodiversity. Over a decade ago, this value was estimated to be in the order of $29.8 billion annually (Conservation International 2008). A recent report on the Great Barrier Reef valued the total economic, social and icon asset at $56 billion with direct economic input of $6.4 billion annually (Deloitte 2017).

Coral reefs around the world are being progressively degraded through local, regional and global anthropogenic drivers (Bellwood *et al*. 2004; De'ath *et al*. 2012; Hoegh-Guldberg *et al*. 2007). Local and regional stressors include water quality (De'ath and Fabricius 2008, 2010; Fabricius *et al*. 2005), contaminants (King *et al*. 2013; van Dam *et al*. 2011), sediments (Jones *et al*. 2015, 2016) and overfishing (Bellwood *et al*. 2004). Overlaying these local and regional stressors is the increasing risk posed by climate change, particularly increasing sea surface temperature, ocean acidification, sea-level rise and increasing intensity of storms and marine heatwaves (Hughes *et al*. 2019b).

Increasing sea surface temperatures by 1–2 ˚C above the average annual maximum in coral reefs can give rise to coral bleaching, a process whereby the coral host expels its symbiotic algae (Hoegh-Guldberg 1999). The first documented case of widespread coral bleaching was reported in 1983 (Coffroth *et al*. 1990) and was followed by other mass-bleaching events, including those in 1998–99 (Berkelmans and Oliver 1999), 2010 (Guest *et al*. 2012), 2014 (Bahr *et al*. 2015), back-to-back bleaching events in 2016 and 2017 (Hughes *et al*. 2019b), and again in 2020 and 2022. The chance of widespread coral bleaching is increasing (Eakin *et al*. 2019). Under current climate projections it is suggested that by 2040, 86 per cent of world heritage reefs can expect to undergo severe bleaching twice per decade (Heron *et al*. 2017). Normal reef-recovery processes following major acute-disturbance events can take years to decades and are now taking longer than they have in the recent past (Arias-Ortiz *et al*. 2021). With the projected increase in coral bleaching frequency and intensity, natural recovery processes are likely to be unable to keep pace.

Other global drivers of change on coral reefs associated with climate change include ocean acidification (Hoegh-Guldberg *et al*. 2007), the increasing risk of large tropical storm events (De'ath *et al*. 2012; Knutson *et al*. 2010), and sea-level rise (Hoegh-Guldberg and Bruno 2010). All these factors are likely to accelerate the degradation of coral reefs and other coastal ecosystems, resulting in major losses of ecosystem services (Heron *et al*. 2017). Globally, we need to address the magnitude of these drivers (e.g. climate change, coastal run-off), but for coral reefs to be sustained in this century, corals also need to become more tolerant of a range of stressors – and fast. Implementing a plan to achieve this is time critical. Alongside emissions reductions and conventional management solutions, we must research and implement solutions to protect existing coral reefs and their biodiversity from the acute impact of climate change and to help them adapt to the rapid pace of change.

## Why is a unified national approach needed?

To date, reef management efforts have predominantly focused on local and regional stressors. Under continuing climate change, however, conventional management approaches are likely to be insufficient to provide ongoing protection and recovery (Cox *et al*. 2017). It has been argued that management approaches require a paradigm shift (Anthony *et al*. 2017; van Oppen *et al*. 2017; Bellwood *et al*. 2019). This paradigm shift will entail moving beyond conventional conservation approaches to implement new interventions that can help sustain key ecosystem functions and support the resilience of species that underpin key ecosystem services (Anthony *et al*. 2017). These interventions require substantial foundational knowledge and new and emerging technologies developed through cross-disciplinary collaborations. Acquiring this knowledge and developing and testing new interventions will require targeted and coordinated experimentation at an unprecedented scale.

One such collaborative effort aimed at protecting the Great Barrier Reef is the Reef Restoration and Adaptation Program (RRAP) (https://www.gbrrestoration.org). RRAP brings together Australia's leading experts to create and test a suite of innovative and targeted measures to help the Great Barrier Reef adapt under conditions of ongoing climate change.

These interventions must have strong potential for positive impact, be socially and culturally acceptable, ecologically sound, ethical and financially responsible. Interventions will be implemented if, when and where it is decided that action is needed – and only after rigorous assessment and testing. RRAP is the

largest, most comprehensive program of its type in the world. It is a collaborative effort of leaders in reef ecology, water and land management, engineering, innovation, systems modelling, decision sciences and social sciences, drawing on the full breadth of Australian and international expertise. It aims to strike a balance between minimising risk and maximising opportunity to save reef species and values.

The $6 million RRAP Concept Feasibility Study which began in 2019, identified and prioritised avenues of research and development (R&D),. RRAP is being progressed by a partnership including the Australian Institute of Marine Science, CSIRO, the Great Barrier Reef Foundation, James Cook University, the University of Queensland, Queensland University of Technology, and researchers and experts from a range of other organisations. The Australian Government allocated a further $100 million for reef resilience and adaptation science as part of the $444 million Reef Trust Partnership (https://www.barrierreef.org/science-with-impact/reef-partnership) announced in the 2018 Budget. This funding is not building on the work of the concept feasibility study.

At the core of the RRAP are the potential actions that can be taken on the reef – the interventions to facilitate the repair of coral reefs, to protect reefs from further damage from the effects of climate change and to promote adaptation to changing environmental conditions. RRAP has identified a first tranche of tools and technologies that can be used to intervene at scale on the Great Barrier Reef to help them to adapt and remain resilient under climate change. The program is producing solutions by combining efforts to reduce exposure to key drivers (e.g. light and warming), enhancing natural resilience where possible, enhancing the adaptive capacity of key species and restoring populations and habitats where feasible and effective.

This lens is consistent with the NMSP framework that addresses drivers of change, builds resilience and identifies solutions that work for the reef and people (Figure A1). RRAP provides a blueprint for similar efforts around the world. In the context of the NMSP, RRAP provides a strong case for R&D anchored in targeted experimentation with three overarching objectives:

1. Develop interventions that have high efficacy at scale.
2. Ensure interventions are safe.
3. Provide intervention options that are cost-effective.

While RRAP is focused on supporting the coral condition of the Great Barrier Reef, the program's coordinated systems approach could provide a blueprint for other ecosystems.

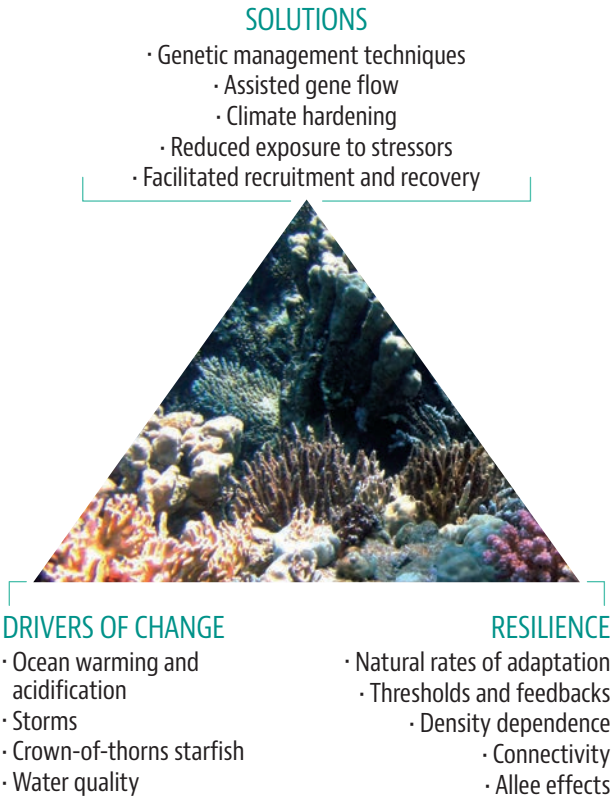



**Figure A1**: National Marine Science Plan framework applied to the coral reef challenge. Resilience and solutions examples are from the Reef Restoration and Adaptation Program but could be generalised to other programs with a reef focus.

## Priority areas for coral experimentation

One of the key novel approaches being investigated by the RRAP for its effectiveness at scale is to seed degraded reefs with corals derived from natural spawning slicks or produced through aquaculture. The breeding stock of corals can be from local or foreign sources and the reseeding may seek to influence local genetic patterns and adaptation. The ultimate success of this type of approach depends on: (i) access to seed corals that have desirable attributes for resisting or recovering from increasing temperatures and more frequent extreme temperature events and (ii) optimised methods to achieve scale and drive down cost in the aquaculture production of both sexually and asexually produced colonies. This also includes on-reef optimisation of growth, survival and retention of seeded corals. Significant experimental research is underway to confirm the benefits of seeding any coral, *let al*one enhanced corals on reefs, and to test methods and engineered seeding devices that increase the survival of those corals post-deployment.

Priority areas for experimental research underway as part of RRAP include:

- developing coral breeding and asexual propagation techniques to reliably produce coral juveniles or fragments
- enhancing growth and survival of coral juveniles and (micro-) fragments after settlement and deployment
- understanding natural and enhanced adaptive capacity of corals and developing markers and methods to identify stock for reseeding
- developing of treatments (microbial and climate hardening) for application during the aquaculture production process to enhance growth, survival and stress tolerance
- designing an aquaculture facility prototype and developing breakthrough processes and automation for the production of seed corals.

To meet objectives of species and genetic diversity and impact at scale, coral seeding programs require combination of traditional asexual propagation methods with advances in the sexual production of corals (Randall *et al*. 2020a). Although there is existing knowledge on asexually propagating corals through fragmentation and out-planting, the techniques have not been widely tested on Australian reefs (e.g. https://mote.org/research/program/coral-reef-restoration, but see Randall *et al*. 2020b). Targeted experimental research is underway to enable successful propagation of coral fragments across a diversity of dominant Indo-Pacific species that play key ecological functions, including habitat provision and early recovery following disturbances. Further, the development of methods to propagate micro-fragments in coral aquaculture is a priority to generate enough warm-adapted explants for these populations to be established on target reefs in time to build resilient and self-replenishing local populations.

The sexual production of corals has additional benefits for restoration programs (Randall *et al*. 2020a). It can be more ecologically sustainable than traditional fragmentation, as it does not depend on the destructive collection of adult colonies. Furthermore, the application of sexual propagules from spawning events is likely to be a cost-effective and feasible way to generate the large number of corals required for restoration and adaptation (Edwards 2010; Doropoulos *et al*. 2019). Most importantly, the sexual reproduction of corals promotes genetic diversity, which is central to adaptation and adaptive potential (Baums 2008; van Oppen *et al*. 2015, 2017). While corals have been bred successfully in experimental systems for decades, current knowledge and techniques do not extend to cover the diversity and functions of corals required to maintain a resilient ecosystem.

A number of novel interventions are now considered to enhance heat and bleaching tolerance, and/or adaptative capacity. These are broadly categorised as assisted adaptation (van Oppen *et al*. 2017). This suite of techniques includes approaches such as the hybridisation of coral species to increase diversity and create novel adaptive options (Chan *et al*. 2019), assisted gene flow, where the movement of existing genetic variation is facilitated across the species range (Quigley *et al*. 2019), and transgenerational adaptation, where exposure induces a heritable acclimatory gain in tolerance (Putnam and Gates 2015; Torda *et al*. 2017).

Recognising that the health and stress tolerance of corals are contingent on their symbiotic relationships with a range of microbes, these host-specific approaches can be crossed with microbial treatments of existing or selected stock. Importantly, most of these techniques are not yet field-ready (NASEM 2019a, 2019b), and require extensive R&D, risk-management (Kaebnick *et al*. 2016) and targeted experimentation before they can be deployed and operational. The challenge for reef adaptation programs like RRAP and for national strategies like the NMSP will be to identify priority functions, processes and species that can be kept resilient with the right approaches. To develop such effective approaches will require urgent targeted, coordinated and large-scale R&D with a strong emphasis on experimentation.

## Experimental facilities to test and validate adaptation approaches

The knowledge around new adaptation and restoration interventions is limited and is often restricted to small-scale testing of one aspect of an intervention. To build experimental R&D capacity and deliver deployable solutions ahead of the curve as the climate crisis grows will require significant infrastructure investment, coordination of facilities and strong governance. Parallel to building experimental R&D capability for developing and testing risks and benefits of proposed new interventions, we also need capacity to mass-produce such corals at a cost point that is consistent with deployment.

RRAP has built a strong governance model and a decision-support system into its R&D program, and this may serve as a template for other national adaptation initiatives for other ecosystems. This program will benefit from the expansion of SeaSim (https://www.aims.gov.au/seasim), funded by the National Collaborative Research Infrastructure Strategy, to double its capacity and elevate its accessibility as a national facility. An integrated and cohesive marine experimental plan to link existing and new facilities across Australia makes logistical and financial sense.

Specific experimental challenges for new adaptation interventions are systems that enable full control of multivariate environments that closely mimic current and future climate scenarios. These include key water quality parameters such as temperature, pH/$pCO_2$, light and water movement but may also need to factor in microbial contexts and challenges (e.g. see https://www.aims.gov.au/seasim).

Traditional experiments where the single or combined effects of a few factors are crossed are feasible within existing capability when the number of factors and corals tested is fairly contained. Quantitative genetic experiments, however, test many corals and their offspring to quantify essential parameters for adaptation such as heritability, adaptability and response to selection. Such experiments are technically feasible but more challenging in terms of space and logistics, especially as coral host genetics is crossed with that of their symbionts. Mesocosm experiments, ideally on field stations with access to large volumes of natural seawater (e.g. Dove *et al*. 2013), or contained field experiments, provide an opportunity to bridge the gap between field and experimental studies by moving from the scale of colonies to the scale of assemblages.

Contained field experiments provide an essential stepping stone in the development of new genetic methods as they provide an opportunity to examine manipulated trait expression in a realistic environmental setting. However, this approach is currently constrained by the development of outplanting R&D. Uncontained field experiments should not be attempted without extensive laboratory and field experiments to help verify that risks can be managed.

To understand transgenerational effects (benefits and risks) of assisted adaptation interventions, experimental systems should ideally enable organisms to live out their whole life history in the experimental setting. This will provide insight into the heritability of evolved traits (i.e. is performance maintained across life stages and generations?), performance trade-offs (among fitness traits and environmental conditions) and the extent of improved performance traits that can be achieved and maintained.

In addition to new interventions, there is a need for continuing research on improving the resilience of coral ecosystems themselves (a major axis in Figure A1). It is important to determine thresholds for other pressures that trigger change and the ways in which these may interact with a changing climate. For example, it has been suggested that improving water quality may play a role in significantly enhancing the resilience of individual corals or of coral reefs in the face of a warming climate (De'ath and Fabricius 2010). Experimental systems are required with the ability to accurately control multiple stressors in environmentally realistic ways; this will provide decision-makers and regulatory bodies with high quality data, enabling informed decisions (Brunner *et al*. 2021).

A recent report from the Western Australian Research Institute has highlighted the need for high-quality marine experimental facilities in improving operational efficiency and environmental protection (https://www.wamsi.org.au/dredging-science-node). Uncertainty around the impacts of dredging-related sediments on critical life history stages in corals led to regulations being implemented by resource managers based on little or no data. Through a process of rigorous research, combining both field observations and laboratory-based experimental systems, knowledge gaps were addressed and significant improvements in operational efficiency and environmental effectiveness were made. Much of this experimental work was enabled using sophisticated experimental systems able to accurately replicate realistic environmental processes found in dredging operations.

Understanding the drivers of coral loss due to cumulative stress via local, regional and global anthropogenic stress, determining drivers of resilience and developing methods of enhancing coral resilience will require robust and novel marine experimental facilities. It is likely that these facilities will need to embrace significant technological innovation and look beyond traditional areas of marine science in order to provide the sophisticated systems needed to tackle the threats facing coral reefs worldwide and provide solutions for their protection. This will require the development of a network of nationally integrated marine experimental facilities across Australia, leveraging and enhancing current knowledge and technologies to form an integrated experimental platform, not only for the key anthropogenic drivers affecting coral reefs but also for all marine coastal communities and their resources.

# **Experimentation to improve management and rehabilitation** of marine macrophytes reefs |

*Melinda A Coleman and Thomas Wernberg*

Marine macrophytes (kelps, seagrasses and saltmarshes) form ecologically and socio-economically important coastal habitats worth billions of dollars (Costanza *et al*. 2014).

In particular, Australia's Great Southern Reef (Bennett *et al*. 2016), a vast, interconnected system of macrophyte forests, extending over 71,000 km$^2$, is worth over $10 billion per year in fishing and tourism alone and supports some of the highest and most endemic biodiversity in the world (Bennett *et al*. 2016; Phillips 2001). Similarly, vegetated coastal systems (saltmarsh, seagrass and mangroves) in Australia support $78 million per year in fisheries values alone (Jänes *et al*. 2019). Macrophytes provide habitat for a myriad of organisms (e.g. Coleman *et al*. 2007; Marzinelli *et al*. 2014), sustain coastal food webs (Bishop *et al*. 2010) and contribute to carbon sequestration (Krause-Jensen and Duarte 2016; Filbee-Dexter and Wernberg 2020).

There has been an accelerating loss of these critical macrophyte habitats in Australia and globally, and an associated rise and persistence of degraded seascapes such as algal turfs, urchin barrens and bare sediment (Waycott *et al*. 2009; Filbee-Dexter and Scheibling 2014; Hyndes *et al*. 2016; Filbee-Dexter and Wernberg 2018). Loss of these habitats threatens ecological, social and economic values, with loss of kelp alone estimated to cost $1 million per kilometre of forest lost per year (Filbee-Dexter and Wernberg 2018). Despite widespread shifts from macrophyte forests to these less desirable habitats (see Figure B1), there has been little documented natural recovery, suggesting that active adaptive management and intervention, including restoration, will be required to reverse these shifts (Filbee-Dexter and Wernberg 2018). Strategies to futureproof macrophyte habitats against predicted stressors including climate change are also badly needed (Wood *et al*. 2019; Coleman *et al*. 2020), but the science to underpin such strategies is in its infancy (Coleman and Goold 2019).

## Why is a unified national approach required?

Many key marine macrophytes across Australia share distributions across vast seascapes, yet the science to understand and mitigate impacts is often disjunct or centred at certain institutions where specific expertise or facilities reside. However, there is often commonality in the key stressors causing macrophyte decline (e.g. climate change, eutrophication), and there are unique opportunities across the Australian continent to understand generality in drivers of change and how to mitigate impacts.

A unified national approach to experimentation on marine macrophyte loss and strategies for recovery would provide the platform and framework to bring together

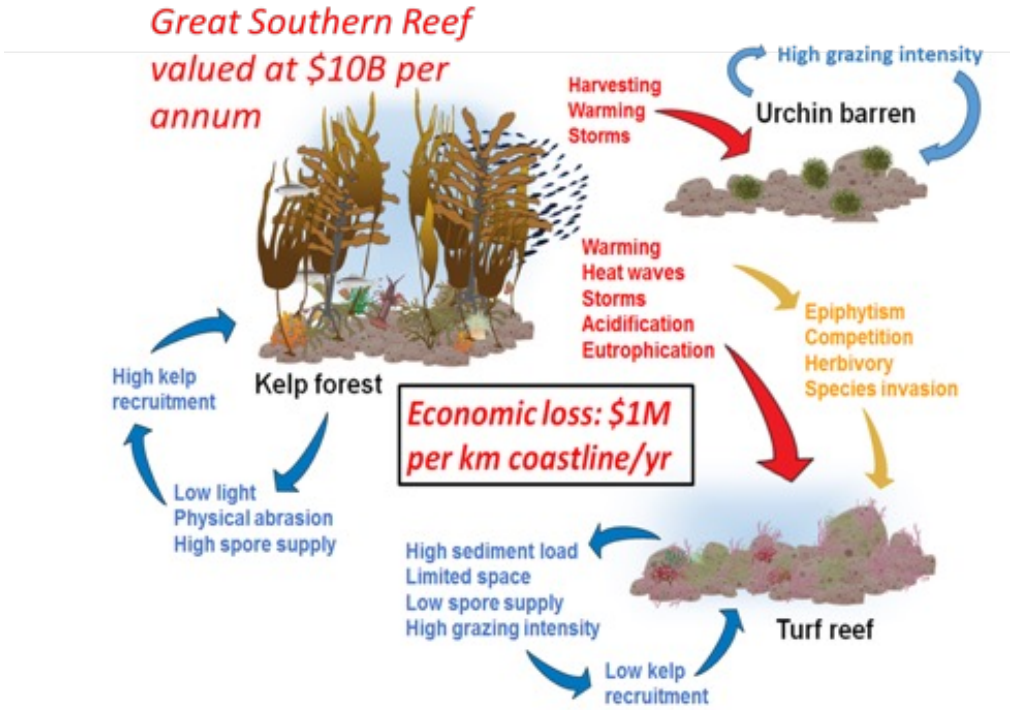



**Figure B1**: Kelp forests, like other macrophyte habitats in Australia and globally, have in many cases shifted to less desirable habitat states, including algal turfs and urchin barrens, resulting in significant economic loss. These changes can be initiated by different direct (red) and indirect (orange) drivers. Once these ecosystems have flipped, they often get locked into the degraded state by feedback mechanisms (blue)

leading expertise across the continent. This expertise is needed to build cutting-edge research capacity and develop new infrastructure, with the common goal of understanding and mitigating macrophyte loss at relevant large scales. For example, comparative manipulative experiments, replicated at multiple locations nationally and characterised by different environmental conditions and latitudes (Borer *et al*. 2014), will identify common causal processes as well as exceptions to that commonality (Wernberg *et al*. 2010; Wernberg *et al*. 2012; Wernberg *et al*. 2019b). It will also be important to perform experiments across tropical–temperate transition zones, where much of the change is occurring. Having the ability to do such experiments on the environmentally similar but geographically separate east and west coasts makes Australia the ideal natural laboratory for such an approach.

Management and restoration of marine macrophytes is significantly constrained due to knowledge gaps in understanding drivers of change and resilience in these systems, including thresholds that trigger regime shifts and the magnitude of hysteresis (the amount of perturbation needed to flip a system from one state to another) and feedbacks. Moreover, these constraints need to be understood in both contemporary and future seascapes to allow us to create futureproof management that anticipates and adapts to predicted environmental change. Controlled field and laboratory experimentation under extant and future scenarios of multifactor change is needed to address these knowledge gaps.

Using kelp forests as a main case study, we outline three key research areas (Figure B2) that require broadscale controlled experimentation to inform and improve management and restoration outcomes. These areas are, however, broadly applicable to all macrophyte systems, which share common threats, ecological processes and constraints on management and recovery.

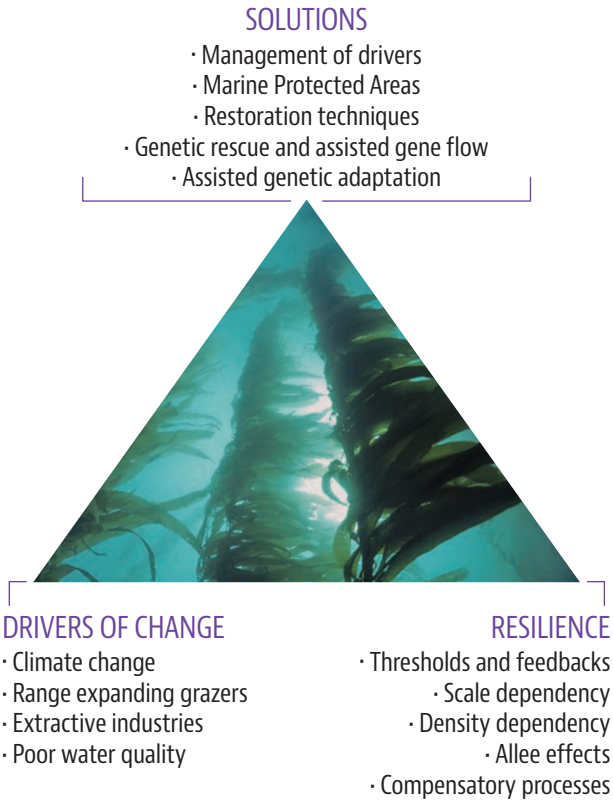



**Figure B2**: Management and restoration efforts for degraded marine macrophyte habitats are limited by knowledge gaps in three areas: processes driving habitat change, factors that confer resilience, including feedbacks that maintain undesirable degraded habitats, and development of solutions to restore and boost resilience. Collectively addressing these gaps will improve the resistance and recovery of degraded marine macrophyte habitats in Australia.

## 1. Identifying drivers of change

The most cost effective and successful management strategies are preventative. That is, they manage to avoid ecosystem shifts and the strong hysteresis usually associated with the new undesirable ecosystem states. Prevention of macrophyte habitat degradation and regime shifts can be achieved via understanding and identification of thresholds that trigger change, and managing to avoid crossing tipping points, for example by increasing resistance (Filbee-Dexter and Wernberg 2018). Such thresholds and tipping points must be understood under both extant and future climatic scenarios, which requires manipulative experimentation under controlled conditions. For example, if we understand the level of predation required to prevent urchin abundance rising to levels that trigger overgrazing of kelp and shifts to barrens formation, then we can alter or design fisheries management to avoid such shifts (Provost *et al*. 2017). Alternatively, if we understand at what level of eutrophication and/or sedimentation algal turfs proliferate to the extent that phase shifts from kelp forest to turf are likely, we can manage that stressor as critical thresholds approach.

Controlled experimentation in both field and laboratory settings will be required to answer such questions and tease apart the multiple interacting drivers of change (Wernberg *et al*. 2012). For example, replicated kelp removal experiments across latitudes and levels of nutrient input can help determine at what density kelps shift to turf habitats and how that threshold changes under different temperature and nutrient regimes. This can then inform management about levels of nutrients that may trigger management intervention.

Moreover, realistic mesocosm experiments that simulate a range of future scenarios of environmental change will provide understanding of changing thresholds and hysteresis to inform futureproof management and conservation. Mesocosm experiments have been used to test the effects of ambient and future temperatures and acidification, as well as predation pressure and invasion, on the health and survival of macrophytes (Miranda *et al*. 2019; Provost *et al*. 2017; Qiu *et al*. 2019; Straub *et al*. 2021). While such experiments are a start, broader and more coordinated experiments are required across large scales, for different macrophyte taxa (kelps, seagrass, mangroves etc.) and for responses measured at different levels of biological organisation (genes to ecosystems).

## 2. Understanding resilience

Overarching factors that limit resilience (resistance or recovery) of macrophyte habitats include propagule limitation, recruitment success, altered environmental conditions and changes in consumer pressure (herbivory), all of which reinforce the negative direct impacts of climate change (Wernberg *et al*. 2010, 2016; Vergés *et al*. 2014; Hyndes *et al*. 2016). For example, compared to cool latitudes, reduced recruit performance at warmer latitudes explained slow recovery of kelp forests following small-scale canopy loss and increased susceptibility to kelp forest collapse and regime shift following a marine heatwave in Western Australia (Wernberg *et al*. 2010, 2018).

A substantial increase in grazing by range-shifting tropical fish herbivores has been linked to the decline of kelp (Vergés *et al*. 2016; Zarco-Perello *et al*. 2017) and lack of recovery via facilitation of turf expansion (Bennett *et al*. 2015). Similarly, changing trophic interactions in warmer oceans can cause kelp loss or hinder recovery when higher order predators relax consumptive pressure on grazers (Miranda *et al*. 2019; Provost *et al*. 2017; Veenhof *et al*. 2022). Similar negative consumptive feedbacks are also predicted for temperate seagrass (Hyndes *et al*. 2016). Understanding the role of changes in these feedback processes under different environmental conditions will provide predictive power for assessing trajectories of macrophyte change and the appropriateness of intervention strategies including restoration.

## 3. Solutions: emerging technologies and techniques to combat macrophyte loss

Although traditional adaptive management approaches including marine reserves, fisheries management, pollution control measures and restoration are helping alleviate stress and recover some kelp forests, these approaches will be challenged in a future of uncertain change (Wood *et al*. 2019). Technological advances will play a key role in overcoming these hurdles (Coleman and Goold 2019). These advances range from improving restoration techniques to allow rehabilitation at the large scales of loss (e.g. Fredriksen *et al*. 2020), through to anticipatory and highly interventionalist approaches such as assisted adaptation and gene editing (Coleman and Goold 2019; van Oppen *et al*. 2015). However, all such techniques require robust experimentation prior to implementation to assess their suitability across taxa and a range of extant and future environmental conditions.

### Restoration techniques

While restoration of terrestrial forests has a long history of successes, restoration of marine macrophyte forests is challenged by the difficulties involved in working underwater, complex species life histories and the large scales of loss (Wood *et al*. 2019). Donor plants must be kept *in situ* in dynamic wave-exposed habitats long enough for reproduction to occur. This can require complex engineered structures to be attached to the substrate underwater, and these are often rapidly removed by storms and waves (Campbell *et al*. 2014). Moreover, deployment of such structures is labour and skill intensive and typically involves scuba diving under challenging and demanding conditions. Such challenges have limited the success of restoration of marine forests (Layton *et al*. 2020).

Experiments are required to inform and develop macrophyte restoration techniques applicable to a variety of extant, future and spatially variable environmental conditions. For example, development of the new 'Green Gravel' restoration technology has been informed and optimised by controlled experiments manipulating factors such as kelp seeding density and outplanting methodology (Fredriksen *et al*. 2020). Such restoration strategies will complement and enhance traditional management strategies including establishment of marine reserves that can restore trophic interactions and lead to kelp recovery (Babcock *et al*. 2010). They should also be done hand in hand with management strategies that seek to mitigate the original drivers of change (Coleman *et al*. 2008).

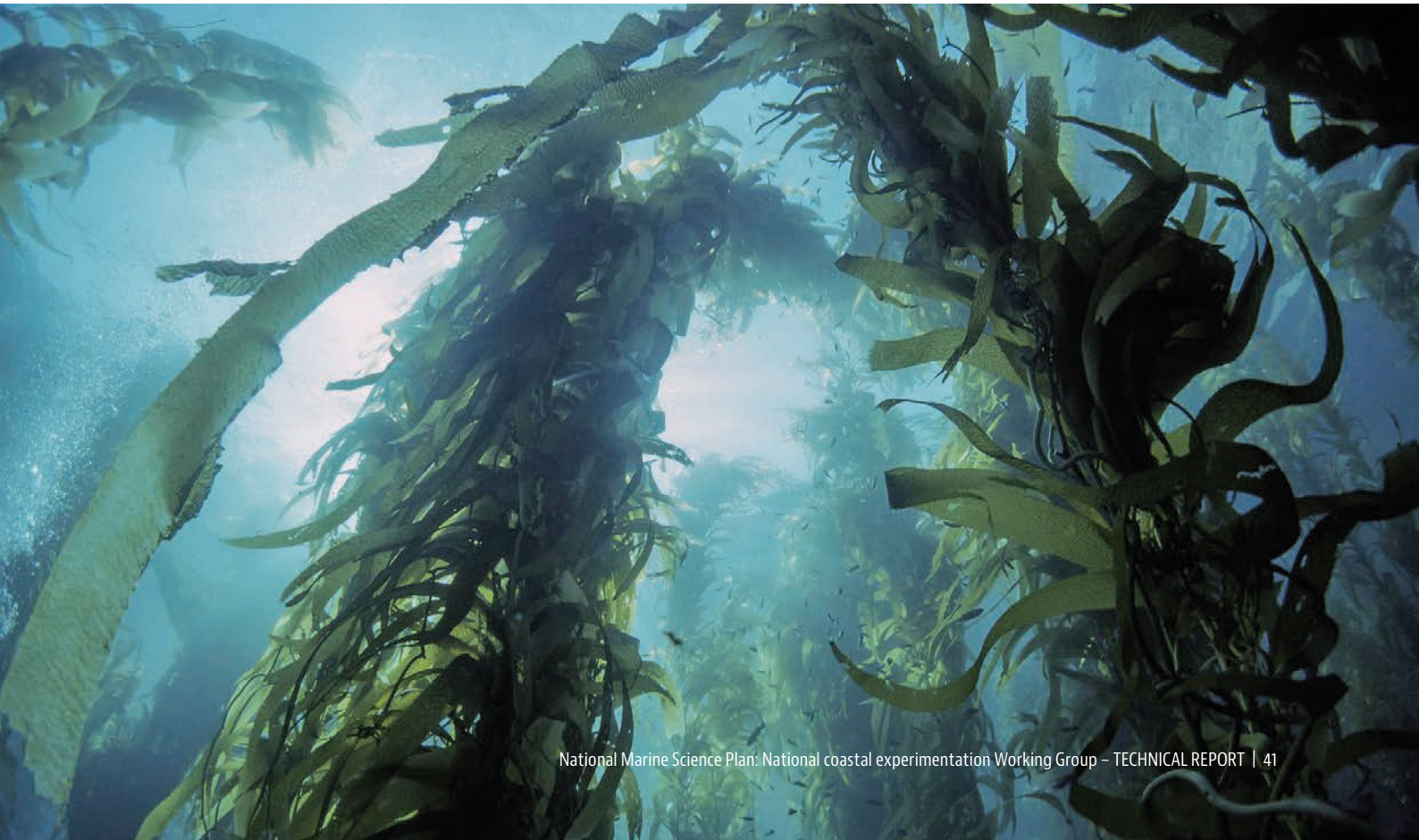
## Restoration under future climates

Controlled experiments can also help us understand and overcome factors hindering macrophyte restoration success under both contemporary and future climates. Restoration allows the possibility of restoring macrophytes for future environmental and climatic conditions, but this requires controlled manipulation of likely future scenarios of change (temperature, pH, nutrients) to understand organismal tolerance and ecosystem responses. In addition, simulation of future conditions may allow better decisions regarding when not to restore (e.g. Johnson *et al*. 2017) or what additional measures should be taken to complement macrophyte restoration (Layton *et al*. 2020). For example, kelp restoration may be paired with other management interventions such as urchin culling, a change in urchin predator (lobster or snapper) harvesting or level of protection (marine protected areas) to enhance success and avoid changing ecological scenarios under future climates. These integrated restoration strategies can be further enhanced and futureproofed by considering which genotypes are most resilient to future environmental conditions (see next section).

## Cutting-edge restoration interventions

Manipulative experiments also allow for consideration and preparation for more interventionist approaches such as assisted gene flow, adaptation or even gene editing that may boost the resilience of populations to future change. Mesocosm experiments that test the resilience of different genotypes (identified from field sampling) to stressors, and their role in ecosystem interactions, can then be paired with restoration technologies for implementation of assisted adaptation.

Although many of these techniques are currently controversial, they also open the doors to never-before imagined solutions to macrophyte loss (Coleman and Goold 2019). It is critical that the body of science required to underpin their application begins to be built up to allow proper decision-making and informed debate about ethical considerations surrounding their application in natural systems (Coleman and Goold 2019; Filbee-Dexter and Smajdor 2019), should the time come for implementation. For example, simulating ecosystem responses under scenarios where kelp populations have enhanced thermal tolerance or resilience to grazing will be critical in predicting possible trajectories of ecosystem change should interventionist approaches be implemented.



APPENDIX C

# **Experimentation to improve management and rehabilitation** of oyster reefs |

*Paul Gribben, Stephen Swearer and Sean Connell*

Globally, estuarine ecosystems and the key habitat-forming species they contain, such as tidal marsh/mangroves, seagrass and oysters, deliver ecosystem services valued around US$5 trillion/year (Costanza *et al*. 2014).

In particular, within estuaries, oyster reefs provide important infrastructure by stabilising sediments, attenuating wave action and reducing storm surge, which can buffer coastlines and coastal structures from erosion (Hemminga and Duarte 2000; Orth *et al*. 2006; Morris *et al*. 2019). They are also important for structuring foodwebs and providing both food and habitat for fauna and flora, including acting as nursery grounds that support fisheries production (Beck *et al*. 2001; Heck Jr *et al*. 2003).

Centuries of environmental degradation, fisheries exploitation and habitat loss have led to estuarine ecosystems becoming one of the most threatened natural systems globally (Cloern *et al*. 2016; Halpern *et al*. 2008; Lotze *et al*. 2006; Worm *et al*. 2006). One of the key consequences of this is to reduce the cover of oyster reefs – the natural kidneys of estuarine ecosystems. Historic overharvesting for food and lime, coupled with disease and pollution in some estuaries, has rendered oyster reefs functionally extinct throughout most of Australia (Alleway and Connell 2015; Beck *et al*. 2011). Across Australia, more than 90 per cent of oyster reefs have been lost, contributing to the long-term degradation of estuarine ecosystems (Gillies *et al*. 2018). Flat oyster (*Ostrea angasi*) reefs (see Figure C1) have been completely lost from the mainland (Gillies *et al*. 2018) and historical baseline data show that, in South Australia, no known *O. angasi* habitat remains, where it once covered thousands of kilometres of seafloor (Alleway and Connell 2015).

These losses have negatively affected the economic and social wellbeing of coastal human populations, reduced the productivity of wild harvest fisheries, increased pollution risks to coastal communities and industries (e.g. aquaculture) and led to the protection of coastal assets with economically and environmentally costly built structures (Anastas and Zimmerman 2007). With the impacts of urbanisation and climate change predicted to increase, restoring lost oyster reefs will be critical to building more resilient estuaries into the future. The Sydney Institute of Marine Science recently engaged a leading financial services company to do a cost–benefit analysis of oyster restoration. The economic appraisal for the restoration of 1 hectare of oyster reefs (at a cost of $55,760) revealed that the 20-year present value of economic benefits would be a minimum of $352,500 per hectare from habitat restoration and fisheries production – valued at $285,000 and $67,500, respectively.

**Figure C1**: Oyster reefs at Towra Point, Botany Bay, New South Wales. Image: P. Gribben

## An explicit need for a national framework

The construction of historical baseline data for oysters, coupled with a desire to find natural solutions for increasing fish production, has motivated, at least in part, a shift in focus from artificial structure additions to the seafloor, to an emerging focus on re-establishing oyster beds (McAfee *et al*. 2020a). Oyster reef restoration may also be critical to meet Australia's National Strategy for Ecologically Sustainable Development, which prioritises ecosystem-based management strategies to ensure socio-ecological wellbeing in fisheries management (Fletcher *et al*. 2003). Indeed, restoration efforts involving various collaborations among state government, local councils, universities and non-profit organisations (e.g. The Nature Conservancy) are occurring on both the eastern and southern coasts of Australia.

These restoration efforts are, however, being conducted in a disparate, ad hoc manner, largely based on a one-size-fits-all approach. Typically, these restoration approaches have a high failure rate because they do not consider the environmental context in which restoration is being conducted. All estuaries are subject to a common suite of stressors. Some of these stressors occur at local scales (e.g. pollution, eutrophication), which are, in turn, modified by processes at larger biogeographic scales (e.g. climate change, ocean and estuarine acidification). Thus, understanding local and biogeographic factors that may impede restoration efforts is critical (Esquivel-Muelbert *et al*. 2021; Leong *et al*. 2022). A unified national framework offers the unique opportunity to understand the key drivers that both promote and inhibit restoration efforts and how they vary geographically. Such an approach has the benefit of informing large-scale adaptive management strategies that locally or regionally tailor restoration efforts towards building resilient oyster reefs into the future. A national framework for oyster restoration would also bring together diverse research and management expertise throughout Australia into a single program, where the objective is to improve estuarine health and environmental resilience by restoring oyster reefs that are resilient to change.

## Experimentation to inform restoration and resilience

Oyster reef systems are fundamentally different to coral reef- and kelp-dominated systems in that they are largely gone from Australia, and we know why. Thus, the focus needs to be on building new resilient reefs. Extractive fisheries (non-aquaculture) for oysters no longer exist, and historical pollution, which has been mitigated by improved management practices in many estuaries, no longer represents a major barrier to restoration.

Understanding the factors that promote and inhibit restoration and the development of resilient oyster reefs can only be determined through broadscale experimental approaches. Moreover, separating the relative influence of local-scale stressors from the influence of stressors acting at broader scales can only be achieved through sufficient replication of common small-scale experiments throughout biogeographic regions in which restoration is being considered. Current restoration efforts are not based on a sound ecological understanding of the processes that enable effective oyster restoration of environmentally resilient reef habitats. Thus, while some restoration efforts may succeed, at least in the short term, if they fail, we have no ability to understand why and adapt strategies to improve restoration success.

Because of the extent of the loss of oyster reefs, building resilient oysters requires two different but complementary research approaches. First, we need to know where and why restoration is likely to succeed and/or fail. Second, once suitable sites have been located, understanding how to construct oyster reefs to maximise their resilience and the ecological and economic benefits derived from them is critical.

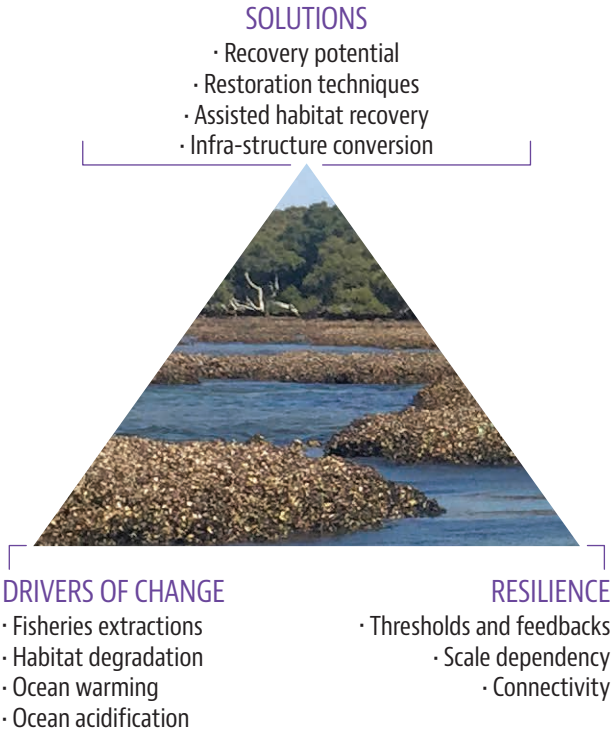



**Figure C2**: Following the functional extinction of 90 per cent of oyster reefs, restoration efforts are limited by knowledge gaps in two key areas: habitats where suitable restoration can be undertaken, and knowledge of the factors that promote reef resilience. Collectively, this knowledge will improve the restoration, resilience and resistance of degraded marine habitats.

## 1. Identifying factors that inhibit restoration

We need to disentangle which environmental and biological factors limit the recovery of oyster reefs across a range of seascape contexts, so that appropriate restoration strategies for overcoming site-specific impediments to restoration can be developed. Key to oyster reef restoration is determining how population processes (recruitment, survivorship, predation and disease) respond to local- and large-scale processes. In removing both live adult oysters and the dead shell substrate on which they grew, dredging reduced spawning stock biomass and hard substrate for oyster attachment. Although a successful oyster aquaculture industry has reinstated spawning stock biomass at some sites, the supply and quality of recruits and of hard substrate may remain insufficient to sustain recruitment. In addition, unsuitable environmental conditions (e.g. sedimentation and pollutants) or biotic interactions (e.g. parasitism and predation) may individually or collectively limit recovery (Gillies *et al*. 2015). However, recent studies indicate oyster recruitment to a number of estuaries and restoration sites, suggesting that larval supply may not limit restoration (Esquivel-Muelbert *et al*. 2021; Leong *et al*. 2022). However, across 15 sites in New South Wales, the density of oyster recruitment displayed spatially variable effects, suggesting that both abiotic (i.e. temperature, turbidity and dissolved oxygen) and biotic (i.e. predation) factors can negatively influence oyster recruitment and, hence, restoration success (Esquivel-Muelbert *et al*. 2021). Consequently, oyster reef restoration projects could be planned to prioritise sites with low turbidity, high dissolved oxygen and low predation, unless these stressors can be mitigated.

## 2. Building resilient oyster reefs

A key question for oyster reef restoration is how much habitat is required to achieve self-sustaining, resilient reefs that provide desired ecosystem services. In particular, landscape ecology predicts that the resilience of oyster reefs and the ecosystem services they provide, including habitat provision to fish and invertebrates, nutrient cycling, sedimentation and wave attenuation, will depend on the number and size of reefs and the total area of habitat they form within estuaries. It is also likely that different ecosystem functions (e.g. biodiversity versus water flow attenuation) will scale differently with reef size. Identifying how different functions and processes scale with reef size and connectivity will be critical for identifying any thresholds in reef size that need to be reached before benefits are gained. Managers will then have the ability to set reef sizes to maximise benefits from one or two desired ecosystem functions and to understand how different functions may trade off as reef size changes.

Although most reefs have been destroyed, remnant oyster reefs for the Sydney rock oyster, Saccostrea glomerata, exist in a few estuaries on the east coast of Australia. Thus, we are in the fortunate position of being able to experimentally investigate the processes maintaining resilient healthy reefs over large spatial scales. The ability to investigate these remnant reefs means that we do not have to develop and test new reefs of different sizes, saving both time and money. Emerging data from these reefs indicates that larger scale processes such as sedimentation may have large consequences for the recruitment of oysters and the biodiversity they support. Thus, choosing which estuary or area to restore oyster beds to may need to be prioritised before deciding how large to build them.

## 3. Using experimental approaches to restoring oyster reefs

Habitat restoration has largely focussed on 'build it and they will come' approaches. While these can prove successful, often they are not. The major problem with these approaches is their inability to inform why restoration is or, equally importantly, isn't successful. We simply cannot learn from previous successes or failures. Key to restoring any habitat is understanding biotic or abiotic factors, or combinations of factors, that limit success. Such factors are also highly dependent on local environmental conditions.

Determining the factors that promote or inhibit the recruitment of oysters and oyster restoration more generally requires standardised experiments replicated across large spatial scales. Such an approach will inform whether the same approach to restoration can be used everywhere or whether efforts have to be 'tailor-made' for each estuary. For example, if predation generally limits recruitment, then protecting small recruited oysters from predation will be essential. Alternatively, various abiotic factors (e.g. sedimentation), appropriate substrate (McAfee *et al*. 2020b) and reef sound (Williams *et al*. 2022) may be critical regulators of recruitment success. In this instance, experimental approaches will inform where restoration is most likely to succeed. Habitat-area ecosystem function relationships also vary with environmental contexts and thus also require experimental approaches to tease apart the role of local versus larger-scale processes in governing ecosystem benefits from restoration. Once suitable areas that support oyster recruitment for restoration have been found, these experiments will guide how restoration can be tailored to maximise their resilience and the ecosystem functions desired from restoring them.

Accruing long-term benefits of oyster restoration requires creating reefs resilient to contemporary conditions and also understanding their likely response to future environmental conditions. Oceans are warming and acidifying. Ocean acidification is already resulting in recruitment failure of oysters on coasts with naturally fluctuating acidity (Barton *et al*. 2012). In many estuaries in Australia, the impacts of climate-driven coastal acidification through mobilisation of acid sulphate soil leachates and other mineral acids is already happening (Fitzer *et al*. 2018). Laboratory experiments clearly demonstrate that different populations of oysters have differential susceptibility to ocean acidification and other water quality parameters associated with climate change (e.g. Benthotage *et al*. 2022). Experiments can be used to forecast the sustainability of large-scale investments into the future, particularly as these investments are inter-generational (during which time ocean temperatures will increase and pH is forecast to continue to decline (Feely *et al*. 2004)).

APPENDIX D

# Experimentation to improve management and rehabilitation of estuarine sediments |

*Bradley Eyre, Steve Swearer and Katherine Dafforn*

Estuaries deliver ecosystem services valued at around US$5 trillion/year globally (Costanza *et al*. 2014). Estuarine sediments (non-vegetated) are an important habitat covering about twice the area of estuaries globally compared to all vegetated habitats combined (Duarte *et al*. 2005; Snelgrove *et al*. 1997).

These sedimentary habitats are species rich and provide key ecosystem services, with substantial economic and social benefits to the 3 billion people globally that live within 100 kilometres of a coastline. In particular, macrofauna, microbial communities and associated biogeochemical processes in sediments play a key role in maintaining water quality and the health of coastal ecosystems (Webb and Eyre 2004; Kristensen *et al*. 2014; Sutherland *et al*. 2017; Birrer *et al*. 2019 2021; Filippini *et al*. 2019). Maintenance of good water quality in turn supports other key habitats such as macrophyte beds (seaweeds and seagrasses) and shellfish reefs (mussels and oysters). For example, denitrification is a key sediment process that removes nitrogen by converting it into a gas that escapes to the atmosphere; this gas would otherwise be available to fuel eutrophication and algal blooms. Based on a US study, nitrogen removal by intertidal sediments is alone worth approximately A$150,000 per km$^2$ per year (Piehler and Smyth 2011).

Estuarine tidal flats globally are being lost at similar rates to seagrasses, mangroves and kelp forests due to coastal development, reduced sediment delivery from major rivers, increased coastal erosion and sea-level rise (Murray *et al*. 2018). Sedimentary habitats are also strongly adversely affected by habitat modification from urbanisation, bushfires and flooding, agricultural and industrial activities, and the complex interactions between these factors (e.g. Barros *et al*. 2022). This potentially leads to the creation of novel ecosystems with significant loss of biodiversity and ecosystem function (e.g. carbon storage, denitrification, nutrient recycling, respiration and production). For example, recent work in Moreton Bay has shown that seabed trawling alone could reduce the capacity of a coastal system to remove nitrogen via denitrification by around 50 per cent (Ferguson *et al*. 2020). Similarly, increased organic matter loading from eutrophication reduces the capacity of sediments to remove nitrogen via denitrification (Eyre and Ferguson 2009). Flooding also reduces the carbon storage capacity of intertidal sediments (Oakes and Eyre 2014).

We need a stronger mechanistic understanding of how these stressors change sediment habitats and of the relationship between biodiversity and ecosystem function/biogeochemical processes, as a loss of biodiversity may result in a loss of ecosystem function and less resilience to disturbance (Thrush *et al*. 2017). For example, a loss of denitrification capacity can result in more nitrogen being retained within the ecosystem (Eyre and Ferguson 2009). Furthermore, little is known about how other global changes, such as increasing temperatures, droughts, floods and ocean acidification, and in particular their interaction with other stressors, will affect sediment communities and biogeochemical processes.

## An explicit need for a national framework

There is an explicit need for a national framework to understand and mitigate impacts on sediment habitats, similar to that for macrophytes and oysters. The key stressors that change sediments are similar across estuaries (e.g. eutrophication) and there is a unique opportunity to understand the drivers of change and how to mitigate their impact(s) across Australia. Sediment microbial and macrobenthic communities and biogeochemical processes are being measured at a few locations in Australia by individual institutions. However, as standardised methodologies are not being used, it is challenging to make comparisons across Australia using existing data from individual groups. A national approach to experimentation would bring researchers together across Australia to standardise approaches and develop new research capacity to better understand and mitigate the loss and modification of sediment communities and biogeochemical processes. Such an approach would involve comparative manipulative experiments replicated at multiple locations nationally and characterised by different environmental conditions and climates.

We need to understand the drivers of change and resilience in sediment habitats to be able to manage and restore critical ecosystem functions and to understand thresholds that trigger regime shifts and any hysteresis and feedbacks in the system. For example, the nitrate that enters an estuary can be converted to $N_2$ gas via anammox metabolism, to $N_2$ and $N_2O$ gas via denitrification, and to $NH_4$ via dissimilatory nitrate reduction to ammonia, in the sediments. As such, nitrate will have a very different fate in the estuary depending on which pathway it follows; $N_2$ will be lost to the atmosphere, as will $N_2O$, which as a potent greenhouse gas will contribute to global warming, and $NH_4$ will be recycled within the estuary, contributing to organic

matter production. As such, anammox is considered the more climate-friendly process (Tan *et al*. 2020) and anammox and denitrification the more eutrophication-friendly processes (i.e. less organic matter production). However, we don't know if there will be shifts and hysteresis in the different nitrate pathways in response to key stressors. These knowledge gaps can be addressed using controlled field and laboratory experimentation with multiple stressors under current and future scenarios.

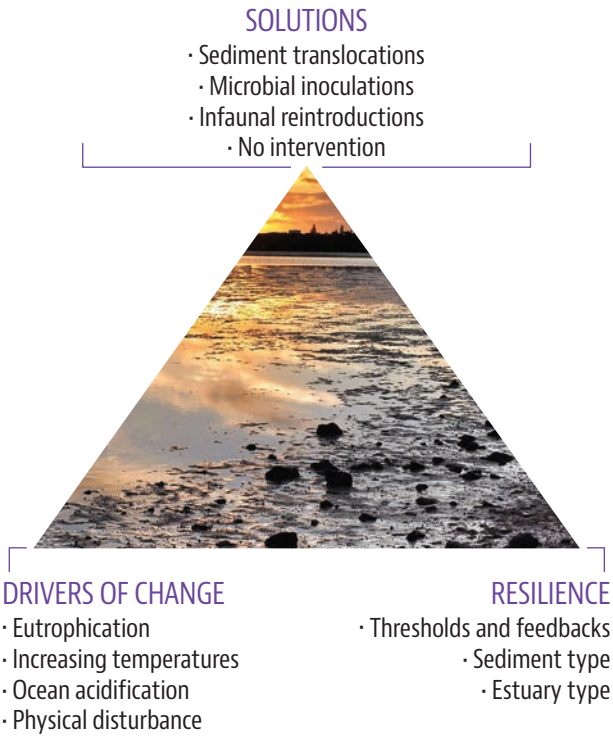



**Figure D1**: Management and restoration efforts for degraded marine sedimentary habitats are limited by knowledge gaps in three areas: processes driving habitat change, factors that confer resilience, including feedbacks that maintain undesirable degraded habitats, and development of solutions to restore and boost resilience. Collectively addressing these gaps will improve the resistance and recovery of degraded sedimentary habitats in Australia.

## 1. Identifying drivers of change

Controlled field and laboratory experimentation with multiple stressors calibrated for current and future environmental scenarios will be required to understand the drivers of change. A nationally coordinated *in situ* manipulative experimental approach to test how disturbance (e.g. nitrogen enrichment, excess organic matter, warming and ocean acidification) affects biodiversity and ecosystem function/biogeochemical processes, would identify thresholds or tipping points above which these key ecosystem services are lost. For example, a large representative intertidal area of similar sediment type (i.e. mud or sand) could be chosen across temperate and tropical locations. Macrofauna and microbial species abundance and richness would then be mapped across each intertidal area and a number of sites chosen with a range of macrofauna (low/high abundance/richness) with functional traits that are likely to influence sediment nitrogen cycling (e.g. bioturbation, mobility, feeding mode). Sites would be chosen at each location for disturbance treatments (e.g. either enrichment with nitrogen or organic matter) and controls. A suite of parameters likely to influence ecosystem function would be measured, such as community diversity indices, habitat characteristics, abundance of ecological engineering species, and functional diversity indices (Thrush *et al*. 2017). We would then determine which measures best predict ecosystem function across the temperate and tropical locations, and how these might change with disturbance, and identify thresholds or tipping points.

Mesocosm experiments could also be used to represent a range of future scenarios of environmental change. A few mesocosm studies have looked at the combined effects of temperature and ocean acidification on sediment carbon cycling and burial (Simone *et al*. 2021a, 2021b). Mesocosms have also been used to look at the effects of temperature or ocean acidification on sediment nitrogen cycling (e.g. Zhou *et al*. 2014; Vopel *et al*. 2018; Tan *et al*. 2020), but only one study has looked at the combined stressors (e.g. Simone *et al*. 2022). Not all nitrogen processes (e.g. denitrification, anammox) have been studied. Furthermore, few studies have considered the interactions between sediment macrofauna, microfauna and biogeochemical processes. Most of these mesocosm studies have also only been done at one or two sites. A national approach will allow these experiments to be done across a broader range of estuaries, sedimentary types and stressors.

## 2. Understanding resilience

The sediment type, the type of disturbance and the type of estuary in which the sediment resides will all be important components of the resilience of benthic communities and sediment biogeochemical processes, and how they will recover following disturbance. Well-flushed estuaries with coarse sediments and high turnover of organic matter (low storage) will most likely recover more rapidly than poorly flushed systems with a legacy of stored organic matter (Borja *et al*. 2010). For example, in the well-flushed Avon-Heathcote Estuary, sediment denitrification rates decreased following removal of wastewater nitrogen loading, but the percentage of the nitrogen load removed via sediment denitrification increased as a result of greater efficiency (Zeldis *et al*. 2019). In contrast, repeated trawling (physical disturbance) at monthly intervals increased

the loss of sediment denitrification capacity in Moreton Bay, showing declining resilience to trawling (Ferguson *et al*. 2020), and increased sedimentation in New Zealand estuaries has resulted in the loss of resilience of nitrogen cycling (Douglas *et al*. 2019). Ecosystem engineering by benthic organisms is important for the resilience of sedimentary systems (Thrush *et al*. 2012; Douglas *et al*. 2017; Bugnot *et al*. 2022a). However, there have been few studies of resilience and recovery of benthic communities and sediment biogeochemical processes and, as such, we known little of the overarching factors and feedbacks that limit resilience and recovery, and how these respond to environmental changes.

## 3. Solutions

The opportunities for remediating or rehabilitating sedimentary habitats in estuaries remain relatively understudied, beyond simply removing or mitigating the stressor or physically dredging and capping contaminated sediments (Adriaens *et al*. 2006). The few examples of remediating sedimentary habitats have focused on contaminated sediments, and none have looked at the key nitrogen cycling processes of denitrification, anammox and dissimilatory nitrate reduction to ammonia. For example, biological remediation (bioremediation) of contaminated sites has become an increasingly popular alternative due to its potential for cost effectiveness and lower environmental impact (Gifford *et al*. 2007).

Bioremediation uses living organisms that interact directly or indirectly with the environment to neutralise or remove contaminants (Iwamoto and Nasu 2001). The restoration of infauna to sediments is being trialled at small and large scales in efforts to oxygenate sediments (through bioturbation) and accelerate microbial remediation activities (Gifford *et al*. 2007; Shen *et al*. 2017; Gonzalez *et al*. 2019; Bugnot *et al*. 2022b). Furthermore, advances in molecular techniques are creating new solutions for bioremediation through the power of microbial inoculations or 'probiotics' for contaminated sediments.

Bioturbation comprises a series of processes driven by macrobenthic fauna that affect the physical and chemical properties of sediment and strongly influence bacterial communities involved in nutrient cycling (Biles *et al*. 2002). Bioturbation considers both particle reworking, bio-irrigation and other behaviours of benthic biota (i.e. feeding or grazing) that are involved in the transport and movement of porewater and particles through the water–sediment interface (Kristensen *et al*. 2012). Sediment reworking and bio-irrigation can affect the mobilisation of dissolved and particulate contaminants by increasing the transport and biomixing rate from overlying water and porewater to deep layers of the sediment (Teal *et al*. 2013). Bioturbators can also increase contaminant sequestration by the formation of complex biofilms derived from bioturbator organic waste (Lalonde *et al*. 2010). In addition, bioturbation activities can increase benthic metabolism and nutrient dynamics by the stimulation of aerobic bacterial communities that participate in contaminant degradation (Shen *et al*. 2017; Bugnot *et al*. 2022b). Removal of bioturbators also decreases denitrification rates, suggesting that the addition of bioturbators would increase denitrification rates, but this has only been trialled at a very small scale (<1 $m^2$; e.g. Webb and Eyre 2004).

Many bacteria naturally degrade chemical contaminants, can rapidly reproduce and are easy to modify and cultivate, making them ideal candidates for inoculations for remediation of contaminated sediments. Bacteria can naturally degrade hydrocarbons, metals and other contaminants in sediments, although this is often done in combination with other physical remediation activities to speed up the process (Arelli *et al*. 2018). More recently, bacteria have been identified that could 'digest' some types of plastic waste. Though plastics are generally not biodegradable, some groups of bacteria can settle on plastics once weathered and use it as a carbon source, potentially speeding up the degradation process (Yoshida *et al*. 2016) or reducing toxicity of associated contaminants (Rosato *et al*. 2020). The microbes applied might be organisms that naturally contain catabolic genes that can target a particular pollutant, or they might be organisms that have been genetically modified to provide this function (reviewed by Perpetuo *et al*. 2011). Significant progress has been made in engineering bacteria for bioremediation, but difficulties remain in applying these biotechnologies at large scales in the field due to cost, site suitability and the concentrations of contaminants present.

One approach to test microbial remediation would be to trial sediment translocations, microbial inoculations, and/or infaunal reintroductions in sediment mesocosms across a gradient of degradation (excess nutrients and/or organic matter) to see if measures of microbial or macrofaunal communities, biogeochemical processes and ecosystem functions converge with those measured in healthy sediments or return to a different state. Outcomes will then help formulate optimum management strategies.

Image: Ian McLeod

NATIONAL MARINE SCIENCE – COMMITTEE –

NATIONAL MARINE SCIENCE PLAN
Towards a nationally integrated approach to experimentation for managing and enhancing Australia's coastal marine ecosystems
Working Group Report

**TECHNICAL REPORT**

This full technical report, and a PDF of the summary, are available at

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