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A national framework for improving seagrass restoration

Inclusion of sediment processes in restoration strategies for Australian seagrass ecosystems

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Contents

List of figures

List of tables

Executive summary

Australia's coastal marine ecosystems are of enormous economic, environmental and socio-cultural value. Globally, seagrasses are one of the most valuable ecosystems in the world, with services valued at $11 billion annually. They are known to increase water clarity, stabilize the sediment and reduce coastal erosion, sequester carbon, and provide habitat and food to many marine animals, including commercially important fish and invertebrates. Seagrasses hence play a critical role in the health of coastal ecosystems and many human populations because of the resources and ecosystem services that they provide.

However, seagrasses are declining at an alarming rate of around 7% per year globally. Seagrass losses in Australia follow global patterns, with a reported total loss of at least 291,783 ha, representing 5.5% of estimated areal extent, since the 1930s. There are many factors that have contributed to seagrass decline, including sediment and nutrient inputs, boating activities, as well as climatic changes. As the human population density along coastlines continues to grow, so will the pressure on seagrasses. There is a clear and urgent need to restore seagrass to enhance the ecosystem functions and services they provide and enhance the resistance and resilience of coastal ecosystems to further environmental change.

Despite some successes seagrass restoration is still often perceived as very unpredictable and risky as efforts to restore seagrass habitats have met with limited success. As a result, seagrass restoration is stuck in an acknowledged stagnation loop, in which poorly performing restoration trials lead to the perception of seagrass restoration being risky, and thus adequate funding to improve restoration methods is lacking.

Breaking out of this "performance-perception-funding" stagnation loop requires two main considerations. Firstly, improved restoration methods that enhance the success of restoration trials are required. To do so, there is a universal need for more basic ecological knowledge on the factors that impact seagrass performance, as well as applied research to incorporate those factors into existing restoration methods. Secondly, there is a need for increased community ownership and participation in successful restoration projects to change the perception of seagrass restoration and enhance project success.

Previous global reviews have highlighted the need for large-scale restoration and discussed how we might achieve that. Similarly, Tan et al. (2020) have reviewed the various methodologies employed in seagrass restoration across Australia and New Zealand, and the relative successes the methods have achieved. Indeed, roadmaps for coordinated landscape-scale coastal and marine ecosystem restoration have been developed in several reviews and are a focus of the partner NESP project (1.6).

One key aspect that has received little to no attention in seagrass restoration projects is the importance of sediment processes. Here, we review how sediment processes, which are ignored in restoration but are critical to seagrass health, can be incorporated into current seagrass restoration frameworks. Sediment processes will affect nearly all facets of the restoration process. For example, sediment quality will determine site selection and whether

any environmental intervention/enhancement is required (e.g. large scale sediment stabilisation, or microbial or nutrient seeding), which in turn will influence the methods used for restoration and the potential outcome for restoration. Yet, frameworks for restoration make almost no provisioning for the inclusion of sediment processes, and can thus be considered incomplete.

In this report, we conducted a workshop of national experts in seagrass biology and restoration to review the current information on how sediment processes influence seagrass health. We identified which processes are amenable to manipulation, at what scale they could be employed to improve restoration strategies, and how community groups could be best engaged to contribute to restoration activities. During the workshop we identified four key interdependent areas by which sediment processes influence seagrass health and performance. Those three areas included how 1) sediment microbial communities control nutrient and chemical cycling for seagrass, 2) seagrass response to sediment processes may be influenced by their life-history and genetics of seagrass species targeted for restoration, and 3) interactions with other species that promote and inhibit seagrass survivorship and growth.

We also present the results of three restoration trials involving collaboration with Indigenous and community groups. These are: use of sediment filled hessian tubes for seed and seedling capture (Malgana Rangers, UWA) and scaling up seed collection for seed-based restoration (Seeds for Snapper, OZFISH, UWA) in Western Australia, and assessing fragment collection techniques and the effects of sediment quality manipulations on engendered *Posidonia australis* in Botany Bay (Gamay Rangers, UNSW). These case studies provide evidence and examples of how local communities and stakeholders can be involved in on-ground seagrass restoration projects.

Our workshop identified significant opportunities to enhance seagrass restoration by explicitly including sediment processes. This includes enhanced methods for restoration, more effective monitoring and assessment of restoration success. Importantly, we suggest decision-making frameworks should be extended to include sediment processes as they are of primary concern in determining initial site suitability and affect subsequent decisions and planning for restoration. At the outset, we recognize that hydrodynamics play a key role in determining sediment factors that may both benefit and hinder the successful restoration of seagrasses. We suggest therefore that an assessment of hydrodynamics and its implications for sediment properties and microbial community development is an important first step in site selection, the choice of restoration strategies, and selection of suitable donor material.

Hydrodynamics play a key role in determining sediment factors that may both benefit and hinder the successful restoration of seagrasses. In general, high-energy environments (e.g. shallow sediments subject to high bed shear stress due to wind waves and / or tidal currents) may preclude the recruitment of seagrasses due to physical disturbance associated with sediment resuspension and smothering. These sites are likely to have coarser sediments, with low organic carbon and nutrient contents, therefore sulfide stress will be low, however nutrients may be limiting especially before meadow continuity is achieved. In contrast, low energy environments promote the accumulation of fine sediments and organic matter therefore potential sulfide stress may be high and limit survival of seedlings and propagules.

As seagrass meadows develop, the canopy tends to attenuate wave and current energy, promoting particulate trapping which can form an important nutrient input to sustain growth. However, in some situations this can lead to complete ‘stilling’ of the water column causing stagnation which can have various negative feedbacks to seagrass health (e.g., large diel oxygen changes, epiphytic and macroalgal growth etc.). We suggest therefore that an assessment of hydrodynamics and its implications for sediment properties and microbial community development is an important first step in site selection, the choice of restoration strategies, and selection of suitable donor material.

One of the key areas in which restoration can be improved is through a more complete understanding of the role sediment microbes play in controlling seagrass performance in relation to sediment properties. Seagrasses have intimate connections with their microbial communities which control a range of critical processes such as nutrient cycling and buffering against sulfide toxicity. Microbial community diversity and its beneficial impacts on seagrass health increase due to positive feedbacks associated with oxygen loss to the rhizosphere as seagrasses grow and meadows develop. Understanding how and which microbes (taxonomic or functional) influence seagrass health and their relation to sediment properties such as grain size, we suggest, will have major implications for site selection, identify suitable donor beds and will greatly improve methods for restoration. For example, site selection may be improved by selecting areas that have sediment properties that support appropriate microbes to promote growth. We suggest, therefore, that the initial phase of seagrass establishment is critical in terms of providing seagrasses with an opportunity to overcome poor sediment conditions. In addition, information on seagrass-microbe interactions should be incorporated in monitoring strategies to check that the manipulation of plants, seeds or sediments does not lead to microbial changes that may negatively affect restoration success.

In the absence of appropriate microbes promising methods include planting shoots or seeds in biodegradable pots that house appropriate microbial communities. We note here that similar techniques involve taking plugs of seagrass from established beds and transplanting them. However, this technique will be largely restricted to small scale ventures given the impacts that extensive plug removal may have for donor beds. One method that may have promise at larger scales is seeding sediments with sediment containing preconditioned microbes that can support seagrass survivorship and growth. Seeding areas with ‘good’ sediment may also be a strategy for enhancing the resistance and resilience of seagrass beds currently under stress.

Molecular tools to investigate microbial communities and functions should, more broadly, be incorporated into and aid in the development of large-scale monitoring programs (see NESP Projects 1.5 and 1.6) as an additional tool to determine the health of seagrass beds, and, if seagrass health/microbe relationships are known then they may be useful for detecting stressed beds even if loss of seagrass is not yet evident. Rapid advances in molecular techniques also allow us to improve current monitoring and reporting approaches by screening sediments for beneficial/harmful microbes that could be early indicators of seagrass performance and the ecological status of a site. However, more basic research in understanding seagrass/microbe relationships is needed as is applied research in how to deliver these techniques. We note the lead author team of this report is currently undertaking some of this research as part of the Australian Research Council Linkage Grant (LP200200220). However, central to developing a framework where seagrass-sediment interactions are amenable to restoration, management and monitoring activities there is the need for standardised or best-practice methodology for sample collection and processing, culturing protocols, primers, and bioinformatics pipelines. Large consortia and associated databases, such as BioPlatforms in Australia and the Mangrove Microbiome Initiative and Earth Microbiome Project worldwide would facilitate standardisation, as well as provide a place for sequence deposits and metadata.

Seagrass life-histories and genetics will have important implications for restoration, including site selection and selection of donor material. For example, genomic analyses can assist in identifying and matching genotypes from donor meadows to environmental conditions at restoration sites. Transcriptomic studies of gene expression also provide significant opportunities for restoration genetics as they allow for the identification of the genes underlying responses to specific environmental stressors. Large-scale genetic structuring as known for *Posidonia australis* and *Zostera muelleri* on the coast of Australia, and low levels of genetic diversity such as occurs in NSW for *P. australis* (Evans et al., 2014), may also have consequences for restoration at scale and for future-proofing seagrass beds against climate change. Ensuring restoration material contains genetic variants that allow for adaptation to future projected environmental conditions will be critical for positive long-term management outcomes. In addition, some fast-growing species such as *Halophila* may be less reliant of microbial interactions and may be used to prime disturbed sediments (Kenworthy et al., 2018; Van Keulen et al., 2003) with good microbes, or by improving below-ground sediment chemistry to support the restoration of slower growing, longer-lived species such as *Posidonia* and *Amphibolis.* Such landscape approaches would complement other current NESP projects (Project 1.6 – A roadmap for coordinated landscape-scale coastal and marine ecosystem restoration). Clearly, a lot more experimental research needs to be done to ensure that the genotypes or functional groups used in restoration trials match local environments. Fortunately, seagrasses are amenable to such manipulations in the field.

Our review also highlighted that interactions with other organisms – positively or negatively – will also influence restoration success. For example, in areas they are absent, bioturbating species may be distributed to enhance sediment oxygenation and chemical cycling to the benefit of seagrass. Alternatively, restoration may be inhibited by species (e.g., sand dollars) that may bury seeds to disturb shoots. Interestingly, there is now a movement towards whole ecosystem management (a focus of NESP Project 1.6), rather than managing individual habitats. Such approaches explicitly acknowledge synergies and energy flows amongst habitat within ecosystems. One aspect that shows promise is co-restoration of seagrass with oyster reefs. Oyster reefs may act to stabilize sediments and increase organic inputs that may enhance seagrass growth. In the USA, restoring oyster reefs has certainly enhanced restoration efforts for other plants such as salt-marsh communities and oyster restoration programs in Australia are growing in number and size.

Encouragingly, our community engagement with recreational fishing groups (OZ Fish) and Indigenous peoples (Malgana Land and Sea Rangers; Gamay Rangers) was successful across all three on-ground projects conducted in New South Wales (NSW) and Western Australia (WA). Common successful elements were the inclusion of community in the collection and distribution of propagules, providing logistical support and infrastructure deployment. These appear to be an aspect of restoration amenable for community group engagement. However, we also identified opportunities for community groups to get involved with the science of restoration, including not only the scientific training of Indigenous students (as in Case Study 3), but also in the training of divers to collect scientific information underwater. Similar strategies have been highly successful in other community science programs such as the Reef Life Survey. Training the community themselves to educate, rather than just participate, will be a valuable tool in increasing community participation and ownership in restoration programs. These on-ground activities also highlighted the potential for the use of seeds for large scale restoration – although this will not always be possible as is likely the case in NSW. The use of seeds also maximises diversity and allows restoration for different parts of the geographic range to future proof restoration sites for future environmental conditions.

Across the areas we identified it is evident that sediment processes are at the heart of many feedback processes influencing seagrass health. The right experimental strategies aimed at understanding the role of sediment processes in seagrass health will provide evidence-based insight into what management actions, at small and large scales, will improve seagrass restoration efforts. A lot of great work has been done, and now it is time to build on current knowledge to work towards the restoration of degraded seagrass habitat by experimentally testing the interactions between seagrasses and their environment, improving current restoration methods, utilising new tools and techniques, and involving local community groups. This will provide better advice for management and advance the field of seagrass restoration.

1. Introduction

1.1 Seagrass value and ecosystem service provision

Marine coastal and estuarine ecosystems are some of the most productive in the world. However, centuries of environmental degradation, fisheries exploitation and habitat loss have led to marine coastal and estuarine ecosystems becoming some 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 consequences of human development and exploitation of marine coastal and estuarine ecosystems is the severe reduction and, in some instances, complete loss of seagrasses and the ecological, and socio-economic services they provide. Seagrass meadows provide critical nursery grounds for fisheries, nutrient cycling, coastal protection and habitat for biodiversity including provision of habitat for iconic species such as dugongs. Seagrasses also represent a globally significant component of carbon sequestration, or Blue Carbon (Macreadie et al., 2019; Serrano et al., 2019; https://www.iucn.org/resources/issues-briefs/blue-carbon). Through these services, seagrasses provide an estimated $6.8 Trillion to the global economy (Costanza et al., 2014) and comprise a substantial component of Australia's $75 billion Blue Economy. 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). Enhancing the resilience (the ability to recover) and resistance (the ability to resist) of seagrasses to environmental stress, and restoring lost seagrass habitat is critical for improving the health and function our marine coastal and estuarine ecosystems, buffering coastal ecosystems from ongoing climate change and sustaining the coastal communities and industries dependent on these.

1.2 Seagrass – an Australian context

Australian coastal ecosystems contain an estimated 51,000 km^2 of seagrass meadows that encompass the country – from cool-temperate to tropical regions. Our coasts are host to some of the most diverse seagrass meadows in the world (Larkum et al., 2018), including many key endemic species. Over 60% of the world's seagrass species are found on Australian coastlines, beds of which form some of the most iconic coastal habitats globally. The Shark Bay World Heritage area in Western Australia, for example, contains the largest seagrass meadow in the world covering an estimated 20,000 km^2.

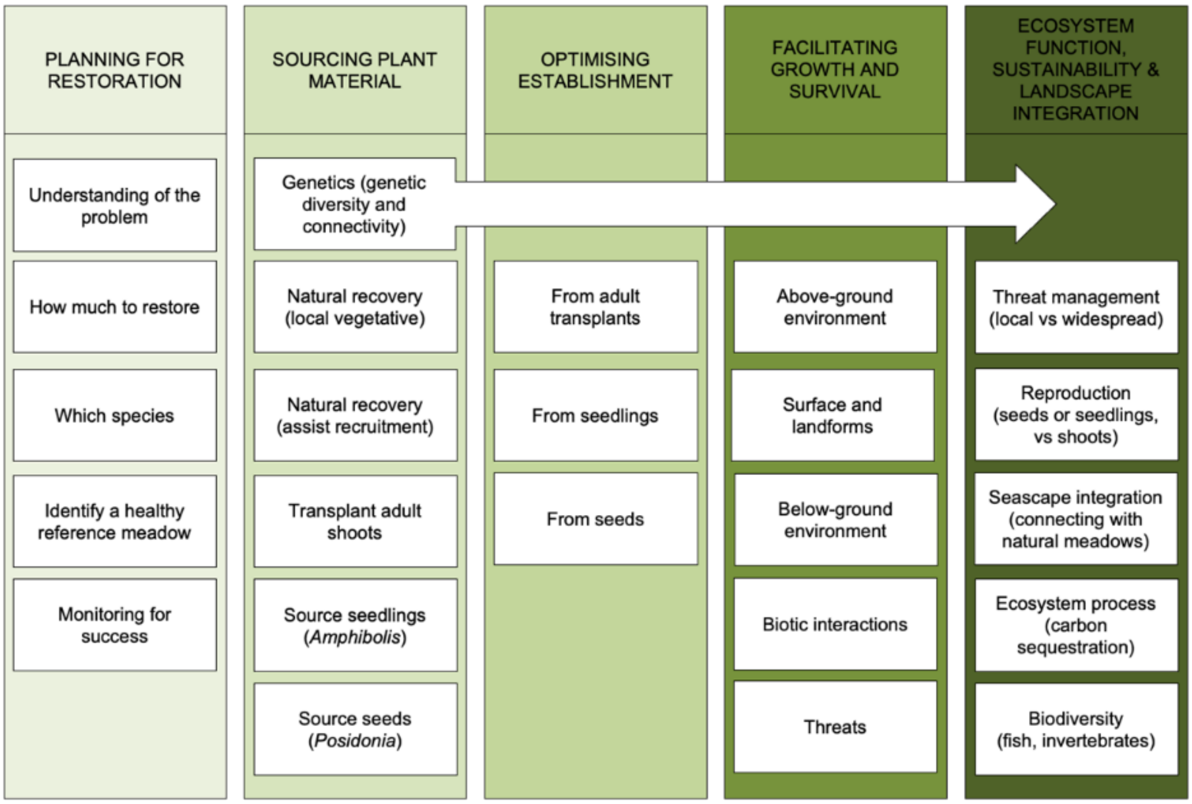
However, seagrasses are declining at an alarming rate of around 7% per year globally (Waycott et al., 2009). Seagrass losses in Australia follow global patterns, with a reported total loss of at least 291,783 ha, representing 5.5% of estimated areal extent, since the 1930s (Statton et al., 2018a). Seagrasses have declined by over 90% in Sydney Harbour and Cockburn Sound, Western Australia, and 36% of Shark Bay's seagrass were lost to a single heatwave in 2011 (Arias-Ortiz et al., 2018). In New South Wales, populations of the long-lived species *Posidonia australis* are now listed as critically endangered. This loss of seagrass represents an associated loss of ecosystem services – valued at AU$11 billion annually (based on 2011 seagrass service values of US$28916 per ha; Costanza et al., 2014).

Table 1. The main environmental factors that cause physical, chemical and biological change to the environment and are involved in seagrass decline (adapted from (Statton et al., 2018a)**.**

FACTOR	PROCESSES INFLUENCED	OBSERVED CHANGES TO SEAGRASS MORPHOLOGY, AND MEADOW EXTENT AND CONFIGURATION
Light	Photosynthesis	Lower depth limits; growth rates; shoot density
Hydrology (i.e. currents, wave action and tide)	Seagrass-sediment feedback	Upper depth limits; vegetative (rhizome) spreading; seedling colonization; accumulation of fine sediments and organic matter; shoot density; direct influence on associated biota; meadow configuration (pattern, shape and juxtaposition of patches)
	Epiphytic biomass growth	
	Sediment grain size and associated nutrient and oxygen exchange	
	Turbidity (see light)	
	Desiccation (tidal exposure)	
	Diffusion of nutrients/gases across leaf boundary layers	
	Erosional/depositional processes	
Geology	Erosional/depositional processes as well as the availability of nutrients and phyto-toxins	Growth, morphology and landscape configuration
Temperature	Plant metabolic rates (seagrass and associated algae)	Growth rates and distribution
	Flowering, germination	
	Dessication	
Oxygen	Aerobic metabolism	If oxygen supply to meristems and roots of the seagrass is inhibited for long periods of time, the plant risks reduced growth rates or mortality
Salinity	Osmoregulation	Biogeographical distribution
Nutrients (C, N, P)	Photosynthesis, growth, light availability	Epiphyte cover, seagrass density

Many factors have contributed to seagrass declines (Table 1), but chiefly responsible among these are massive historical and continuing land-based sediment and nutrient inputs (Orth et al., 2006), as well as contemporary climate related stressors. For example, following an extreme heatwave event in 2010/11, 1,310 km^2 seagrass habitat was lost from the Shark

Bay World Heritage Area (Strydom et al., 2020). To date, management actions have focussed on improving light quality by mitigating sediment and nutrient loads (Orth et al., 2006). Previous global reviews have highlighted the need for large-scale restoration, discussed how we might achieve that and subsequently developed ecological decision-making frameworks for seagrass restoration (Figure 1). Similarly, Tan et al., (2020) have reviewed the various methodologies employed in seagrass restoration across Australia and New Zealand, and the relative successes the methods have achieved. Indeed, roadmaps for coordinated landscape-scale coastal and marine ecosystem restoration have been developed in several reviews and are a focus of the partner NESP project (1.6). Here, we review how sediment processes, which are largely ignored in restoration and initial decision-making making frameworks (Figure 1) but are critical to seagrass health - influencing all aspects of restoration from selecting donor sites, restoration site selection, development of improved methods and monitoring regimes -, can be incorporated into these seagrass restoration frameworks to enhance their success.



(adapted from Miller et al. 2017 for marine restoration)

Figure 1. Ecological decision-making framework for seagrass restoration (reproduced with permission from Gary Kendrick).

1.3 Successful restoration requires integrated approaches to restoration

Most current seagrass restoration efforts in Australia are small scale with experiments focused on understanding the efficacy of restoration techniques (Sinclair et al., 2021). Seagrass restoration has traditionally been focussed on shoot transplanting, either at small scales as sprigs, plugs or cores, and at larger scales as mechanically moved sods (summarized in Statton et al. 2018). Seed-based restoration offers the opportunity to scale-up seagrass restoration to address the loss of seagrasses in Australian at the ecosystem scale (Sinclair et al., 2021). It also addresses the cost of restoration, seen to be excessive by some (Bayraktarov et al., 2016), through an integrated community-based restoration approach. In sedimentary unstable areas, current restoration efforts are focused on developing improved methods to stabilize the sediment for seeding and anchoring of shoots. Methods generally involve tying seagrasses to metal frames or nets that are subsequently lowered to the seafloor, which enhances the anchoring of shoots. The use of biodegradable material such as jute or hessian bags enhance seagrass survival, for example by excluding bioturbating animals (Tan et al., 2020). These restoration efforts are improving seagrass growth and survivorship, particularly at smaller scales (Tan et al., 2020). For some seagrass systems, these experiments are beginning to lead to larger scale efforts. Following experimental testing of methodologies (e.g., https://www.seagrassresearch.net/restoration) seagrasses are now being restored at scale in Cockburn Sound, and Shark Bay, Western Australia.

In providing pathways towards successful restoration, particularly at scales at which they are being lost and which are capable of enhancing ecosystem functions and services and building climate resilience, recent reviews highlight a variety of ecological, biological and social-economic factors that need to be integrated for large-scale restoration to be effective (Abelson et al., 2020, 2016; Figure 2). Fundamentally, however, successful restoration is contingent on appropriate site selection and removal/abatement of stressors that provide barriers to natural recovery or restoration. In general, high-energy environments (e.g. shallow sediments subject to high bed shear stress due to wind waves and/or tidal currents) may preclude the recruitment of seagrasses due to physical disturbance associated with sediment resuspension and smothering. These sites are likely to have coarser sediments, with low organic carbon and nutrient contents, therefore sulfide stress will be low, however nutrients may be limiting especially before meadow continuity is achieved. In contrast, low energy environments promote the accumulation of fine sediments and organic matter therefore potential sulfide stress may be high and limit survival of seedlings and propagules. As seagrass meadows develop, the canopy tends to attenuate wave and current energy, promoting particulate trapping which can form an important nutrient input to sustain growth. However, in some situations this can lead to complete ‘stilling’ of the water column causing stagnation which can have various negative feedbacks to seagrass health (e.g. large diel oxygen changes, epiphytic and macroalgal growth etc.). We suggest therefore that an assessment of hydrodynamics and its implications for sediment properties and microbial community development (see below) is an important first step in site selection, the choice of restoration strategies, and selection of suitable donor material.

Improvement in water quality has led to efforts across Australia to restore many of the major habitat forming organisms of coastal zones, including seagrasses (McLeod et al., 2018a). Yet, seagrass recovery or active restoration often fails even after water quality is improved. Importantly, sediment and nutrient deposition also affect sediment grain size, nutrient and chemical cycling under microbial control, which can impact seagrass performance and natural recovery long after water quality is improved. However, current restoration methods make no provision for the inclusion of sediment processes in the outcome of restoration.

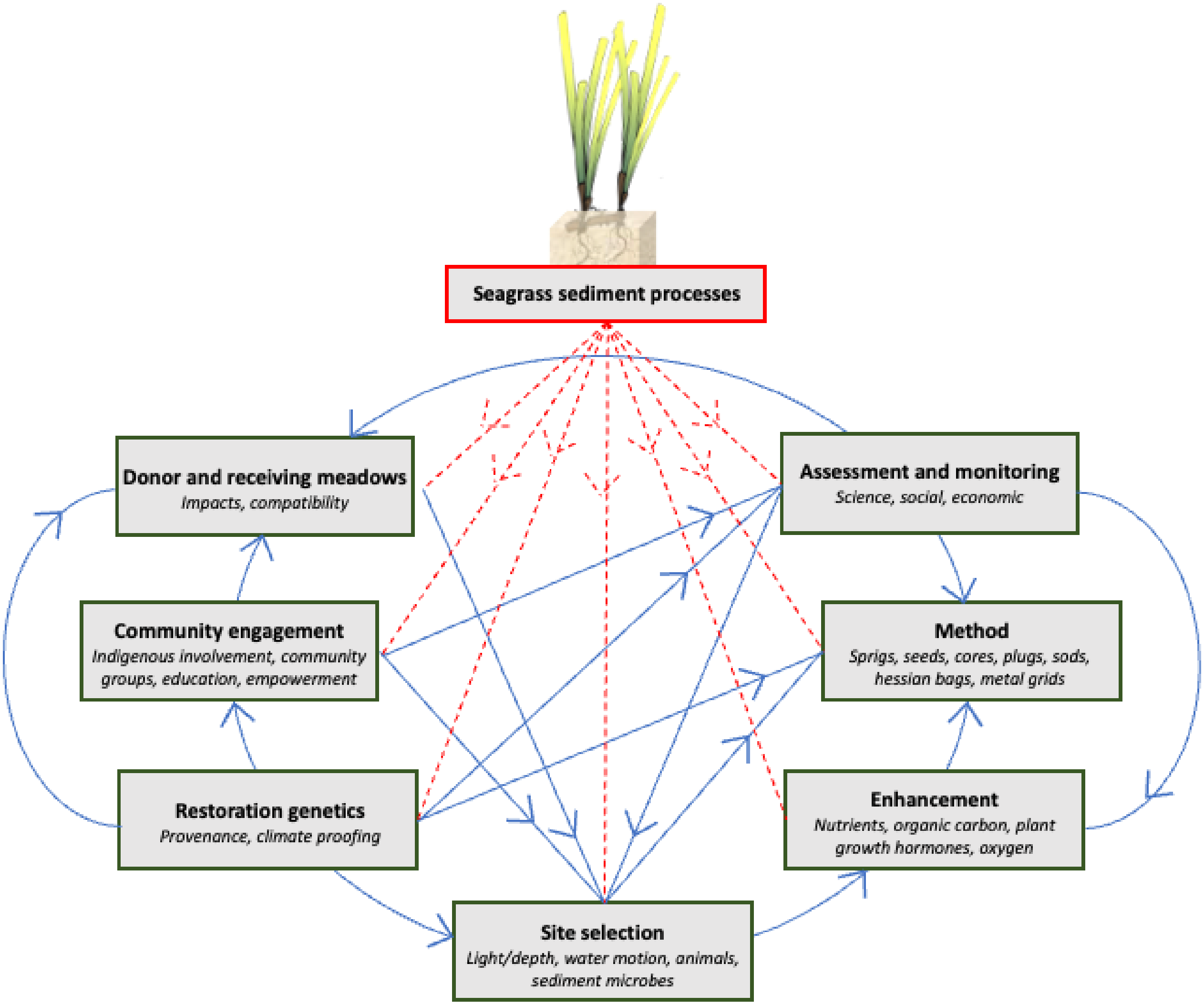


Figure 2. Seagrass restoration network including major ecological, biological and socio-economic components required for restoration success. Sediment processes are at the heart of many components involved in restoration success. Arrows indicate flow of knowledge, labour and other monetary values. (Figure adapted from WAMSI Westport seagrass restoration workshop; reproduced with permission from Gary Kendrick).

Ultimately, seagrass health is determined by the interaction between seagrasses and their environment. Seagrasses are keystone species that create feedbacks that influence hydrodynamics, particulate trapping, sediment quality, microbial processes, redox-based cycling of sediment chemistry, and bioturbation (Figure 3). The expression of these feedbacks is to an extent dependent on the seagrass species and the structure/extent of the meadow (e.g. (Kilminster et al., 2015). A particular challenge for the restoration of seagrass meadows is creating conditions that promote the establishment or 'seeding' of critical feedbacks that allow plants to survive and persistent in a given site. Sediment processes are at the heart of these feedbacks and thus critical for improving seagrass health and restoration outcomes (Figure 3). For example, sediment quality will determine site selection and whether any environmental intervention/enhancement is required (e.g. microbial or nutrient seeding) which in turn will influence the methods used for restoration. The sediments themselves can be influenced by larger-scale hydrodynamics which can influence sediment stability. Aspects at the smaller plant scale, such as their life-history and genetics may dictate how they respond to differing sediment conditions and influence the outcome of restoration efforts. Interactions with other organisms can also affect seagrass survivorship and growth. For example, bioturbating organisms can improve sediment conditions by enhancing below-ground oxygen conditions which can enhance seagrass performance. However, bioturbation can also result in the burial of seagrass seeds decreasing survivorship. Thus, whilst bioturbators may be used to augment restoration in some instances it may not be effective in others.

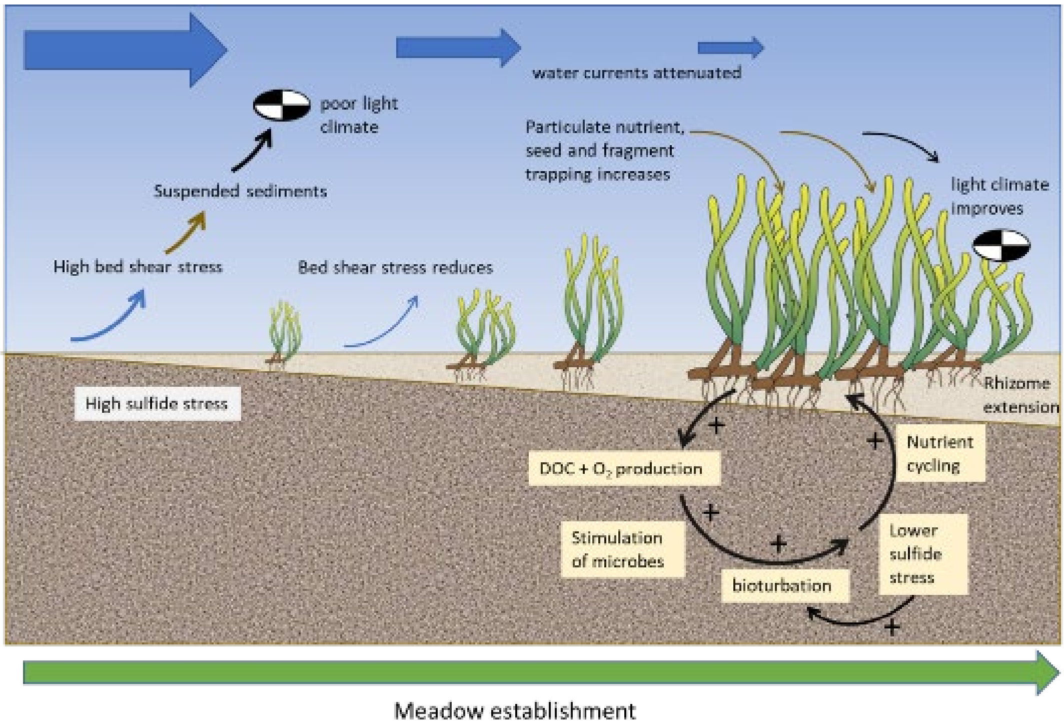


Figure 3. Seagrasses are keystone species that create feedbacks that influence hydrodynamics, particulate trapping, sediment quality, microbial processes, redox-based cycling of sediment chemistry, and bioturbation.

1.4 Restoration perceptions, problems and needs

Seagrass restoration is often seen as a risky undertaking, because restoration trials often fail to deliver the desired outcomes resulting in reluctance for communities to engage. The perceived lack of restoration success has resulted in hesitancy from policy-makers and resource managers to provide the necessary funding to develop adequate restoration methods. This has led to a 'stagnation loop' whereby a lack of funding to improve the science behind restoration leads to a lack of restoration success and community disengagement and continued low restoration success (Figure 4). Globally, it is acknowledged that to break this stagnation loop (as described in Abelson et al. 2020; Figure 4), we need 1) more successful restoration through a better scientific understanding of the factors influencing seagrass health and growth, and 2) an increase in community participation and ownership in restoration trials (Abelson et al., 2020, 2016). Ecological knowledge of seagrasses can then be utilised to develop better tools to accelerate recovery and enhance the resilience of restored systems. Involving stakeholders and local communities from an early stage can greatly benefit restoration projects, because it increases the amount of support from local groups, or because scientists can benefit from the often specialised knowledge that local communities have on the area and system that needs to be restored. However, we need to better understand the steps in the restoration process that communities are best suited to contribute to.

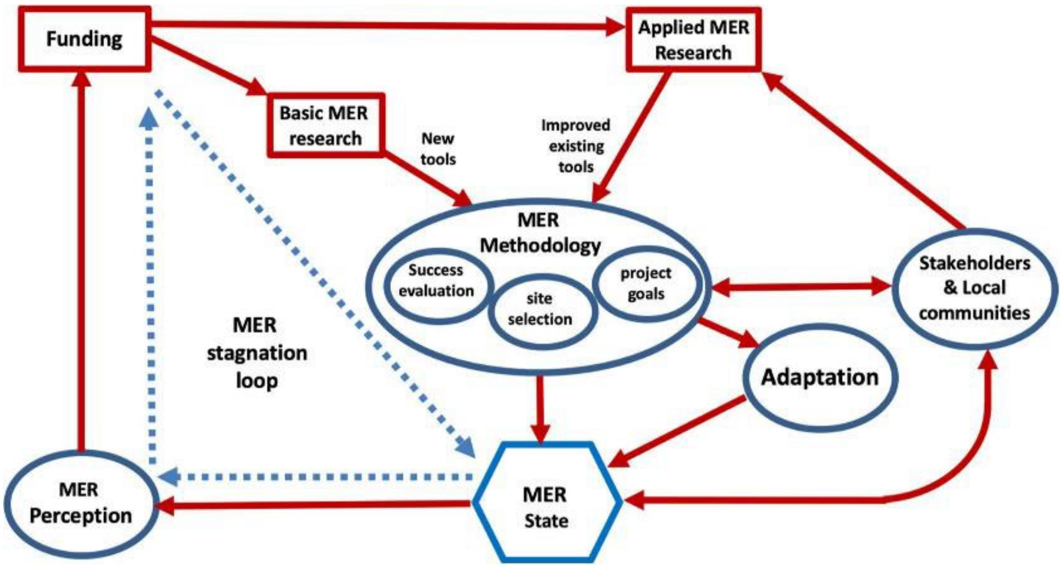


Figure 4. Conceptual framework of the four major coastal marine ecosystem restoration (MER) challenges (from Abelson et al., 2020). (1) development of effective, scalable restoration methods, (2) incorporation of innovative tools that promote climate adaptation, (3) integration of social and ecological restoration priorities, and (4) promotion of the perception and use of coastal MER as a scientifically credible management approach (indicated in blue circles). All these factors influence the success of marine ecosystem restoration projects (blue hexagon). Red rectangles indicate the governing or interacting factors involved in the major restoration challenges. Solid red arrows indicate flow of knowledge, labor and other monetary values. Broken arrows indicate interactions among the coastal MER "stagnation loop".

1.5 This report

2021–2030 is the *UN Decade on Ecosystem Restoration* and there are opportunities and desire from government, community groups and the scientific community to restore degraded ecosystems. However, successful restoration and building climate resilient coastal ecosystems is contingent on understanding the key environmental processes that both inhibit and promote restoration and recovery. Despite the well described influence of sediment processes on seagrass performance they are not considered in seagrass restoration, despite their potential to transform restoration success at scale.

In this report, we synthesise the current information on how sediment processes influence seagrass health and identify which processes are amenable to manipulation and at what scale they could be employed to improve restoration strategies and decision-frameworks. We also present the results of three restoration trials involving collaboration with Indigenous and community groups. These are: the use of sediment filled hessian tubes for seed and seedling capture (Malgana Rangers, UWA) and scaling up seed collection for seed-based restoration (Seeds for Snapper, OZFISH, UWA) in Western Australia and; assessing fragment collection techniques and the effects of sediment quality manipulations on engendered *Posidonia australis* in Botany Bay (Gamay Rangers, UNSW). Finally, using small scale experiments, we provide proof of concept of utilising sediment processes to enhance restoration success. These case studies also provide evidence and examples of how local communities and stakeholders can be involved in on ground seagrass restoration projects.

1.6 Workshop – review of sediment processes and their inclusion in seagrass restoration strategies

A 2-day online workshop was held with seagrass experts from universities, government and non-government agencies (see list in Appendix A) from around Australia. The workshop participants identified three key interdependent areas by which sediment processes influence seagrass health and performance, including how 1) sediment microbial communities control nutrient and chemical cycling for seagrass, 2) seagrass response to sediment processes may be influenced by life-history and genetics of seagrass species targeted for restoration and 3) interactions with species that promote and inhibit seagrass survivorship and growth.

For each theme, the participants reviewed the primary published scientific literature and provided a critical overview of the current state of knowledge. Each theme then identified the key opportunities for using this knowledge to improve restoration strategies, the scale which the knowledge can be applied, and the opportunity for community engagement in the activities. The report is not meant to contain an entire synopsis of the published literature for seagrass restoration as many aspects on frameworks, methodologies and successes have been extensively reviewed elsewhere (as discussed above). The review focuses on how to improve restoration outcomes through the inclusion of sediment processes and identify key impediments and knowledge gaps to doing this.

2. Workshop

2.1 Seagrass sediment microbes

Authors: Renske Jongen, Stacey Trevathan-Tackett, Belinda Martin, Matthew Fraser, Craig Sherman, Angus Ferguson, Ezequiel Marzinelli

2.1.1 Introduction

Seagrass conservation and restoration as a discipline and a practice has traditionally focused on the biology of the target plant species and their interactions with other macroorganisms and the environment – particularly above ground. However, there is mounting evidence of the vital roles microorganisms play in the health and function of their plant host, with critical microbial processes occurring below ground. Plants – and macroorganisms more generally - are no longer viewed as independent entities but rather as "holobionts", i.e. coherent functional entities comprised of the 'macrobial' host and its microbiome (Dittami et al., 2021). The emergence of the holobiont concept is rapidly transforming our understanding of plant and ecosystem health and has the potential to revolutionize the way we manage seagrass meadows.

The relationships between seagrasses and their rhizosphere microbiome are complex, constituting both mutualistic interactions and antagonistic feedbacks (Crump et al., 2018). Seagrasses influence sediment microbial communities by altering sediment redox zonation and biogeochemistry through the loss of oxygen from roots and rhizomes (Martin et al., 2019) and via the exudation of dissolved organic carbon (DOC) compounds which form a rich substrate for microbe productivity (Hansen et al., 2000). This can lead to a complex and dynamic balance between limiting conditions (e.g. sulfide toxicity due to the simulation of sulfate reduction), and ameliorating factors (e.g. sulfide oxidation and iron buffering within the oxic zone surrounding roots). Further complexity is introduced by environmental conditions such as light climate and sediment type, which can affect seagrass biomass allocation between above- and below ground compartments (Collier et al., 2021; Premarathne et al., 2021) as well as the production of DOC and oxygen (Martin et al., 2018; Zabarte-Maeztu et al., 2020). These interactions are significant in facilitating seagrass colonisation of sediment habitats, however their influence can vary significantly over temporal and spatial scales as well as a function of meadow maturity.

Here we identify several emerging areas of research that show promise in advancing our understanding of the roles microorganisms play in seagrass function and broader ecosystem health, and their implications for management. We argue that a healthy microbiome is critical to the successful restoration of seagrass meadows now and into the future, but to date has typically been ignored. Further, given the complexities, an in-depth functional understanding of seagrass-sediment microbe interactions and their relationship to environmental drivers is required for successful restoration strategies.

2.1.2 Current knowledge: plant-microbe interactions

In terrestrial systems, significant progress has been made in recognizing the importance of plant-soil interactions and the link between below-ground processes mediated by microbes and above-ground performance. As plants germinate and grow in the soil, they can influence the biotic and abiotic properties of the soil, e.g. through the release of chemical compounds and input of organic matter, which can result in changes of the microbial community composition and function (Van der Putten et al., 2013; Veen et al., 2019). These changes in soil properties and its microbiome can in turn affect the establishment and performance of plant individuals of the same or a different species, a process known as plant-soil feedbacks (PSF) (Bever et al., 1997). PSF can be negative (resulting in a net growth-reducing effect to individuals of the same species), neutral (the net effect of all influences to plant growth are zero), or positive (growth of the same plants or other individuals of the same species is promoted) (Van der Putten et al., 2013). PSF are now widely recognized on land as important drivers of plant community dynamics, plant coexistence and plant responses to environmental change (Kardol et al., 2006). Given the analogies between seagrasses and their terrestrial counterparts, there is huge potential for using these above-below ground links to advance the field of seagrass restoration.

Our understanding of seagrass-sediment interactions and feedbacks has only recently started to develop. Emerging studies show that seagrasses harbour diverse microbial communities on the surfaces and within their above- and below-ground structures (Garcias-Bonet et al., 2012; Tarquinio et al., 2019; Ugarelli et al., 2017), as well as on their seeds (Tarquinio et al., 2021). These studies show that microbes have the potential to strongly influence above- and below-ground processes related to carbon-, nitrogen- and sulfur cycling, all of which are linked to the performance of seagrass and the diverse ecological communities they support. For example, seagrass root-associated and rhizosphere (i.e. the region of sediment in the immediate vicinity of the roots) microbiomes are typically enriched in sulfur cycling bacteria, many of which are likely to play key roles in sulfide detoxification, ultimately contributing to the ability of seagrasses to persist in high sulfide environments (e.g. Martin et al., 2020; Scholz et al., 2021). Some of these bacteria also possess the genes to fix nitrogen (Mohr et al., 2021; Petersen et al., 2016), and breakdown organic matter, releasing nutrients that contribute to plant growth in otherwise oligotrophic oceans (Fraser et al., 2018). Epiphytic bacteria on leaf surfaces are a key component in the ability of seagrass to uptake dissolved organic nitrogen from the water column (Tarquinio et al., 2018). Some bacteria that occur on seagrass tissues can help defend against pathogens and saprophytes (Tarquinio et al., 2019). Seagrasses also host diverse fungal communities on and inside their leaves, roots and rhizomes, although their role in seagrass functioning is largely unknown (Ettinger and Eisen, 2020, 2019).

There is significant variation in the composition of the microbiome between seagrass species, particularly between different functional types of seagrasses (colonizing vs opportunistic vs persistent, sensu Kilminster et al., 2015). Significant variation can also be found among plants of the same species growing in different locations (Martin et al., 2022), which suggests that microbial composition is mediated by both the host and the environment. There is now experimental evidence that has linked alterations in seagrass microbiomes with changes in light (Martin et al., 2018), sediment organic matter (Fraser et al., 2016), nutrient enrichment (Wang et al., 2020), and temperature (Nguyen et al., 2021a). Such changes in environmental conditions can not only impact the health of seagrasses directly but also through changes to the associated microbiome. However, experiments that establish causal effects of microbial changes on seagrass performance are rare (but see Gribben et al., 2018, 2017).

Given the fundamental role that microorganisms have in biogeochemical cycling in seagrass ecosystems and their potential effects on plant performance, incorporating seagrass-microbiome interactions into restoration planning can significantly improve restoration success rates. The following sections outline how knowledge of seagrass-microbiome interactions and novel molecular tools can be used to enhance seagrass management and restoration efforts.

2.1.3 Management opportunities and knowledge gaps

Knowledge of seagrass and sediment microbiomes can be broadly used in a management context for monitoring, as well as for intervention. The former may involve the use of molecular tools to characterize seagrass restoration success by following the structure and function of plant and sediment microbiomes through time and space to establish a baseline against which the health status of meadows can be assessed. However, understanding of which microorganisms or functional groups are linked with poor plant performance is necessary in order to reveal key indicators or early warning signals that can be used as triggers of preventative management actions.

Monitoring via molecular tools can also be used for management interventions such as rehabilitation and restoration. For instance, information on plant and/or sediment microbiomes may be used to (i) identify “healthy” meadows that can be used as donors, either of shoots, seeds or sediment, (ii) select sites where microbiome composition is likely to increase the chances of restoration success, and (iii) check that the manipulation of plants, seeds or sediments does not lead to microbial changes that may negatively affect restoration success.

Seagrass restoration practitioners may still face considerable challenges that require active manipulations of sediments or plants focused on their microbiome. Reintroduced shoots and seeds can fail to establish in restored sites (Katwijk et al., 2016) because of the lack of an “appropriate” below-ground microbiome (Koziol et al., 2018). Emerging evidence suggests that ecosystem development can be steered by manipulating belowground microbes through different approaches, which we discuss below.

Sediment manipulations – plant-sediment interactions

Restoration of above-ground plant community properties may require steering of belowground ecosystem processes and those organisms that drive them (Wubs et al., 2016). Manipulations may thus focus on promoting the conditions that would facilitate the desired sediment microbiome, for example by providing appropriate levels and types of nutrients or by manipulating the physical environment (e.g. grain size). To achieve this, however, we need a much better understanding of what microorganisms or functional groups make up a "healthy" microbiome that facilitates seagrass establishment and which sediment characteristics, such as nutrient and chemical profiles, support such microbiome. Experiments testing under what sediment characteristics seagrasses grow best, and which microbial communities are present under those conditions are needed before we can incorporate sediment manipulations that promote desired microbiomes at larger scales.

An alternative approach for promoting seagrass-sediment interactions is to directly inoculate desired microbiomes in the sediment. Evidence from terrestrial systems has shown that the active reintroduction of beneficial soil microorganisms through soil inocula can steer the soil microbial community composition to favour the growth of specific target plants (Wubs et al., 2016), and can be critical to enhance the establishment of plants in degraded sites (Grman et al., 2020). For seagrasses, this could be achieved through inoculations with sediment from sites with healthy seagrass communities. This could be done either by transplanting seagrass in, for example, biodegradable pots containing the sediment inoculum, or by dredging a disturbed site and replacing the degraded local sediment with sediment from a healthy donor site. The use of pots containing healthy sediment may act as a buffer against hostile sediment conditions until the young, vulnerable plant is established. Dredging would likely work better at larger scales, however, we do acknowledge that this is a risky undertaking as this can damage a healthy donor meadow. More targeted and larger-scale inoculations could be achieved through culturing beneficial microbes, and coating seeds or spraying these inoculants as a liquid solution on degraded sites prior to restoration. The latter is now a commonly used method in the on-site bioremediation of oil-contaminated sites (Kuiper et al., 2004).

However, inoculated bacteria must compete with the often resistant and resilient native microbes, and shifting the microbial community from one stable state to another is challenging. Inoculants for field-scale use have to provide a dependable source of microbes that survive in the sediment and become available to seagrass (Bashan et al., 2014). In addition, inoculation success depends on several factors, including the abiotic sediment conditions of the recipient site (Emsens et al., 2022; Kardol et al., 2009). A ‘mismatch’ in sediment conditions between the donor and recipient site may limit the establishment of the introduced microbial communities and, as a consequence, the desired seagrass community. Combining inoculation with the manipulation of sediment properties as described above, could prepare a site for the establishment of the introduced microbiome. Additionally, the microbiome which might be considered ‘optimal’ could vary between species, environments, life-stage and even host genotypes. A first step when considering inoculation of seagrasses with beneficial microbes is to determine which functional groups make up a healthy microbiome that facilitates the intended establishment of seagrass seeds or shoots. Experiments testing which microbial taxa/functional groups may be most important for seagrass performance under a range of environmental conditions are needed to build healthy seagrass-sediment feedbacks.

Plant-sediment feedbacks

Restoration of below-ground ecosystem functions can be achieved by using plants as tools to alter soils, as plants can influence soil characteristics and microbiome structure and function (Angers and Caron, 1998; Kardol and Wardle, 2010). From terrestrial studies we know that facilitation processes during early succession are key to ecosystem development. These early successional stages are often linked to positive plant-soil feedbacks, as early arriving plants form associations with beneficial bacteria and fungi. This results in changes to soil microbiomes that in turn facilitate the establishment of other plant species (Van der Putten et al., 1993). From a seagrass management perspective, we could use such understanding to "fast-track" succession, e.g. by planting or encouraging the growth of early-colonizing species to set the belowground foundation for the target species. After the sediment is stabilized and microbial associations are established, shoots or seeds of the target species could be planted. Indeed, a study by Van Keulen et al., (2003) in Western Australia showed that cores of *Posidonia sinuosa* survived better when transplanted in a *Heterozostera tasmanica* bed compared with bare sand, or bare sand stabilized with mesh. In another study, shoots of the colonizing species *Halodule wrightii* were planted, with the goal of facilitating succession of the climax species *Thalassia testudinum* (Kenworthy et al., 2018). Experiments testing changes in sediment microbial communities following the growth of early-colonizing and target species, and the effects on seagrass survival are needed to validate this potential method.

Environmental feedbacks

The choice of appropriate restoration strategies depends on an assessment of site-specific environmental factors that influence seagrass-microbiome interactions, with a view to working within environmental constraints and promoting beneficial microbial processes. An understanding of local hydrodynamics and resultant impacts on light climate and sediment quality provides critical information on the likely barriers to seagrass restoration and informs the choice of establishment sites and donor populations (e.g. Statton et al., 2013). For example, higher energy environments are generally characterised by mobile sandy sediments that favour morphs with a higher allocation of below ground biomass (Peralta et al., 2006). This combined with lower sulfide stress and potential nutrient limitation in these environments has a large bearing on the rhizosphere microbial community and its function (Zhang et al., 2020). In contrast, sediments at more quiescent locations tend to have higher organic matter and fine sediment contents resulting in greater potential sulfide stress, a shift towards higher above ground biomass allocation, and distinct rhizosphere microbial communities (Fraser et al., 2016). Local geology can also influence important sediment factors such as iron contents which can significantly ameliorate sulfide stress in organic-rich sediments (Ruiz-Halpern et al., 2008).

Seasonal variations in light and temperature can also significantly impact seagrass productivity and biomass allocations, with flow-on impacts on sediment biogeochemistry and the rhizosphere microbiome (Martin et al., 2018; Nguyen et al., 2021b). These effects are also modulated across depth gradients and different sediment types which has implications for the identification of optimal windows of opportunity for establishing seeds and/or fragments.

2.1.4 Emerging techniques

Emerging techniques and approaches show promise for facilitating the discovery of microbes or microscale conditions that benefit seagrass germination, growth and health, a missing piece of the puzzle for understanding how microbiomes can be manipulated to improve seagrass management and restoration success. Such techniques build on the current foundation in seagrass root and rhizosphere microbiome biodiversity and correlative connections to novel observations that directly connect microbe function to the host, as well as host response to environmental conditions and the microbiome.

Developing methods to ‘remove’ or add microbes in different holobiont compartments or life-stages can be used to understand the cause-effect of restoration success. By manipulating the presence/absence of below-ground microbial communities in specific locations by sterilizing roots and/or sediments, we can determine the effects of sediment and root microbial communities on seagrass performance. Combining these manipulations with ‘omics’ techniques, would allow us to investigate which microbial taxa/functional groups are driving seagrass health and functioning. Another promising approach would be to use high-throughput culturing methods to isolate seagrass-associated microbes (Ettinger and Eisen, 2020), that can be screened and identified as conferring a beneficial trait/function, and suitable for probiotic inoculations (e.g. mangrove bacteria; Soldan et al., 2019).

Approaches that track direct seagrass-microbe interactions through exchange of elements, molecules and primary and secondary metabolites, include enriched bulk or compound-specific stable isotopes (Kaldy et al., 2013, 2006), and isotope probes viewed over highly resolved spatial scales within the rhizosphere or plant tissue (i.e. NanoSIMS; Tarquinio et al., 2018). Such approaches will allow us to move beyond simply cataloguing what microbial species are present in seagrass meadows, and instead focus on the ecological functions they perform, including their impact on seagrass health. Non-destructive techniques for measuring plant responses, such as microsensors, planar optodes, plant biometrics and chlorophyll fluorometry, could help make the connection between the microbiome and seagrass health, stress and metabolism (Brodersen et al., 2018; Martin et al., 2020; Nguyen et al., 2021a).

As metagenome-assembled genomes (MAGs) and long-read technologies continually improve, seagrass and sediment-specific sequencing databases will become better resolved. For example, seagrass genomes will also allow researchers to develop markers to tease apart host responses during seagrass-microbe interactions (Duffin et al., 2020). The development of on-site qPCR screening would allow for rapid detection of specific microbes, e.g. pathogens.

Ultimately, multidimensional experimental designs and manipulations will be necessary to move beyond correlative connections to more closely connect seagrass to microbes, including controlled field experiments, e.g. sealed chambers (Olivé et al., 2016; Silva et al., 2008), and restoration/planting activities (Wang et al., 2021). For example, the use of multiple technologies and experimental manipulations to map seagrass-associated microbial and community and activity has led to the discovery of a symbiotic relationship where an N2-fixing Candidatus *Celerinatantimonas neptuna* provides NH4 and amino acids to *Posidonia* oceanica roots, while the seagrass provides sugar (Mohr et al., 2021).

Central to developing a framework where seagrass-sediment interactions are amenable to restoration and management activities is the need for standardised or best-practice methodology for sample collection and processing, culturing protocols, primers, and bioinformatics pipelines. Large consortia and associated databases, such as BioPlatforms in Australia and the Mangrove Microbiome Initiative and Earth Microbiome Project worldwide, would facilitate standardisation, as well as provide a place for sequence deposits and metadata.

2.2 Seagrass life-history, genetics and sediment processes

Authors: Elizabeth Sinclair, Tim Glasby, Michelle Waycott, Emma Jackson, Craig Sherman

2.2.1 Introduction

Seagrass restoration research to date has focused largely on technical and logistical issues relating to transplanting methods, seed collection and dispersal and the physical suitability of areas for restoration (Bastyan and Cambridge, 2008; Fonseca, 2011; Tan et al., 2020). Although it is well understood that restoration of habitats should only be considered after first removing any impacts that caused the initial habitat loss (Seddon, 2004; van Katwijk et al., 2009), there is perhaps less appreciation that loss of seagrass habitat may have resulted in a switch to an alternative stable state (Fonseca, 2011; Maxwell et al., 2017; Scheffer et al., 2001; West et al., 1990). In such circumstances, restoration might need to include methods for modifying the current environment, for example sediment modification or improvement. The interaction between seagrass genetics and sediment conditions will likely play an important role in determining restoration success within highly modified environments and more consideration needs to be given to matching genotypes to local environmental conditions at restoration sites. Related to this, there is increasing awareness that restoration may benefit from incorporating knowledge of positive species interactions, including facilitation and successional processes (Valdez et al., 2020). Finally, it is also becoming increasingly apparent that restoration should consider climate change (Coleman et al., 2020); future proofing restored seagrass populations may need to involve selecting for traits such as greater tolerance to warm water or more frequent low salinity events. Molecular tools can make important contributions to addressing many of the aforementioned challenges, including characterizing and enabling manipulation of communities in the sediment microbiome, selecting for particular plant traits that will best suit future environments, maximizing growth or reproduction of transplants and maximizing genetic and genotypic diversity.

2.2.2 Current knowledge: life histories, genetics and sediment processes

Seagrass species display a diverse range of life histories, growth forms and physiological tolerances, enabling them to occupy a diverse range of coastal environments, including varying sediment types and conditions. Life history strategies and growth forms in seagrasses include short-lived, colonising species with fast growth rates (e.g. *Ruppia*, *Halophila*) through to longer lived species with moderate growth rates (e.g. *Zostera*) and long-lived species with relatively slow growth rates that form persistent meadows (e.g. *Amphibolis*, *Posidonia*; Kilminster et al., 2015). We are becoming increasingly aware of how restoration success may be influenced by these different growth strategies and sediment conditions, and how seagrasses modify the sediment environment as they colonise and expand within an area. Growth of transplanted *P. australis* rhizomes can vary greatly within and among sites (e.g. 9.1 – 22.3 cm yr^{-1} in the same New South Wales estuary (Meehan and West, 2002) and 10 - 35 cm yr^{-1} in Western Australia (Renton et al., 2011). *P. australis* seedlings are slower growing, with rhizome extension ranging from 5 – 17 cm yr^{-1} in NSW (Meehan and West, 2004). Growth rates of leaves and rhizomes can depend on sediment nutrient levels (Cambridge and Kendrick, 2009), and it is likely that some genotypes perform better under some sediment conditions.

Sediment properties (grain size, nutrients, microbiome) can play a role in influencing rhizome elongation and root architecture, which may in turn influence establishment success. For example, species of *Zostera* tend to produce greater below ground biomass in oligotrophic sediments, with longer rhizome nodes (e.g. Ferguson et al., 2016; Song et al., 2021), whilst sediment type (specifically grain compactness (Statton et al., 2013) and nutrients (Hovey et al., 2011) can affect root architecture and hence anchoring of seagrass. These studies highlight the need for restoration programs to consider the interaction between growth form, seagrass genetics and sediment conditions at an early stage. It may be possible for example to use fast growing species (of seagrass, or even algae) to rapidly colonise an area and modify and improve sediment conditions that then enable longer-lived species to establish and grow in these areas (Williams, 1990). This conditioning of sediments through the succession of different species could provide restoration practitioners with a valuable tool for modifying less suitable sediment conditions at a restoration site to more favourable conditions that are able to support a large mature and healthy seagrass meadow. Further research is needed to understand how mixed species and successional approaches can be used in seagrass restoration programs. Most seagrass restoration attempts to date have focused on a single species (Valdez et al., 2020), despite good evidence that increased species diversity can enhance restoration success (Williams et al., 2017) and result in greater ecosystem functioning (Duffy, 2006; Hughes and Stachowicz, 2004, 2011).

Seagrass species display a variety of life history strategies which will influence the spatial and temporal patterns of genetic diversity and connectivity (Kendrick et al., 2012). Some seagrass meadows favour vegetative reproduction leading to a few local dominant clones (e.g. *P. australis*, (Evans et al., 2014). These large individual seagrass clones may persist almost indefinitely if left undisturbed (Digiantonio et al., 2020). Clonal expansion can also occur through dispersal of vegetative fragments over varying distances (e.g. rhizomes and shoots of *Zostera muelleri;* (Sherman et al., 2016). Genetic diversity represents the raw material that natural selection acts on, and is likely to be important for seagrass to establish in a range of sediment conditions within restoration sites. There is a lack of knowledge associated with links between genetic diversity in seagrass meadows and their associated microbial communities, despite health and nutrient benefits for seagrasses and adjacent ecosystems (e.g. (Lamb et al., 2017). Some genotypes may be adapted to particular sediment conditions and restoration needs to match restoration material (seeds or shoots) from environments that more closely match the conditions at the restoration site (van Katwijk et al., 2009). However, detailed range wide knowledge of patterns of genetic diversity is limited to less than five of Australia’s 30+ seagrass species. The spatial scale of these studies varies widely from range wide studies providing overall patterns of genetic diversity and connectivity over 100s – 1,000s of km, to detailed studies within meadows at a scale of metres. Finer spatial scale studies provide useful estimates within highly modified industrialised environments where active restoration is ongoing, for example *Z. muelleri* in Port of Gladstone (Jackson et al., 2021) and *P. australis* in Cockburn Sound (Sinclair et al., 2021, 2014).

2.2.3 Management opportunities and knowledge gaps

The focus of seagrass restoration is shifting from logistics and practicalities related to sourcing, storing and deploying propagules and identifying key characteristics that determine site suitability for species, to considerations about rehabilitating or experimentally manipulating sediments prior to restoration, multi-species planting, and selecting for particular plant traits that will maximize the success of restoration now and into future.

Modified and/or contaminated sediments lead to poor health of existing seagrasses and create challenging environments for re-establishing meadows. Therefore, understanding the links and feedback loops within naturally-occurring microbial communities may be important for improving success, particularly in highly disturbed environments (see section 2.1; Maxwell et al., 2017). A greater understanding of links between genetic diversity in seagrass meadows and their associated microbial communities may also help optimise restoration success. Research could include investigating the role of microbial communities in promoting seagrass establishment and facilitating seagrass succession.

Despite some successful outcomes with shoot-based seagrass restoration, the greatest areas of seagrass have been restored using seeds. Seeds are generally more easily handled, more robust (Orth et al., 2012), and often less destructively harvested. Developing seed-based restoration opportunities for a wider range of species may therefore be a useful focus of research. The use of seeds also maximises diversity and allows restoration for different parts of the geographic range to future proof restoration sites for future environmental conditions. Collection and dispersal of *Posidonia* seeds in WA has led to high numbers of seedlings (see onground Case study 2; 'Seeds for Snapper' in Sinclair et al., 2021), however, in NSW limited natural seed production in many *P. australis* meadows may limit the success of this approach (see alternative approach Case study 3; "Operation Posidonia" in Ferretto et al., 2021.

The longer term impacts of changing climate have the potential to significantly influence natural seagrass populations and the practice and outcomes of seagrass conservation and seed-based restoration (Kendrick et al., 2022). Impacts to critical stages in life history stages will be difficult to predict, however, greater tolerance to warm water, more frequent low salinity events, and reduced light are likely to be important traits to select for. There may also be changes in dominant modes of reproduction (a shift from flowering and seed production to vegetative growth), which could potentially be offset if we able to select for propagules for restoration based on seed production under warmer conditions.

The rapid development of 'omic' technologies provides unprecedented opportunities to integrate these data to inform and enhance seagrass restoration. For example, population genomic analysis not only provide greater sensitivity in understanding population connectivity and patterns of genetic diversity (see above), but can also provide an understanding of the genetic basis underlying adaptive variation associated with particular environments and how a seagrass species may respond to local sediment conditions. This can assist in identifying and matching genotypes from donor meadows to environmental conditions at restoration sites, or ensuring restoration material contains genetic variants that allow for adaptation to future projected environmental conditions.

Transcriptomic studies of gene expression also provide significant opportunities for restoration genetics as they allow for the identification of the genes underlying responses to specific environmental stressors (Mohammadi et al., 2019; Nguyen et al., 2020). These analyses provide important insights into the tolerance of individuals to different sediment stressors and an understanding of the resilience of restored populations to future environmental change. Metagenomic analysis allows for the characterisation of microbiome communities associated with the above and below ground components of seagrass meadows. These communities are known to play an important role in plant, and wider environmental health, but are rarely considered as part of the restoration process. As an extension of metagenomics, the application of these approaches has led to the field of environmental DNA (eDNA). This is where environmental samples are used to detect the presence of species through the DNA shed into the local environment and is now routinely used for detecting target species or more broadly characterizing community composition.

This can be particularly useful for monitoring restoration sites and determining whether the wider sediment associated communities and ecosystem services provided by seagrasses are restored.

2.3 Bio-engineers and their effects on seagrass-sediment interactions

Authors: Ana Bugnot and Jeffrey Wright

2.3.1 Introduction

Ecosystem engineers (sensu Jones et al., 1997) and their interactions are key drivers of sediment processes in seascapes. For example, shellfish reefs attenuate waves and redirect currents, creating a hydrodynamic ‘shadow’ behind them, which affects sediment characteristics. Seaweed block light and add organics to the sediment affecting sediment physico-chemistry and microbial communities. Bioturbating macrofauna mix sediments and create burrows that they actively irrigate. These processes change the stability of sediments, and the flux of oxygen and nutrients between the sediments and sediment water column. Moreover, animal bio-engineers directly contribute to nutrient cycling by producing biodeposits that settle in surrounding sediments. Thus, bio-engineers have the capacity to affect seagrass by changing sediment conditions and influencing restoration success.

Here, we focussed on three key groups of bio-engineers that occur in close proximity to seagrass beds; bioturbators, seaweed and shellfish. Bioturbators, seaweed and some species of shellfish can occur amongst seagrasses, although reef-forming shellfish and seaweed are often found in areas surrounding seagrass beds. Hence the interactions between bio-engineers and seagrass beds can play a critical role in the establishment and maintenance of seagrass.

2.3.2 Current knowledge

Bioturbation

Animal bioturbators belong to a range of taxonomic groups, including fish, rays, echinoderms, crustaceans, worms and molluscs. They have different sediment reworking strategies, leading to sediment destabilisation (e.g. sea urchins, rays) or stabilisation (e.g. tube building-worms; Figure 5, Volkenborn et al., 2009). Large fauna in particular can rework large amounts of sediments, negatively affecting seagrass by sediment destabilisation. For example, Callianassid shrimps reduce seagrass growth via sediment resuspension during burrow creation, reducing light availability and sediment stability (Siebert and Branch, 2006; Suchanek, 1983). The tube-building worm *Arenicola marina*, has been shown to reduce seagrass density and growth by burial (Philippart, 1994; Suykerbuyk et al., 2012), while sea urchins and sand dollars have been shown to dislodge seeds (Johnson et al., 2018). As a result, seagrass restoration strategies often avoid areas where these bioturbators are present, or are developing tools to minimise their impact. For example, coir mats have been successfully used to exclude Callianassid shrimps and improve transplant success and shoot growth of *Zostera muelleri* seagrass in Australia (Wendländer et al., 2019). Studies are now underway to test the applicability of this technique at large scales.

Bioturbating animals present an array of competitive behaviours for space and food, and therefore have varying effects on sediment biodiversity (Mermillod-Blondin et al., 2018; Widdicombe and Austen, 1999), including positive effects on seagrass. For example, the activity of clams and some worms can bury seagrass seeds to a sediment depth suitable for germination within a few days after seed deposition, providing escape from predation and promoting seed retention (Blackburn and Orth, 2013; Fales et al., 2020; Li et al., 2017). Alternatively, bioturbators can provide nutrients for seagrass growth in areas where nutrients are limited, such as sandy environments (de Boer, 2007). Invertebrate bioturbators excrete ammonia and drive an efflux of ammonia from sediments (Stief, 2013), which can then be available for seagrass growth. Moreover, amphipod and gastropod bioturbators can drive changes in the relative abundances of ammonia oxidising bacteria and archaea in sediments, leading to increased nitrate release (Gilbertson et al., 2012; Stief, 2013). Importantly, in eutrophic sediments, Lucinidae and Solemyidae bivalves can reduce sulphide stress in seagrasses by hosting sulphide-oxidizing bacteria in their gills (Gagnon et al., 2020).

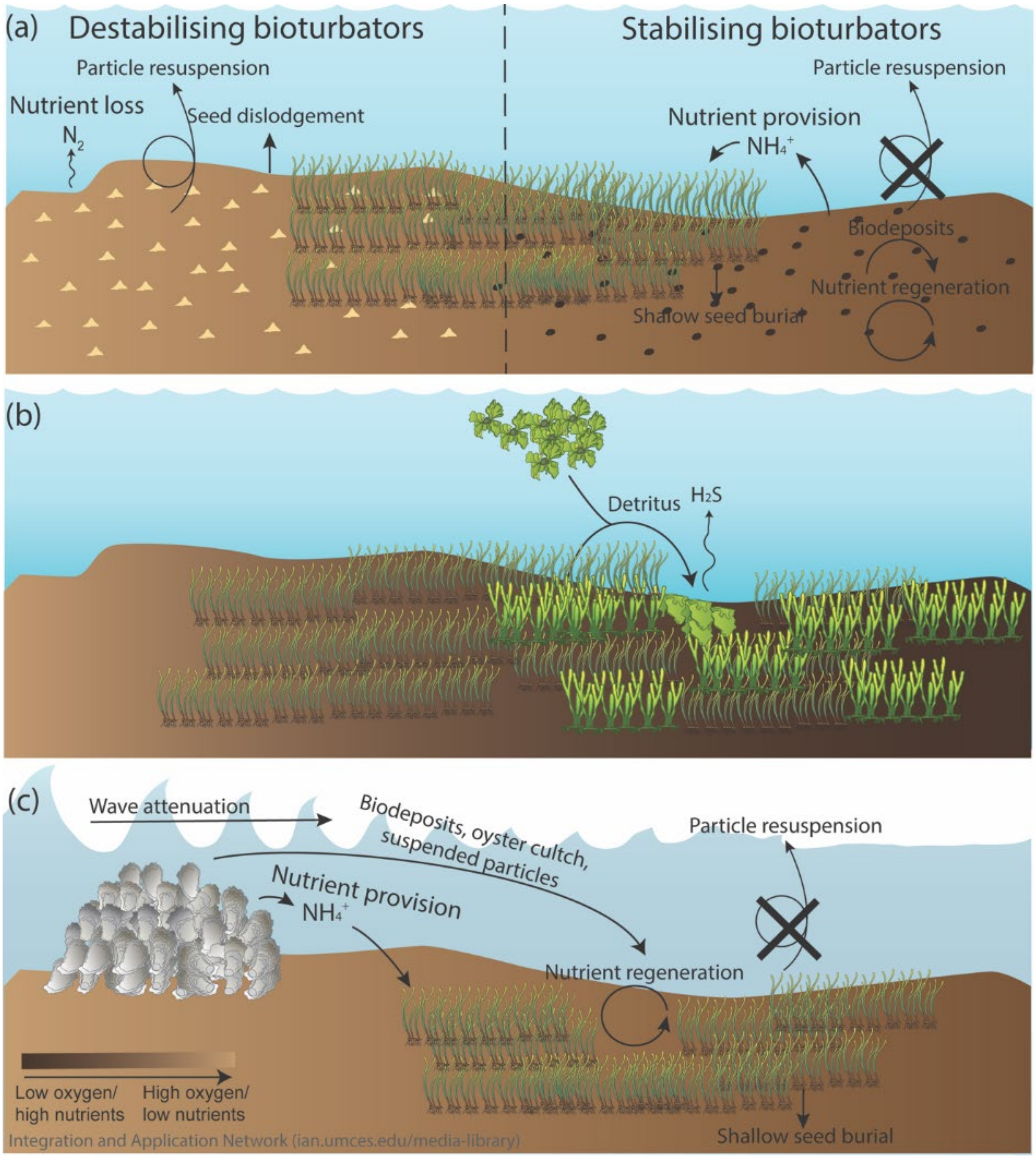


Figure 5. The effect of a) bioturbators, b) seaweed, and c) shellfish reefs on seagrass-sediment interactions.

Seaweed

Seaweed are likely to affect seagrass-sediment interactions in two ways: 1) benthic seaweed that either live in the sediment or attached to biogenic structures within seagrass beds (e. g. bivalve shells or epiphytically on the seagrass) or, 2) unattached free-floating seaweed that can settle on top of seagrass (Figure 5). In both cases the most likely mechanism for an effect of seaweed on seagrass-sediment interactions is modification of the sediment chemistry, physical structure and microbial communities due to increased input of seaweed detritus.

Caulerpa species are among the few seaweed that grow directly in soft-sediments and several species co-occur with seagrass (Ceccherelli et al., 2000; Glasby, 2013). At high densities, *Caulerpa* sediments generally have higher organics (due to a high detrital input of fragments (Wright, 2005)) silt content, anoxia and sulphide concentration compared to seagrass sediments (Holmer et al., 2009; McKinnon et al., 2009). Moreover, there are very different microbial communities in *Caulerpa* and seagrass sediments. *Caulerpa* sediments typically contain bacteria associated with fermentative pathways and sulphate reduction (i.e. low oxygen environments; Chisholm and Moulin, 2003; Gribben et al., 2017), whereas seagrass sediments contain bacteria associated with aerobic pathways (i.e. higher oxygen environments; Gribben et al., 2018, 2017). An important role for seagrass sediment in reducing the success of invasive *Caulerpa* species has been demonstrated: *Caulerpa* fragments grow worse in sediments with intact seagrass (*Zostera* and *Posidonia*) microbial communities compared to disturbed seagrass sediments. However, once *Caulerpa* is established in seagrass beds it creates reduced conditions to which it is tolerant suggesting a positive feedback (self-facilitation), between *Caulerpa* sediment and propagule success. Whether seagrass propagules are similarly positively affected by the presence of seagrass microbial communities has not been tested but evidence suggests that they are (reviewed in Section 2.1). Overall, there is strong evidence that modifications to the sediment caused by *Caulerpa* is likely to influence the established seagrass-sediment feedbacks via modification of sediment properties microbial communities which may limit seagrass restoration in areas that may now be occupied by *Caulerpa* (Gribben et al., 2018, 2017).

Similarly, high densities of seaweed attached to biogenic structures (including epiphytic on seagrass) triggers chemical and microbial changes to seagrass sediment. For example, in Chesapeake Bay, dense macroalgal canopies growing on *Zostera* had negative effects on seagrass production possibly due to changes to sediments (lowered redox and higher concentrations of ammonium) or light limitation (Hauxwell et al., 2003, 2001). Other studies have also shown negative effects of epiphytic seaweed on seagrass due to a reduction in light (Drouin et al., 2012), but in general, the effects of increased detrital input of epiphytic seaweed on seagrass-sediment interactions is not well tested.

Blooms of free-floating seaweed, typically the result of increased nutrients, are increasing and can cause large, high-density floating mats that settle on benthic habitats (Liu et al., 2013; Lyons et al., 2014; McGlathery, 2001). If these seaweed mats eventually settle on seagrass beds, they can change water and sediment conditions making them more anoxic, increasing the sulphide content (Goodman et al., 1995), and potentially impacting sediment microbes and seagrass propagules. Although a recent study showed seaweed blooms can increase the decomposition of *Zostera*, the seagrass-associated microbiome community did not change (Liu et al., 2020). However, the effects of these macroalgal blooms on seagrass is not well studied.

Shellfish reefs

Shellfish affect sediments by the addition of oyster cultch and the release of biodeposits (faeces and pseudo-faeces; Figure 5) These changes have been shown to facilitate underwater vegetation via nutrient enrichment, sediment stabilisation and seed trapping (Gagnon et al., 2020; Meysick et al., 2019). Increases in sediment nutrients can boost growth rates of seagrass *Halodule wrightii* at intermediate oyster densities, which were related to intermediate levels of ammonia and phosphates in sediments (Booth and Heck, 2009). Survival of *Zostera marina* transplants was increased by the presence of mussels in high and medium exposure sites, but not in sheltered sites, indicating an effect on sediment stabilisation and storm protection (Bos and Katwijk, 2007). Even though most studies assessing interactions between seagrass and reef-building shellfish have found positive effects, negative interactions can also occur mostly due to eutrophication effects, epiphyte growth and competition for space (Gagnon et al., 2020). For example, high loads of biodeposits can intensify sediment eutrophication, driving sulphide production and reducing seagrass growth (Vinther and Holmer, 2008). Negative effects have mainly been identified when seagrass and shellfish occur in the same habitat, while positive effects have mainly been recorded when they are located in independent, but fringing habitats (Gagnon et al., 2020).

2.3.3 Management opportunities and knowledge gaps

Bioturbation

Given the important role bioturbators can play on seagrass restoration success, site suitability models should incorporate information on naturally occurring ‘harmful’ and ‘beneficial’ bioturbators. Moreover, additionally to designing strategies to exclude bioturbators by coir mats as discussed above, harmful bioturbators can be removed at planting stage in areas where historical records show that the local presence of these species increased after seagrass loss. Moreover, strategies can also be developed to harness the beneficial effects of bioturbators to improve restoration outcomes. For example, practitioners can use beneficial bioturbators to pre-condition sediments for seagrass planting which can help exclude harmful bioturbators, increase nutrient availability in low nutrient sediments, decrease sulphide stress in eutrophic sediments, and/or inoculate or promote the growth of beneficial microbial communities. The natural capacity for reproduction and dispersal of bioturbators makes this strategy ideal for large scales projects. Moreover, these pre-conditioning activities can be done with the help of community members.

To inform these approaches, it is important to understand the full-array of negative and positive seagrass-bioturbator interactions. For example, the potential beneficial effects of animal bioturbators on seagrass growth, survival and reproduction, including the provisioning of nutrients and microclimates for beneficial microbial community development and microbial function, remain largely unassessed. Moreover, bioturbators cannot only affect seagrass health, but they may also affect the provision of ecosystem services by seagrasses. Bioturbators have been shown to decrease carbon sequestration in saltmarshes by oxygenating sediments and boosting aerobic decomposition of organic carbon (Martinetto et al., 2016), while at the same time facilitating arbuscular mycorrhizal fungi which promote saltmarsh growth and carbon sequestration capacity (Martinetto et al., 2016). However, no studies have assessed how bioturbators affect ecosystem services provided by seagrasses. Large scale field surveys of bioturbators co-occurring with seagrass and how they relate to seagrass health and function are needed.

Interestingly, studies comparing the effects of a few species of bioturbators have suggested that idiosyncratic effects play a key role in seagrass-bioturbator interactions (Lacoste et al., 2018). However, no studies have done a fully replicated experiment to assess if the nature of these interactions are related to bioturbator functional groups. For example, seed burial capacity has been related to bioturbation rates (as measured by grams of sediment moved per day per individual), but only three species were assessed (Blackburn and Orth, 2013). To inform these approaches, surveys are needed to assess the bioturbators that relate to increases or decreases in seagrass health and the ecosystem services they provide, and identify functional traits associated with positive or negative effects on seagrasses. Furthermore, manipulative experiments should compare the effects of multiple bioturbating species, including replicate species per functional group, on sediment burial, survival and growth of seagrasses to identify if there are particular traits of bioturbators that are more likely to have a positive or negative effects on seagrass health and the services they provide. The information produced can inform global seagrass efforts, as the focus on functional traits will make results transferable between systems, even for new sites where there is little understanding of the ecology of sediment biodiversity.

Seaweed

As highlighted previously (see Section 2.1), many seagrass propagules fail to successfully establish in restored sites (Katwijk et al., 2016). This may be linked to a breakdown or absence of positive feedbacks whereby the environmental conditions engineered by seagrass creates conditions that favour propagules of the seagrass itself. For example, self-facilitation (or positive feedbacks) has been described in *Zostera* where high-density beds reduce hydrodynamic stress and/or water turbidity allowing higher seagrass cover (Bos and Katwijk, 2007). However, whether propagules per se are facilitated and the mechanisms behind the facilitation is unclear. Despite propagules of *Caulerpa* performing better in *Caulerpa* sediment, we have no tests for seagrass. A major knowledge gap, and an area requiring increased research effort are tests of the importance of positive feedbacks between seagrass sediment and seagrass propagule success for increasing restoration success. This could allow practitioners to include approaches such as sediment manipulation or inoculation of microbes in their restoration programs (see Section 2.1).

High densities of invasive *Caulerpa* associated with seagrass could be targeted for removal. Although community divers could be trained to do this, recreational activities create and spread fragments (West et al., 2009, 2007), and any removal would be better done by government natural resource managers.

High levels of epiphytic and free-floating seaweed are often the result of increased nutrients into catchments. Thus, ongoing monitoring and management of nutrient input into estuaries and coastal habitats is critical. Globally, high nutrient input and eutrophication are known to negatively impact seagrass (Orth et al., 2006). Although a greater understanding of the effects of increased detrital input from epiphytic or free-floating seaweed on sediment characteristics and seagrass-sediment interactions is needed, managing nutrients will reduce the biomass of these algae and their potential impacts on beneficial sediment conditions.

Shellfish reefs

Shellfish reef restoration projects are burgeoning in Australia (*Saccostrea glomerata* and *Ostrea angasi),* opening opportunities for the development of co-planting initiatives with seagrass. Shellfish reefs can be used to pre-condition sediments for seagrass plantation in areas where sediments are less stable as shellfish reefs attenuate water promoting the deposition of small particles suspended in the water column (Meyer et al., 1997) and increasing sediment cohesion (Bugnot et al., 2022). Moreover, pre-conditioning with shellfish can be beneficial in low nutrient areas, as shellfish biodeposits increase nutrient content in sediments at distances up to 100m away from reefs (Bugnot et al., 2022). Therefore, there is potential for shellfish reefs to enhance seed retention and seagrass growth and reproduction via the provision of nutrients in more exposed and nutrient deprived areas.

So far, the role of shellfish as nutrient providers for seagrasses has been mostly assessed for those shellfish species that occur in close association with seagrasses, such as the mussel *Modiolus americanus* (Peterson and Heck, 1999), *Mytilus edulis* (Reusch et al., 1994), and the oyster *Crassostrea virginica* (Booth and Heck, 2009). It is however less clear how shellfish reefs occurring in the surrounding areas, such as the ones in Australia, affect seagrasses. However, shellfish reefs might drive sediment eutrophication in more protected areas, with possible negative impacts to seagrasses. Pilot studies are needed to test these ideas and understand context-specific effects, therefore pre-empting any negative effects of shellfish on seagrass.

3. Case studies

3.1 OZFISH 'Seeds for Snapper' Seed-based Seagrass Restoration Program

Authors: Rachel Austin, Tania Douthwaite, Andrew Matthews and Gary Kendrick

3.1.1 Introduction

The Marine and Coastal NESP hub supported the community science restoration 'Seeds for Snapper' program, with the program coordinated through OZFISH and funded via a RecFish West Grant, OZFISH and The University of Western Australia (UWA). 2021 was the 4th year of operation and the most successful year to date. The NESP funding was specifically used to pay for technical support and coordination of the community-based program.

Seagrass restoration has traditionally been focussed on shoot transplanting, either at small scales as sprigs, plugs or cores, and at larger scales as mechanically moved sods (summarized in Statton et al., 2018). The 'Seeds for Snapper' program is one of the few Australian programs focused on seeds. UWA started investigating seed-based seagrass restoration in 2008 during the Cockburn Seagrass Research Rehabilitation program (2003-2012) with onshore nurseries to grow seedlings from the seeds of the temperate seagrass, *Posidonia australis* (Statton et al., 2014, 2013), but found seedlings were difficult to transplant into the field, were heavily grazed and not a viable alternative to shoots. Further investigation by the UWA team found we could collect 104 to 105 fruits relatively easy, have seed release occur in onshore aquaculture facilities, target deployment of seeds to subtidal unvegetated sands that have high suitability for seagrass colonisation (Statton et al., 2017; Kendrick et al. in prep) and result in 100s to 1,000s m^2 restoration success (Sinclair et al., 2021). Further research with other seagrass species (e.g. Waite et al., 2021) indicate that if a large source of seeds can be collected then seed-based restoration is a viable and scalable alternate to shoots.

Seed-based restoration offers the opportunity to scale-up seagrass restoration to address the loss of seagrasses in Australian at the ecosystem scale. It also addresses the cost of restoration, seen to be excessive by some (Bayraktarov et al., 2016), through an integrated community-based restoration approach. This report will document the 2021 'Seeds for Snapper' season, outline community effort and give some guidelines for building this seed-based restoration program beyond 1 million seeds and 1,000s of m^2.

3.1.2 Context and Methodology

The OZFISH 'Seeds for Snapper' program (Figure 6) started in 2019 and developed from discussion at the Marine Restoration Workshop (McLeod et al., 2018b) held at the DAWE offices in Canberra in 2018 between Craig Copeland (CEO-OZFISH), Gary Kendrick and

John Statton (Researchers - UWA). The first two years built up the community group, coordinated by Andrew Matthew and diver coordination by Tania Douthwaite, and developed a community-based methodology through John Statton. By 2020 the scale of operations had increased to 100s of participants, and required a revisit of the technology being employed and the aquaculture facility holding fruit and seeds.

Figure 6. Seeds for Snapper logo. Seeds for Snapper is an OZFISH - UWA collaboration sponsored by the Recfishwest Recreational Fishing Initiatives Fund, BCF, WA DPIRD, Cockburn Power Boats Club, City of Cockburn, Kwinana Industries Council and diving supported by Adreno and Divetub diveshops.

There are now well developed steps that community volunteers drive (Figure 7). Firstly, seed production is determined in donor meadows using 5 x 2 m belt transects. Fruit is then collected with free divers and SCUBA divers by hand and net which is then transferred into aquaculture tanks that are circulated and aerated with pumped seawater. When the fruit splits open, the seeds sink and are collected from the bottom of the tanks and placed in holding aquaria until counted (volumetrically) and bagged for delivery to the restoration sites via the UWA team or by recreational fishers and boaters who wish to get involved. Present activities are highly targeted to occur every day over a 6 week period between late-October to mid-December each year.

Figure 7. The ‘Seeds for Snapper ‘ fruit collection, seed release, seed delivery and seedling development process. From top left to right: *Posidonia australis* fruit, collection in nets, volume of fruit in collection net, transfer to buckets, counting fruit to determine daily amounts collected. From bottom left to right: fruit in aquarium tanks, released seeds (handful), tossing seeds from boat, seeds settling onto sea floor, a 1-2 day old seedling on seafloor. Photos: Rachel Austin, Tania Douthwaite, Andrew Matthews, Marta Sanchez Alarcon, Lara Oppermann, Sharmini Jayasinghe

3.1.3 2021 Outcomes

The 2021 season has proven that we can scale up restoration using seeds and a dedicated community group (Figure 8). Between 18th November and 15th December 2021, the OZFISH ‘Seeds for Snapper’ Community group collected 1.18 million fruit. We obtained 370,000 viable seeds that were dispersed to 6 restoration sites (Figures 8 & 9). A total of 42 dive sessions were conducted with over 300 individual collection dives done by the community. Over 1,000 hours were volunteered during this time. Our group grew during the season and now the ‘Seeds for Snapper’ Facebook Group page has 645 active members.

We did have some breakdowns during the activity. Collection of seeds far outpaced our ability to process the fruit and seed, and combined with equipment failure and extremely hot daytime temperatures, this resulted in the loss of many fruit. To prevent this from reoccurring, we have now bought purpose built tanks for faster processing and larger pumps to increase circulation in tanks. We have also considered having two facilities to reduce the risk of another catastrophic breakdown of pumps.

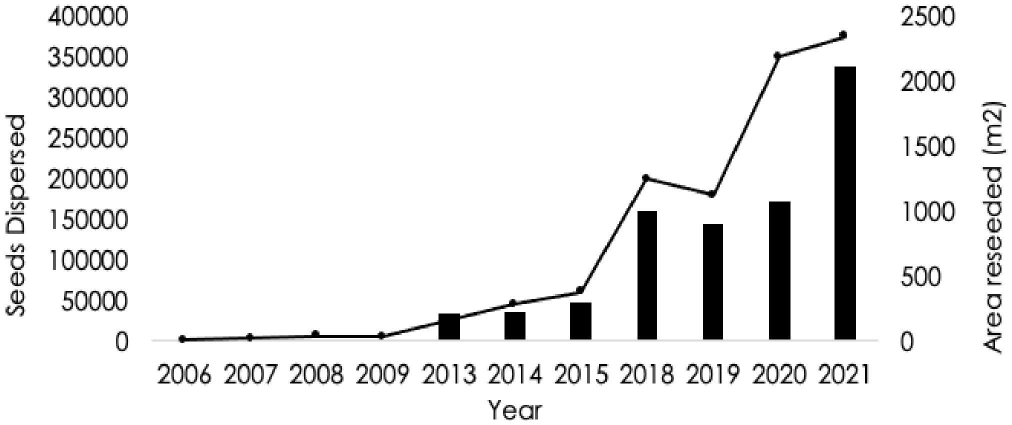


Figure 8. Progress with scaling up seeding through the OZFISH ‘Seeds for Snapper’ community restoration program. UWA trialed diver based seeding of small trial plots between 2013-2015 for proof of concept, then in 2019 UWA-Ozfish volunteer divers became involved and larger plots with boat seeding were set up, in 2020 we trialled the Ozfish volunteer involvement, learnt a lot and massively scaled it up for 2021 which incredible success. *Line with points = seeds dispersed, Columns = area reseeded*

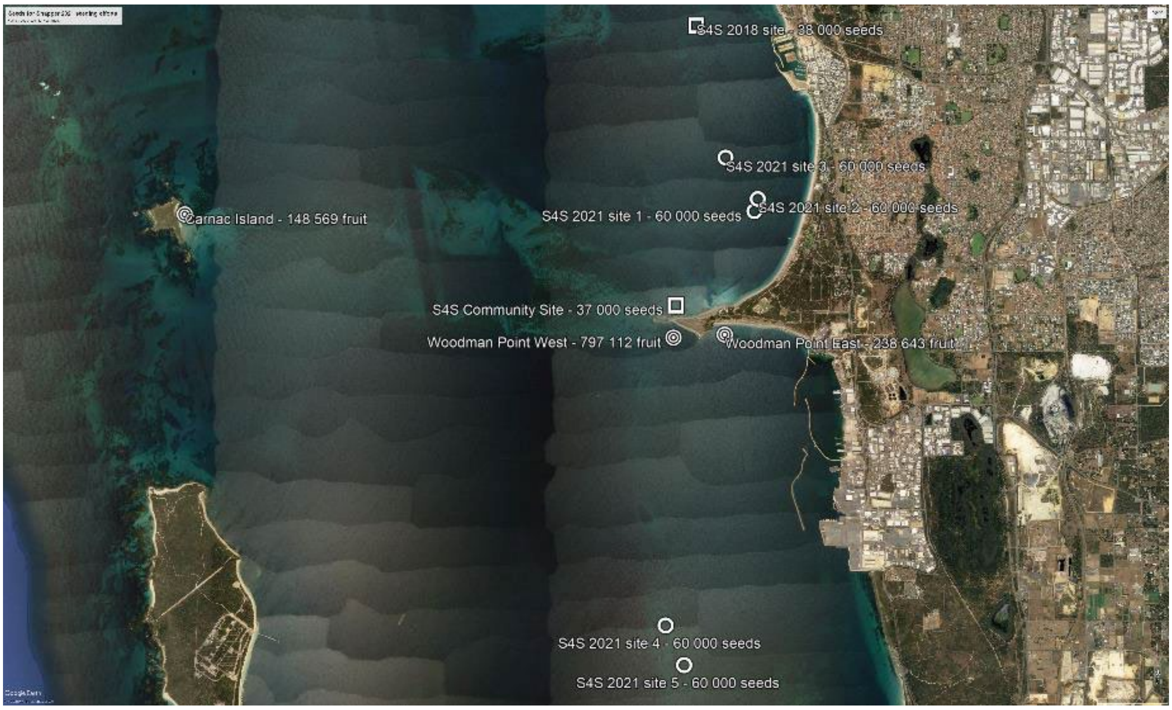


Figure 9. Location of ‘Seeds for Snapper collection sites (filled circles), 2021 restoration sites (open circles) and community and previous years site (open squares).

In late February (16th and 17th February), the UWA dive team surveyed recruitment of seedlings at all 'Seeds for Snapper' restoration sites. Note that most plants and seagrasses have a type III survivorship curve where there is an exponential decline between the population density of seeds, early recruits, 1 year old recruits and multi-aged individuals. So a power of 102 to 103 individuals loss is expected between seeds delivered and seedlings developing over 3 months, and we did not observe that in our results. Results were promising and demonstrated a range of success among sites. Our seeding density for 2021 restoration was approximately 85 seeds m^2. We found between 23 and 34 seedlings m^2 at Cockburn Sound restorations sites 4 and 5. Site 4 was disturbed by high densities of sand dollars resulting in a patchy distribution in seedlings associated with existing structures like patches of seagrass and worm tubes. Owen Anchorage sites were more variable with 5, 17 and 47 seedlings m^2 observed at Sites 1, 2 and 3, respectively.

The causes of variable recruitment was the amount of sediment movement by swells, bioturbation by sand dollars and shallow reef pavement over a veneer of sand. The community site has not been surveyed as it sits within the sediment plume of the Cockburn Cement washplant and visibility was too poor. The furthest northern site in Owen Anchorage (2BA18) recorded 8 seedlings m^2 from a seeding density of approximately 50 seeds m^2. We noted this site has the largest of sand waves and more *Amphibolis griffithii*, both indicators of wave exposure, and the recommendation is to monitor this site but not re-seed it in 2022. The other considerations include increasing sites in Cockburn Sound, experimenting with excluding sand dollars, and reducing effort in areas that have shallow reef pavement and sand waves observed.

3.2 Seagrass restoration at Shark Bay, WA

Authors: Rachel Austin, Amrit Kendrick, Pat Oakley, Richard Cross, Tiahna Oxenham, Talarah Pedrocchi Roelofs, Laetitia Wear, Kai Kruger, Emilie Perez-Wright, Gary Kendrick

3.2.1 Introduction

During the summer of 2010-2011 an extreme marine heatwave hit the West Australian coastline, with sea surface temperatures increasing 2-5°C above average for ~10 weeks (Strydom et al., 2020). In Shark Bay this resulted in ~1,310 km^2 of seagrass loss, composing predominately of the temperate species *Posidonia australis* and *Amphibolis antarctica*, for which Shark Bay is the northern limit of their distributions (Strydom et al., 2020). This major loss of seagrass caused significant ecological, economic, and cultural impacts on the Shark Bay community. Stocks of scallops, crabs, and tiger prawns collapsed, fish catches and stocks declined (e.g. whitebait, Pink Snapper), fish distributions changed (some permanent, some temporary), and dolphins experienced a decline in reproductive success (Caputi et al., 2016; Gaughan and Santoro, 2020; Wild et al., 2019). It was also estimated that 2-9Tg of CO_2 was released due to this loss of seagrass, which is equivalent to 4-21% increase in Australia's annual C generation from landuse but is not factored in the Australian annual, terrestrial C budget (Arias-Ortiz et al., 2018). Since then, over the past 8 years recovery has been observed in some areas and some seagrass species (Kendrick et al., 2019), and with climate change set to increase the intensity and frequency of such events, restoration efforts will be critical in the long-term persistence and protection of these ecosystem forming seagrass species (e.g. Statton et al., 2021).

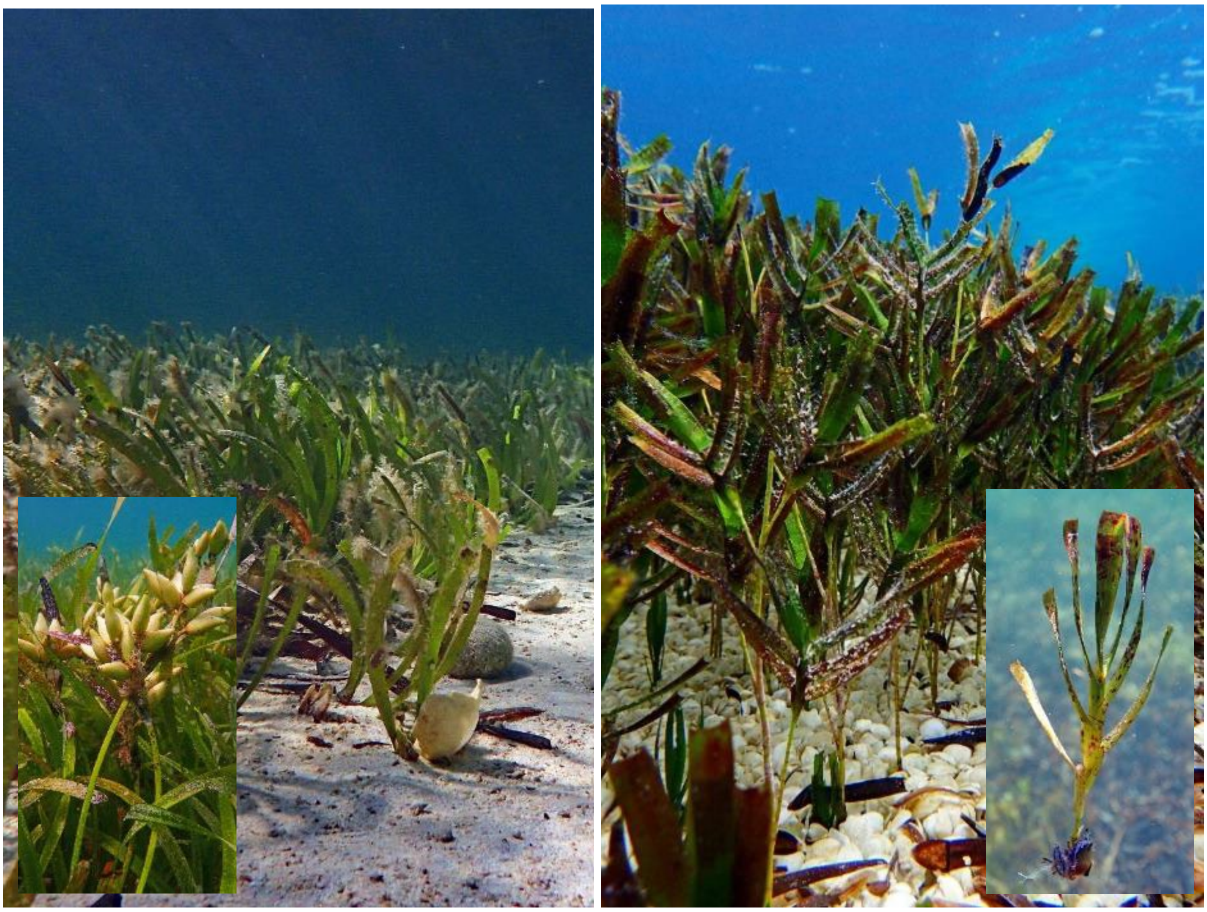


Figure 10. *Posidonia australis* (strapweed, left) and *Amphibolis antarctica* (wireweed, right) and their sexually reproduced propagules (seed within a fruit for strapweed, and directly developed seedlings for wireweed). Photos: Rachel Austin

The dominant species in Shark Bay are *Posidonia australis* and *Amphibolis antarctica* which are long lived and persistent temperate species of seagrass. This means they are highly resistant to disturbances with high carbon storage capacity but are slow to recover from large environmental perturbations (Kilminster et al., 2015). *Posidonia australis* is more commonly known as strapweed because of its long wide leaves, while *Amphibolis antarctica* is commonly known as wireweed because its stems are slim but strong. Both species reproduce vegetatively by growing runners (rhizomes) and shoots like terrestrial grasses. Both also reproduce sexually with flowers that are pollinated underwater which then develop into fruit encased seeds in the case of *Posidonia australis*, or develop directly into seedlings in the case of *Amphibolis antarctica* (Figure 10). We can take advantage of all these reproductive methods when sourcing plant material for restoration to expand the scale of restoration while spreading the impact of material acquisition yet increasing the genetic diversity/adaptability of restored areas.

3.2.2 2022 Seagrass Restoration training in Shark Bay, WA

In March 2022 a team composed of UWA researchers and Malgana Rangers (Pat Oakley (Ranger Coordinator), Richard Cross, Tiahna Oxenham, Talarah Pedrocci Roelofs, Laetitia Wear) and met in Denham for 10 days of seagrass restoration workshops and seagrass snagger deployment. We began the 10 days with a Welcome to Country and gathering of people invested in the conservation and restoration of seagrass in Shark Bay. This included people from UWA, MAC, Malgana Elders, DBCA, Bush Heritage, Shire of Shark Bay, and Shark Bay Resources. We discussed the current state of seagrass restoration in Shark Bay, the issues we are facing ecologically, logistically, economically, and culturally, and what we want to achieve now and into the future regarding the Shark Bay ecosystem and partnerships for conserving and restoring it. This meeting was a great success with everyone agreeing that it is time for science and culture to come together to protect Shark Bay from the dangers that climate change present.

During the 10 days, workshops were held to educate both groups on a range of topics from both perspectives. The Malgana Rangers were given short assignments to help them explore and reflect on the material covered, and such activities were documented so they could contribute to their TAFE certificates. The topics covered in the workshops include:

- Job safety analyses, occupational health and safety planning, and risk assessments for general field work, diving and boating
- The World Heritage Status of Shark Bay and why it is a globally recognised site and why it has been so studied by scientists
- Seagrass biology and ecology including the different seagrass species, their life history traits, the roles they play in ecosystem function and what depends on them
- Factors to consider when planning and selecting a site for restoration, for example biological factors, physical factors, and logistics
- How to monitor restoration sites in terms of the biological, physical, and social/cultural aspects
- How to interact with the general public and communicate what you are doing in simple terms
- Inquiring into the overlap, interactions and differences between Western science and Indigenous culture, and opportunities to improve and facilitate the partnership

Running alongside these workshops were the seagrass snagger deployment activities. Approximately 100 hessian snaggers were filled with sand, ferried to the restoration site, and manoeuvred into position ready for the *Amphibolis antarctica* seedling season (Figure 11). Every year during the autumn and winter months hundreds of thousands of *Amphibolis* *antarctica* seedlings are released by adult plants. The seedlings tend to float on the surface during the day, being dispersed by surface currents, then sink during the night. The seedlings have a little grappling hook structure which helps them to attach to a single spot on the seafloor long enough for them to develop roots. The aim of these seagrass snaggers is to provide extra attachment points and increase the number of seedlings that survive into adulthood. The snaggers are positioned perpendicular to the prevailing water flow and are organised into lines 4-5 m apart to optimise hydrodynamically-assisted seedling settlement. Seedlings that are washed on to beaches can also be collected and either dispersed at the restoration site or physically attached to the snaggers as an additional enhancement. Over the next 4-5 months the Malgana Rangers will check on sedimentation around the snaggers and will monitor seedling development and recruitment until our next meeting in August 2022.

Figure 11. UWA and Malgana Rangers working together to deploy 100 seagrass snaggers. Photos: Laetitia Wear and Gary Kendrick.

3.2.3 Monitoring 2020 shoot-based Malgana restoration activities

A previous shoot-based restoration site was also visited and monitored for survival and growth of transplant units. These were set up in In March 2020 by Gary Kendrick and John Statton from UWA and the Malgana Land and Sea Rangers Sean McNeair, Richard Cross and Alex Dodd at a transplant trial at Dubaut Point, just south of Monkey Mia.

Figure 12. The two-year-old transplant trial (March 2020 – March 2022) at Dubaut Point. Top images left to right: *Amphibolis antarctica* transplant area with sprigs planted 1 m apart); *A. antarctica* transplants showing rhizome extension of up to 0.5 m. bottom images left to right: *Posidonia australis* transplant area showing 1 m spacing; *P. australis* transplant size noting lateral extension was less than *A. antarctica* but still approx. 20-25 cm. Photos: Gary Kendrick.

The March 2020 trial involved harvesting shoots of *Posidonia australis* and *Amphibolis antarctica* (generally 15-20 cm long rhizome with 3-6 shoots) from nearby natural meadows and then planted them in sand patches to aid in their recolonisation. These transplants (sprigs) were secured by a wire peg so tides and waves would not wash them away while the transplant developed its root system, and with time the peg rusts away. In total 36 sprigs of each species were transplanted and secured at 1m intervals within a rectangular grid/plot.

Two years later, in March 2022, we went back to determine transplant survival and growth (Figure 12). For *Posidonia australis* 31 of the 36 (>86%) transplants survived and had on average 8.7± 0.77 (SE, n=31) shoots. For *Amphibolis antarctica* 34 of the 36 (>94%) transplants survived and had on average 17.5 ± 1.44 (SE, n=34) shoots. These numbers clearly demonstrate that this joint transplant trial was highly successful with excellent survival and is evidence that larger scale seagrass restoration projects can be successful in Shark Bay.

3.3 Preparing the ground: scaling up *Posidonia australis* restoration using beach-cast fragments in Gamay (Botany Bay)

Authors: Clayton Mead, Bryce Liddell, Shannen Smith, Gamay Rangers, Alistair Poore and Adriana Vergés

3.3.1 Introduction

Often the distribution of seagrass meadows overlaps with where human use of the coast is most concentrated. This is particularly true in In New South Wales (NSW), where shallow, sheltered estuaries around Australia's most populous city have been ideal for coastal development, industry and recreation. As people have encroached on these waterways, seagrasses have declined resulting in loss of habitat for commercially and culturally important species and increased vulnerability of coastal communities to climate change impacts.

Posidonia australis is the largest seagrass species in NSW. It has a wide distribution around the southern half of Australia, however it has declined dramatically in six NSW estuaries around Sydney (Butler and Jernakoff, 1999; Larkum and West, 1990). Historical causes of *Posidonia* decline have been coastal development and pollution, which affect sediment movement, water clarity and nutrient loads. *Posidonia australis* meadows are listed as an Endangered Ecological Community under the Commonwealth EPBC Act and as Endangered Populations under the NSW Fisheries Management Act. Despite legislative protection, physical disturbances, for example from boat moorings and anchors, continue to cause the species to decline in these estuaries, pushing these populations close to local extinctions (Evans et al., 2018; Glasby and West, 2018).

Posidonia australis is a slow growing species. It can take several decades to revegetate impacted areas. Further, *Posidonia* does not reproduce sexually in many NSW estuaries and therefore does not produce a high volume of seeds (Larkum et al., 2006), meaning the species relies mostly on vegetative growth for recovery and has very little dispersal capacity The very slow rate of natural recovery for this species means revegetation efforts are needed, however it also presents a significant challenge for the development and scaling of restoration methods.

Transplanting seagrass shoots is a proven method for seagrass restoration, but typically relies on removal of donor material from existing meadows (Ganassin and Gibbs, 2008) *Posidonia australis* is naturally detached from the seafloor by swell and winds and often accumulates on shorelines as wrack. Recent methods developed by Ferretto et al. (2021) use beach-cast fragments of *Posidonia* with intact rhizomes for transplantation. Transplants can survive and grow in restoration plots and the use of beach-cast fragments removes the need to remove donor material from vulnerable populations. Collecting these viable beach-cast fragments, which are only available in small quantities compared to the total accumulation of seagrass wrack, before they become dry or are lost to tides is a challenge.

The project ‘Operation Posidonia’ was developed to enlist citizen scientists to survey their local beaches for viable *Posidonia* fragments and store them at public collection stations where they are kept in seawater until they are moved to aquaria and later used in restoration. This model is a promising solution for *Posidonia* restoration in NSW with major social co-benefits (increasing community engagement in science, creating stewardship behaviours) (Ferretto et al., 2021), which in turn has the potential to influence future institutional support for expansion of the project.

Replicating the Operation Posidonia project in additional estuaries and on a larger scale requires significant scoping work to understand the availability and health of beach-cast fragments, establishment of necessary infrastructure for collection and storage of fragments, engagement with stakeholders with diverse social, cultural and economic interests and a large community-based science communication campaign. Indigenous knowledge, culture and interests are often neglected in the design and implementation of ecological restoration projects, especially in marine environments where restoration is a young field and Indigenous ownership is not well recognised.

Delivering *Posidonia* restoration projects on larger scales will also rely on continuing to develop methods that optimise survival and growth of transplanted seagrass fragments. This includes both the storage and transplanting phases, which to date have relied on land-based aquarium infrastructure and SCUBA diving, both of which require significant materials, time and labour costs. Further to restoration logistics, understanding the role of sediment microbe communities in *Posidonia* fragment survival and growth will be important to inform the design of new storage and transplanting methods that utilise optimal sediment microbe interactions for best possible restoration outcomes (as outlined in Section 2.1).

This case study had two main objectives; 1) to engage the local community in Gamay (Botany Bay, Sydney) in a scoping study to understand availability and health of beach cast *Posidonia* fragments and; 2) initiate an infrastructure trial to begin upscaling *Posidonia* restoration efforts (including sediment quality manipulations) as developed by ‘Operation Posidonia’ to Gamay (Botany Bay) in Sydney, where *Posidonia* meadows are endangered.

3.3.2 Methods

Scoping work to understand availability and health of beach cast Posidonia fragments

Botany Bay has large areas of publicly accessible shoreline with varying aspect. Being able to predict accumulation of *Posidonia australis* fragments with intact rhizomes on these beaches based on environmental conditions would greatly increase the efficiency of collection of fragments for restoration, especially by citizen scientists who volunteer their time and may need to drive up to an hour between beaches in Botany Bay. This information is also useful in deciding where to install public collection stations and where to host community engagement activities.

A scoping study led by UNSW undergraduate marine science student and Indigenous Ranger Bryce Liddell (Gamay Rangers) aimed to predict *Posidonia* fragment accumulation based on wind, tide and swell conditions in Botany Bay. Bryce and the Gamay Rangers surveyed seven beaches in Botany Bay, subsetted into two regions (North-eastern Botany Bay and South-western Botany Bay). A total of 39 surveys were completed between late September and early November 2021. Location and time data were recorded and cross-referenced with publicly available environmental data (daily swell, wind and tides). Morphological traits of individual fragments known to influence survival (percent leaf necrosis and number of shoots per fragment; Ferretto et al. 2021) were recorded for each fragment found during a survey.

This scoping study is the first major on-ground collaborative research activity conducted with the Gamay Rangers, from the local Indigenous community. This partnership is likely to be highly beneficial to the restoration project as the Gamay Rangers are well resourced and have the necessary skills to conduct marine-based research and restoration activities. They also bring in depth local knowledge and understanding for the Botany Bay system. Collaboration on this project in turn provides the Gamay Rangers new training opportunities and an opportunity to be key actors in the restoration of seagrass habitats, which are a culturally significant species.

Infrastructure trial to optimise fragment storage, transplanting and sediment microbe manipulation

Previous ‘Operation Posidonia’ restoration efforts relied on large land-based flow-through aquaria with boxes containing sediment for the storage of *Posidonia* fragments. No such facility currently exists in Botany Bay and permits for transplanting *Posidonia* do not allow specimens to be moved between estuaries for biosecurity reasons. Recognising the need for an in-field storage system in Botany Bay, we developed a floating cage in which we could trial:

1) Storing fragments in floating boxes containing sediment, replicating the aquaria-based storage system

2) Use of sediment pouches, ‘SeaPod’ prototypes, to reduce space and floatation requirements, and in which sediment microbial communities could be manipulated in the future

Sediment pouches were designed with future restoration efforts in mind, where long-term storage is eliminated altogether, and seagrass fragments could be outplanted directly inside biodegradable pouches, or ‘SeaPods’. We stored seagrass fragments experimentally in pouches with different sediment microbe treatments to determine if seagrass health was improved through co-planting with different sediment types. Sediment types utilised were beach sand, sterilised beach sand and beach sand plus *P. australis* wrack. However, the experiment was impacted by prolonged inclement weather, and we were unable to gain useful results on fragment survival. This summary therefore focuses on the infrastructure trial only.

3.3.3 Results and Discussion

Scoping work to understand availability and health of beach cast Posidonia fragments

The number of beach cast fragments available varied spatially and temporally (Figure 13; Table 2). The highest number of fragments were found in Silver Beach, which is the beach in closest proximity to large *Posidonia* meadows which likely explains why more fragments are found there. We found that leaf necrosis and number of shoots was fairly constant across locations.

This information is useful in allocating future collection effort by citizen scientists and designing outreach materials and activities, indicating all regions of the Bay can be surveyed for viable fragments, while also pinpointing two easily accessible beaches that have particularly high numbers of fragments: Silver Beach and Yarra Bay. It is also useful to know that some leaf necrosis (which impacts fragment viability) should be expected and these fragments should be collected rather than excluded to maximise total number of potential transplants.

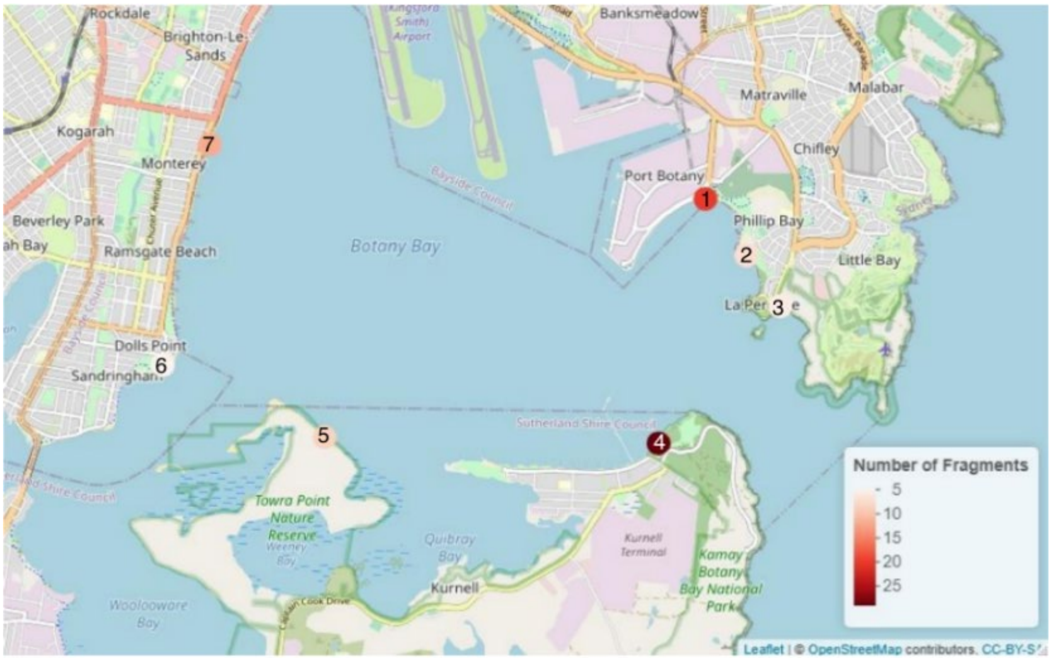


Figure 13. Map of Botany Bay showing total number of fragments found at seven sites (Clockwise: 1. Yarra Bay, 2. Frenchman's Bay, 3. Congwong Bay, 4. Silver Beach, 5. Towra Point, 6. Dolls Point, 7. Brighton Le Sands).

Table 2. Number of fragments, leaf necrosis and number of shoots per fragment for each sampling location from 39 surveys.

		North-eastern region			South-western region			
	All sites	Yarra Bay	Frenchman's Bay	Congwong Bay	Brighton Le Sands	Dolls Point	Towra Point	Silver Beach
Mean leaf necrosis (%)	47.44	47.25	45	48.33	56.67	28	56.67	42.5
Mean no. shoots	2.98	2.9	2	2.67	3.33	2.8	3.33	3.16
Total fragments	89	20	8	6	12	5	9	29

Our surveys show wind direction is a useful environmental predictor of where viable fragments are likely to be found in Botany Bay (Figure 14). This information is very useful in guiding citizen scientists about where to search for fragments under different conditions. A likely application of this data will be weekly social media and mailing list posts to inform citizen scientists of the best collection locations for that week based on forecasted weather conditions.

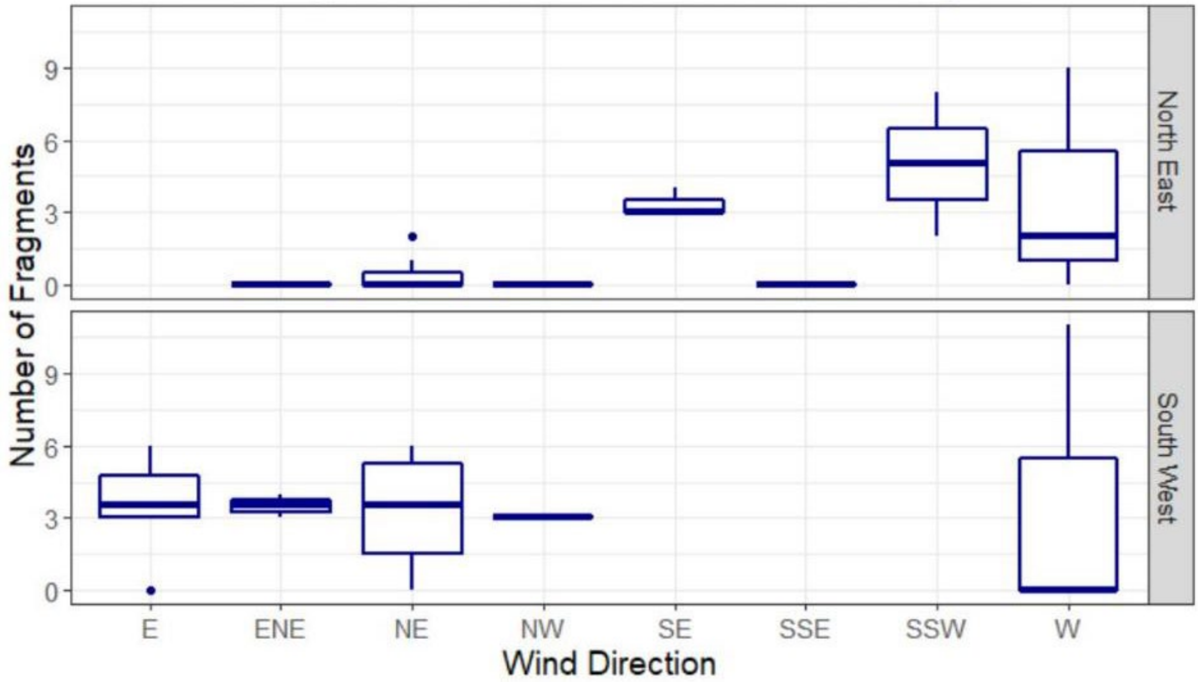


Figure 14. Number of fragments found per region of Botany Bay and wind direction at time of surveys. Winds from Southerly directions best predicted fragment availability at beaches on the North-eastern side of the bay and winds from Northerly directions best predicted fragment availability on the South-western side of the bay.

Infrastructure trial to optimise fragment storage, transplanting and sediment microbe manipulation

The floating pen we established was affected by heavy fouling and frequently collected floating debris (Figure 15). Fouling is heavier in the summer months when the collections occurred, and we were also unable to maintain the pen as frequently as planned due to COVID, as well as Christmas and New Year breaks. We expect this to be less of a problem in the future as we have since found that with regular (approximately fortnightly) maintenance, fouling can be kept to an acceptable level. We found that collapsible boxes held within the pen did not retain enough sediment for the temporary storage of *Posidonia* fragments, likely due to turbulence created by wind and tidal movement. Promisingly, the floating pen and boxes were robust to damage, and it is likely that the infrastructure will be useful for seagrass storage with modification of the sediment system used.

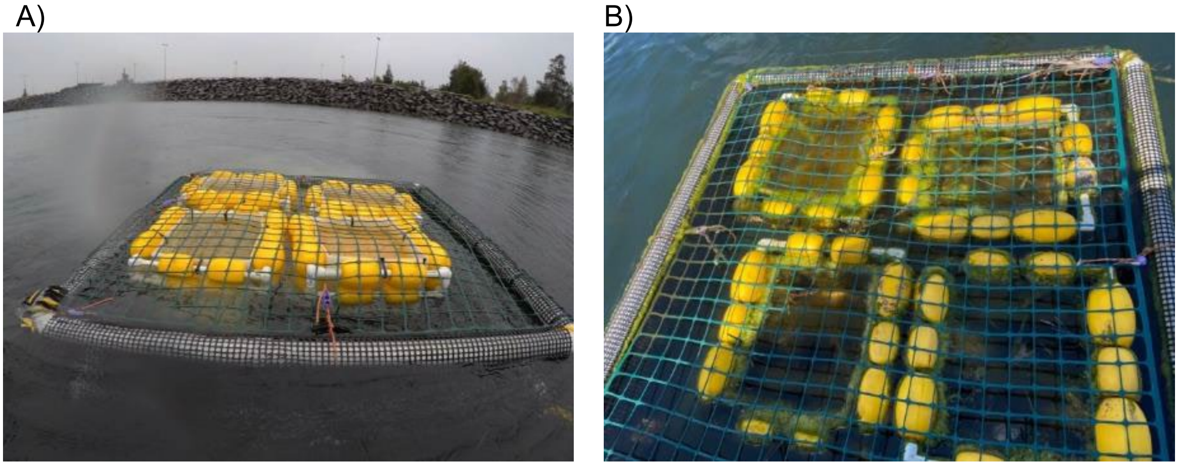


Figure 15. Photos showing floating storage pen A) on day of deployment and B) after three months in situ. Significant algal fouling occurred in and around the seagrass boxes.

We trialled the use of small sediment pouches suspended across the pen on wooden dowel, which reduces the total volume of sediment required and therefore the total floatation required (Figure 16). Cotton pouches retained sediment well, however degraded after approximately five weeks at which point sediment began to escape. Although pouches would likely need to last longer in this storage context and for any future microbial manipulation experiments, for future applications of the pouch method a rapid degradation period may be favourable. For example, sediment pouches containing seagrass fragments and housing a favourable microbial community could be buried directly into restoration sites. Most fragments did not survive inside pouches, however this was likely due to smothering by fouling.

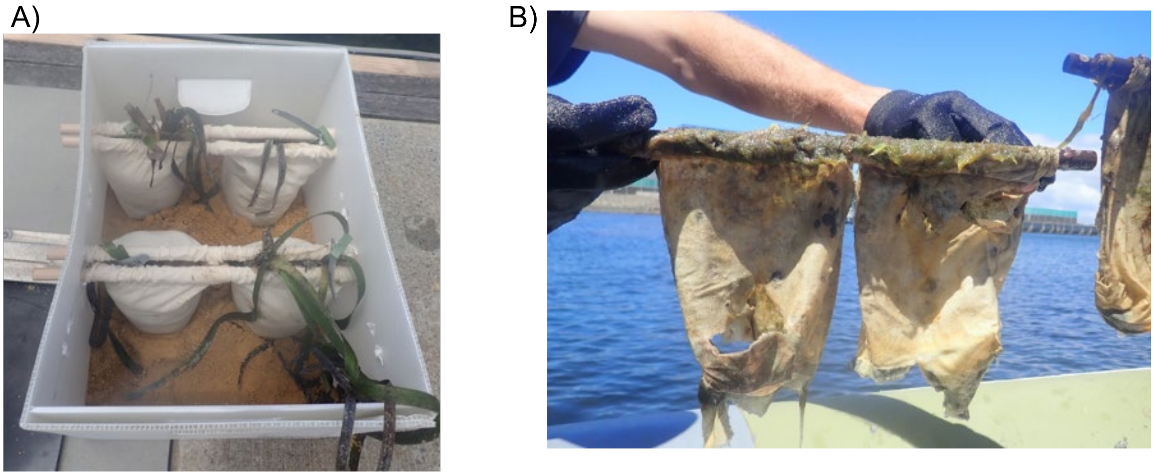


Figure 16. A) Cotton pouches containing *Posidonia* fragments and sediment suspended across wooden dowel. The use of plastic boxes with some sediments was to act as a ballast and hold the pouches and fragments upright. B) Cotton pouches that had been degraded significantly after five weeks, especially at the base which held the most weight.

4. Conclusions and recommendations

Seagrass beds are declining at alarming rates in Australia and globally (Statton et al., 2018b; Waycott et al., 2009). Many factors have contributed to seagrass declines, and efforts are on their way to preserve and restore these valuable seagrass ecosystems. There are already frameworks for seagrass restoration (Abelson et al., 2020), and some attempts are being made at scale. However, we are somewhat stuck in a stagnation loop whereby poor outcomes from restoration attempts have led to a disengaged community and insufficient funding to fill key basic and applied knowledge gaps to improve community ownership and restoration outcomes. Because they influence almost all components of restoration (see Figure 2), one of the key knowledge gaps is the role of sediment processes in controlling seagrass performance, yet they are poorly incorporated in restoration design and frameworks. In this report we outlined significant opportunities to enhance seagrass restoration by explicitly including sediment processes. This includes enhanced methods for restoration, more effective monitoring and assessment of restoration success. Importantly, we suggest decision-making frameworks should be extended to include sediment processes as they are of primary concern in determining initial site suitability and affect subsequent decisions and planning for restoration (Figure 17).

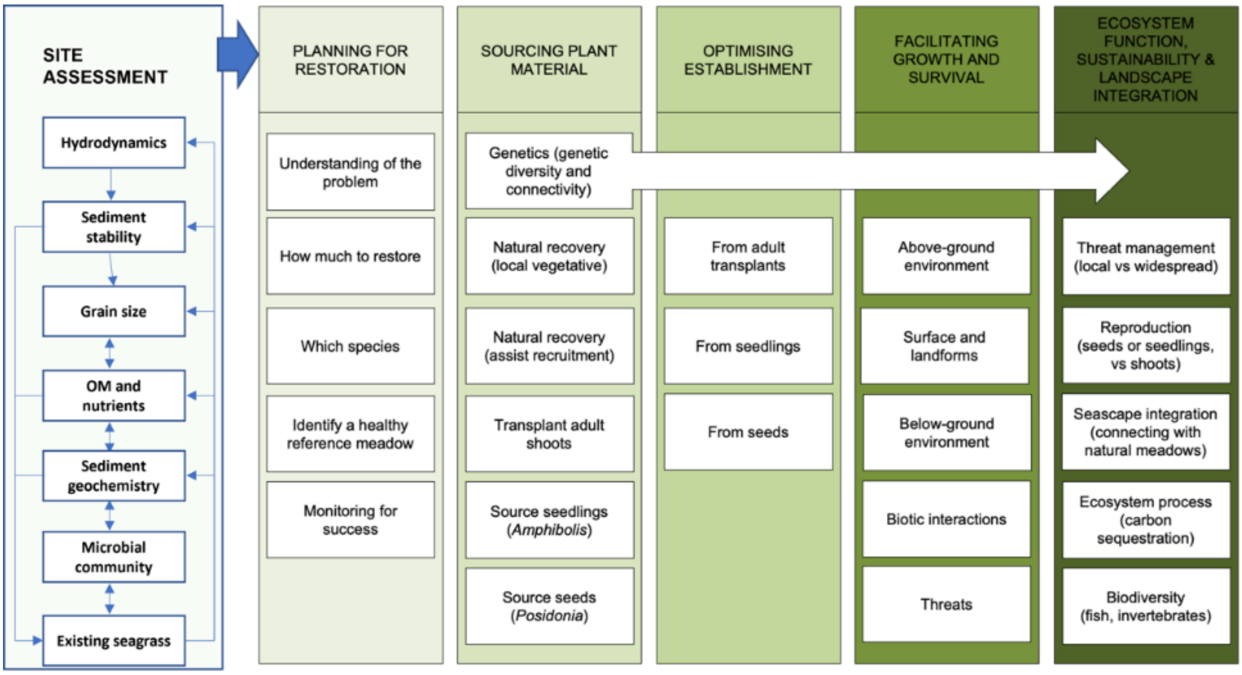


Figure 17. Extended ecological decision-making framework for seagrass restoration that explicitly include sediments processes (first vertical panel). Vertical panels 2-5 to the right adapted from Miller et al., 2017 for marine restoration (reproduced with permission from Gary Kendrick). Additional first vertical panel explicitly incorporates sediment process as a primary consideration into the decision-making framework for seagrass restoration.

At the outset, we recognize that hydrodynamics play a key role in determining sediment factors that may both benefit and hinder the successful restoration of seagrasses. In general, high-energy environments (e.g. shallow sediments subject to high bed shear stress due to wind waves and / or tidal currents) may preclude the recruitment of seagrasses due to physical disturbance associated with sediment resuspension and smothering. These sites are likely to have coarser sediments, with low organic carbon and nutrient contents, therefore sulfide stress will be low, however nutrients may be limiting especially before meadow continuity is achieved. In contrast, low energy environments promote the accumulation of fine sediments and organic matter therefore potential sulfide stress may be high and limit survival of seedlings and propagules. As seagrass meadows develop, the canopy tends to attenuate wave and current energy, promoting particulate trapping which can form an important nutrient input to sustain growth. However, in some situations this can lead to complete 'stilling' of the water column causing stagnation which can have various negative feedbacks to seagrass health (e.g., large diel oxygen changes, epiphytic and macroalgal growth etc.). We suggest therefore that an assessment of hydrodynamics and its implications for sediment properties and microbial community development is an important first step in site selection, the choice of restoration strategies, and selection of suitable donor material.

One of the key areas in which restoration can be improved is through a more complete understanding of the role sediment microbes play in controlling seagrass performance in relation to sediment properties. Seagrasses have intimate connections with their microbial communities which control a range of critical processes such as nutrient cycling and buffering against sulfide toxicity. Microbial community diversity and its beneficial impacts on seagrass health increase due to positive feedbacks associated with oxygen loss to the rhizosphere as seagrasses grow and meadows develop. Understanding how and which microbes (taxonomic or functional) influence seagrass health and their relation to sediment properties such as grain size, we suggest, will have major implications for site selection, identify suitable donor beds and will greatly improve methods for restoration. For example, site selection may be improved by selecting areas that have sediment properties that support appropriate microbes to promote growth. We suggest, therefore, that the initial phase of seagrass establishment is critical in terms of providing seagrasses with an opportunity to overcome poor sediment conditions. In addition. information on seagrass-microbe interactions should be incorporated in monitoring strategies to check that the manipulation of plants, seeds or sediments does not lead to microbial changes that may negatively affect restoration success.

In the absence of appropriate microbes promising methods include planting shoots or seeds in biodegradable pots that house appropriate microbial communities. We note here that similar techniques involve taking plugs of seagrass from established beds and transplanting them. However, this technique will be largely restricted to small scale ventures given the impacts that extensive plug removal may have for donor beds. One method that may have promise at larger scales is seeding sediments with sediment containing preconditioned microbes that can support seagrass survivorship and growth. Seeding areas with 'good' sediment may also be a strategy for enhancing the resistance and resilience of seagrass beds currently under stress.

Molecular tools to investigate microbial communities and functions should, more broadly, be incorporated into and aid in the development of large-scale monitoring programs (see NESP Projects 1.5 and 1.6) as an additional tool to determine the health of seagrass beds, and, if seagrass health/microbe relationships are known then they may be useful for detecting stressed beds even if loss of seagrass is not yet evident. Rapid advances in molecular techniques also allow us to improve current monitoring and reporting approaches by screening sediments for beneficial/harmful microbes that could be early indicators of seagrass performance and the ecological status of a site. However, more basic research in understanding seagrass/microbe relationships is needed as is applied research in how to deliver these techniques. We note the lead author team of this report is currently undertaking some of this research as part of the Australian Research Council Linkage Grant (LP200200220). However, central to developing a framework where seagrass-sediment interactions are amenable to restoration, management and monitoring activities is the need for standardised or best-practice methodology for sample collection and processing, culturing protocols, primers, and bioinformatics pipelines. Large consortia and associated databases, such as BioPlatforms in Australia and the Mangrove Microbiome Initiative and Earth Microbiome Project worldwide, would facilitate standardisation, as well as provide a place for sequence deposits and metadata.

Seagrass life-histories and genetics will have important implications for restoration, including site selection and selection of donor material. For example, genomic analyses can assist in identifying and matching genotypes from donor meadows to environmental conditions at restoration sites. Transcriptomic studies of gene expression also provide significant opportunities for restoration genetics as they allow for the identification of the genes underlying responses to specific environmental stressors. Large-scale genetic structuring as known for *Posidonia australis* and *Zostera muelleri* on the coast of Australia, and low levels of genetic diversity such as occurs in NSW for *P. australis* (Evans et al., 2014; Waycott et al., 1997), may also have consequences for restoration at scale and for future-proofing seagrass beds against climate change. Ensuring restoration material contains genetic variants that allow for adaptation to future projected environmental conditions will be critical for positive long-term management outcomes. In addition, some fast-growing species such as Halophila may be less reliant of microbial interactions and may be used to prime disturbed sediments (Kenworthy et al., 2018; Van Keulen et al., 2003) with good microbes, or by improving below-ground sediment chemistry to support the restoration of slower growing, longer-lived species such as *Posidonia* and *Amphibolis*. Such landscape approaches would complement other current NESP projects (Project 1.6 – A roadmap for coordinated landscape-scale coastal and marine ecosystem restoration). Clearly, a lot more experimental research needs to be done to ensure that the genotypes or functional groups used in restoration trials are matched to the local environment. Fortunately, seagrasses are amenable to such manipulations in the field.

Our review also highlighted that interactions with other organisms – positively or negatively – will also influence restoration success. For example, in areas they are absent, bioturbating species may be distributed to enhance sediment oxygenation and chemical cycling to the benefit of seagrass. Alternatively, restoration may be inhibited by species (e.g., sand dollars) that may bury seeds to disturb shoots. Interestingly, there is now a movement towards whole ecosystem management (a focus of NESP Project 1.6), rather than managing individual habitats. Such approaches explicitly acknowledge synergies and energy flows amongst habitat within ecosystems. One aspect that shows promise is co-restoration of seagrass with oyster reefs. Oyster reefs may act to stabilize sediments and increase organic inputs that may enhance seagrass growth. In the USA, restoring oyster reefs has certainly enhanced restoration efforts for other plants such as salt-marsh communities and oyster restoration programs in Australia are growing in number and size.

Encouragingly, our community engagement with recreational fishing groups (OZ Fish) and Indigenous peoples (Malgana Land and Sea Rangers; Gamay Rangers) was successful across all three on-ground projects conducted in New South Wales (NSW) and Western Australia (WA). Common successful elements were the inclusion of community in the collection and distribution of propagules, providing logistical support and infrastructure deployment. These appear to be an aspect of restoration amenable for community group engagement. However, we also identified opportunities for community groups to get involved with the science of restoration, including not only the scientific training of Indigenous students (as in Case Study 3), but also in the training of divers to collect scientific information underwater. Similar strategies have been highly successful in other community science programs such as the Reef Life Survey. Training the community themselves to educate, rather than just participate, will be a valuable tool in increasing community participation and ownership in restoration programs. These on-ground activities also highlighted the potential for the use of seeds for large scale restoration – although this will not always be possible as is likely the case in NSW. The use of seeds also maximises diversity and allows restoration for different parts of the geographic range to future proof restoration sites for future environmental conditions.

Across the areas we identified, it is evident that sediment processes are at the heart of many feedback processes influencing seagrass health. The right experimental strategies aimed at understanding the role of sediment processes in seagrass health, will provide evidence-based insight into what management actions, at small and large scales, will improve seagrass restoration efforts. A lot of great work has been done, and now it is time to build on current knowledge to work towards the restoration of degraded seagrass habitat by experimentally testing the interactions between seagrasses and their environment, improving current restoration methods, utilising new tools and techniques, and involving local community groups. This will provide better advice for management and advance the field of seagrass restoration.

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Appendix A

Table A1. List of workshop participants and report authors from universities, government and non-government agencies from around Australia.

INVITED	*ORGANISATION*	*EMAIL*	*ROLE*
Paul Gribben	University of New South Wales	p.gribben@unsw.edu.au	Lead workshop organiser/Lead workshop report author
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Michael Rasheed	University of Queensland	michael.rasheed@ jcu.edu.au	Did not participate
Catherine Lovelock	University of Queensland	c.lovelock@uq.edu.au	Did not participate

	Australian Department of Agriculture, Water and the Environment		Did not participate
	Western Australian Department of Water and Environmental Regulation		Did not participate
	Western Australian Department of Biodiversity, Conservation and Attractions		Did not participate

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