Seagrass Ecosystem Restoration Guidelines

for the Western Indian Ocean Region

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1. INTRODUCTION

Background

These Seagrass Ecosystem Restoration (SER) Guidelines are intended to serve as a tool in support of seagrass restoration opportunities in the Western Indian Ocean Region. The guidelines were developed in response to increasing incidents of seagrass degradation across the region either through direct anthropogenic pressures and/or climate change related impacts. The initiative is part of a wider GEF-funded 'Implementation of the Strategic Action Programme for the protection of the Western Indian Ocean from land-based sources and activities' (WIOSAP) by the United Nations Environment Programme (Nairobi Convention). It is anticipated that these guidelines will offer necessary technical guidance on seagrass restoration for the implementation of demonstration projects across the region under the broader objective of reducing stress on seagrass ecosystems from land-based sources and activities.

The guidelines comprise best practice approaches and methodologies for seagrass restoration and is based on a thorough review of global scientific and grey literature on seagrass restoration methods and documented experiences from experimental, small-scale pilot projects and large-scale restoration programs around the world.

The guideline has been tailored for practical applicability (fit-for-purpose) to the WIO region by considering locally relevant drivers of seagrass decline, dominant seagrass species, environmental settings, management context, logistic and economic constraints specific to the WIO region, and three case studies from within the region.

Objectives of the guidelines

The objective of preparing these WIO specific guidelines on seagrass restoration is to help practitioners in the region to focus on what is most likely to work for them when planning a seagrass restoration project and to assist them to better match the vast array of available restoration methods and approaches to their particular local situation. This will prevent failures due to a repeat of approaches that don't work and avoid haphazard seagrass restoration activities without key consideration of the lessons learnt from methods tested elsewhere and their workability in the region.

Target audience

The guidelines are intended for stakeholders and actors in seagrass restoration in the WIO region, including resource managers, restoration practitioners, scientists, students, NGO's and communities. The guide is written in a language style that is easily understandable and transferable. It integrates and makes use of existing global literature and guidelines/protocols/manuals on seagrass restoration, complemented by the practical experience from seagrass research and restoration projects in the Indian Ocean region.

2. SEAGRASS ECOSYSTEMS IN THE WIO REGION

The Western Indian Ocean (WIO) region encompasses the Comoros, France (Réunion), Kenya, Madagascar, Mauritius, Mozambique, Seychelles, Somalia, South Africa and Tanzania. Seagrasses in the WIO region cover extensive areas of nearshore soft bottoms along ~12,000 km of coastline from the intertidal to depths of more than 30m (Gullström et al., 2002; Ochieng and Erftemeijer, 2003; Bandeira and Gell, 2003). Seagrass meadows in the region often occur in close connection to coral reefs and mangroves. Mixed seagrass beds are common (esp. in Kenya, Mozambique and Tanzania), but monospecific meadows also occur.

Seagrass species

A total of 12 seagrass species[1] have been documented from the WIO region. Two of the most common species are *Thalassia hemprichii* and *Thalassodendron ciliatum*, both forming extensive beds in most parts of the region. *Thalassia hemprichii* is usually found in more protected habitats or on intertidal flats, whereas *Thalassodendron ciliatum*[2] normally inhabits exposed or semi-exposed sandy habitats (such as the reef lagoons along parts of the Kenyan coast). *Halophila ovalis, Cymodocea rotundata, Cymodocea serrulata, Syringodium isoetifolium* and *Halodule uninervis* are also common throughout most of the region. *Enhalus acoroides, Halophila stipulacea* and *Halophila minor* (a member of the *Halophila ovalis* complex) appear to be restricted to northern Mozambique and Tanzania and some locations in Kenya. *Zostera capensis* (which is listed in the IUCN Red List as endangered) is only common in southern Mozambique and South Africa, where large monospecific stands may occur, but the species has also been recorded from Kenya. *Ruppia maritima*[3] is common in estuaries in South Africa, and occurs in coastal lakes in southern Mozambique and Madagascar.

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[1] Several other seagrass species (*Halodule pinifolia, Halodule wrightii, Halophila ovata, Hlophila decipiens* and *Halophila beccarii*) have been reported for the region, but these may constitute misidentifications or need further confirmation. Taxonomy here follows Waycott et al. (2004).

[2] A new *Thalassodendron* species (*T. leptocaule*) was recently described from rocky habitats in southeast Africa, but the distribution of this new species in the WIO region is not yet well-understood.

[3] *Ruppia maritima* has often been described as a freshwater plant species with a pronounced salinity tolerance. It is included here as a true seagrass species, in line with recent seagrass guidebooks and key literature.

Ecosystem functions and values

The seagrass beds in the WIO region, harbor a highly diverse array of associated plant and animal biodiversity. Due to their high primary production and complex habitat structure, seagrass beds support a variety of benthic, demersal and pelagic organisms. Many fish and shellfish species, including those of commercial interest, are attracted to seagrass habitats for foraging and shelter, especially during their juvenile life stages. Seagrass beds in the WIO region also support sizeable populations of two endangered species that feed on seagrasses, i.e. the green turtle *Chelonia mydas* and the dugong *Dugong dugon.*

The great importance of East African seagrass ecosystems for fisheries is gradually emerging from an increasing research effort on the role of the seagrass meadows in this region as nursery, breeding and feeding grounds for marine fish and crustacean species of economic importance such as shrimps (*Penaeus*) and spiny lobster (*Panulirus*). Harvesting of bivalves and other invertebrates for food from intertidal seagrass areas is a locally important economic activity (e.g. Mozambique).

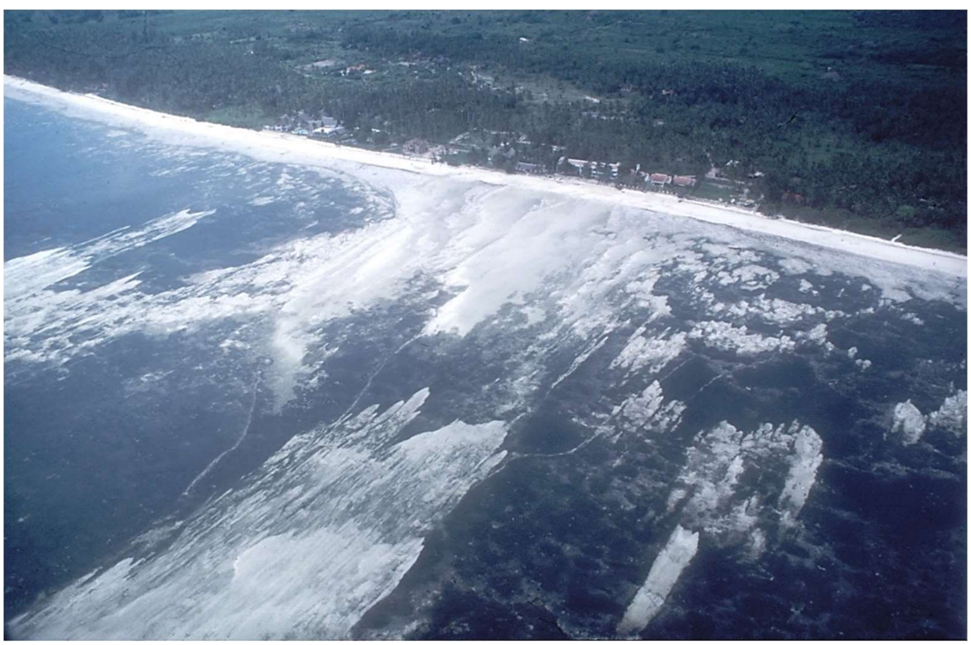

Due to the complex architecture of the leaf canopy in combination with the dense network of roots and rhizomes, seagrass beds stabilize bottom sediments and serve as effective hydrodynamic barriers reducing wave energy and current velocity, thereby reducing turbidity and coastal erosion. Further, seagrass beds trap large amounts of nutrients and organic matter in the bottom sediment. Through microbial decomposition, seagrass biomass enters the marine food web as detritus and thus supports productivity through recycling of nutrients and carbon.

More recently, seagrass meadows have been acknowledged for their considerable carbon storage potential and it has been estimated that globally as much as 19.9 Pg of organic carbon are stored in seagrass meadows. Organic carbon in seagrass sediment accumulates from both in situ production and sedimentation of particulate carbon trapped from the water column. Carbon accumulation in marine sediments provides long-term storage of organic carbon and has been referred to as "blue carbon" to distinguish it from carbon in terrestrial sinks. Seagrass meadows cover only 0.1% area of the world's ocean floor, yet account for 10–18% of the total oceanic carbon burial, accumulating carbon at rates of 48 to 112 Tg C yr^{-1}.

The huge economic benefits that seagrass ecosystems provide to the WIO regional economy through these various ecosystem functions have been estimated to represent a total economic value of some 20.8 billion US$ (Obura et al., 2017).

Drivers of decline

Seagrasses in the WIO region are under a range of threats (Eklöf, 2008; UNEP, 2009; Nordlund, 2012; Lugendo, 2015). Sedimentation from upland deforestation and erosion in river catchments are affecting seagrass areas in the Comoros and northern Kenya. Trampling and heavy concentration of fishing and tourist activities are an issue along parts of the coasts of Mozambique, Mauritius and Kenya. Eutrophication and physical damage from anchors, propeller scarring and boat groundings have affected seagrasses near urban centres such as Dar es Salaam (Tanzania), Mombasa (Kenya) and Maputo (Mozambique). Destructive effects of certain types of fishing gear on seagrasses, such as beach seining, have been reported from Tanzania and southern Madagascar. Digging to collect intertidal bivalves is common on intertidal seagrass meadows near Maputo (Mozambique), where it has affected seagrasses and associated biodiversity. Seaweed farming in Zanzibar (Tanzania) is causing short- and long-term effects on seagrass growth and abundance (through shading, removal, trampling and boat mooring), which is affecting local fish catches. Impacts on seagrasses due to herbicide leakage and sugar industry runoff have been documented from Mauritius. Overgrazing by the sea urchin *Tripneustes gratilla* due to overfishing of its predators has been implied as a potential cause of seagrass decline along parts of the Kenyan coast.



Underlying drivers behind some of these threats include rapid demographic growth, poverty, lack of education and awareness, inadequate law enforcement, and climate change. Rapid coastal development (involving dredging, clearing and pollution) and oil pollution (including the risk of oil spills) have not yet caused dramatic impacts on seagrasses in the WIO region to date. However, emerging economic growth and population demographics are likely to put an increasing pressure on the coastal and nearshore environment in the region in the years to come. For example, recent plans for major port developments in Kenya and Tanzania that will involve considerable dredging activities, and proposed installation of gas pipelines in Northern Mozambique following the recent discovery of large natural gas reserves are likely to pose further risks for impacts on seagrasses and their associated livelihood benefits in the WIO region.

The case for seagrass restoration

The rationale for seagrass restoration is to restore damage to or rehabilitate a seagrass ecosystem that has been altered to such an extent that it can no longer sufficiently self-correct or self-repair. This is generally in response to the observation (e.g. through remote sensing, mapping and/or field investigations) that there has been significant degradation or loss of seagrass in certain areas. While the highest priority should always be given to avoid such degradation and loss, this is not always possible or practical (e.g. when the cause of seagrass loss is outside management control) and seagrass restoration through active intervention may then be necessary. The ultimate goal of seagrass restoration would be to not only revegetate damaged or degraded areas but also to restore the lost ecosystem services these areas used to provide. In some cases, seagrass restoration may be considered to re-introduce a seagrass species that was lost completely from an area.

Incorporating seagrass restoration into policy frameworks

There are benefits to considering the incorporation of seagrass restoration as a management tool into regional and national policy frameworks and decision-making contexts. Some countries in the WIO region have already done so quite specifically. The National Strategy and Action Plan of Biological Diversity of Mozambique, for example, makes specific mention of the importance of seagrasses and gives due attention to the need for restoration of degraded ecosystems (MITADER, 2015). In Kenya, environmental restoration is anchored in the 1999 Environmental Management and Coordination Act (National Council for Law, 2018) and a 'Coral Reef and Seagrass Ecosystems Conservation Strategy 2014-2018' has been developed, which specifically promotes the development and implementation of seagrass restoration protocols and activities along with dedicated monitoring and evaluation programs (Kenya Wildlife Service, 2013). Such policy instruments are also strategically important during environmental impact assessments, when setting compensation for environmental damage or negotiating blue carbon offsets. Seagrass restoration does not stand alone but is part a suite of management options and tools for environmental conservation, protection, management and rehabilitation. This is important, especially when considering the wider context of the need to address the underlying causes of seagrass decline and protect seagrasses from land-based sources and activities (GESAMP, 2001).

3. SEAGRASS RESTORATION – GENERAL CONSIDERATIONS

The widespread loss of seagrass meadows worldwide, coinciding with the growing knowledge and awareness of the resource value of these systems, has led to increasing attention for seagrass restoration, with a range of methodologies having been developed and tested in a variety of environments, with varying degrees of success and plenty of lessons to learn from.

Seagrass restoration or rehabilitation may be recommended when the seagrass ecosystem has been altered to such an extent that it can no longer sufficiently self-correct or self-renew. Under such conditions, normal processes of secondary succession or natural recovery from damage are inhibited in some way. Unfortunately, for a long time the practice of seagrass restoration has emphasized planting seagrasses as the primary tool in restoration, rather than first assessing the reasons for the loss of seagrasses in an area and working with the natural recovery processes that all ecosystems have. Seagrass restoration may also be considered where there is a need to re-introduce a seagrass species that was lost from an area.

In other cases, seagrass restoration is sometimes conducted as a form of compensatory mitigation by creating seagrass meadows in areas that appear suitable for growth, in an attempt to substitute for unavoidable loss of healthy seagrass elsewhere due to the 'footprint' of a certain development (e.g. port expansion or land reclamation). This may be an obligatory requirement as part of environmental permit approvals under a principle of 'no-net-loss'. Such mitigation may include seagrass relocation or salvage operations (see below). However, it is emphasized here that seagrass restoration should never be considered the first alternative when planning for the mitigation of coastal development projects or to justify mitigation as a compensation measure for economic activities.

Another purpose for seagrass restoration, suggested more recently in response to concerns over climate change, could be to plant seagrasses for 'blue carbon farming' or to reduce ocean acidification, but this has not yet been tried anywhere.

Terms and definitions

In the context of this manual, the term 'seagrass *restoration*' has been adopted to mean any process that aims to return a seagrass system as much as possible to a pre-existing condition (whether or not this was pristine), with consideration of natural recovery processes. This broader definition includes *rehabilitation* efforts that aim to improve conditions but not necessarily returning seagrass of the same species, abundance or equivalent ecosystem function. The term 'seagrass *transplantation*' is used to describe the planting of seagrass shoots or sods derived from another seagrass area into a restoration site, while the term 'seagrass *relocation*' is used to describe salvage operations to rescue seagrass patches that would otherwise be lost under the footprint of planned developments and move them to other areas.

Common sense considerations

If seagrass is not growing somewhere, there are two possibilities: [1] it has never grown there because the conditions at the site are unsuitable, or [2] it used to grow there in the past but it disappeared due to an adverse (human or natural) impact. In both cases, the environmental conditions are apparently not suitable for seagrass at present. As such, it would not make much sense to plant seagrass at such sites and expect any of these transplants to survive. Instead, the underlying cause(s) of the seagrass loss needs to be addressed first by improving the environmental conditions.

Once conditions have significantly improved or returned back to what they were before the disturbance, seagrass generally comes back by itself, gradually recovering its former cover and ecological functioning with time (Vaudrey et al., 2010). The only potential bottleneck to such natural recovery could be recruitment limitation (a lack of supply of seeds or fragments), either due to barriers to connectivity with adjacent (unaffected) meadows or due the absence of any significant populations remaining nearby, from which the site could be re-populated. In such cases, it would make sense to bring seagrass seeds or plant material from elsewhere to restore some vegetative cover. When such revegetated patches are large enough, they will eventually be capable of sustaining themselves, expand and gradually recolonise the site.

Inappropriate site selection and a lack of planning (given little or no consideration to why the seagrass disappeared in the first place) are among the most frequently cited reasons for failure of seagrass restoration attempts (Table 1).

Table 1. Common reasons for failure of seagrass restoration attempts

COMMON REASONS OF FAILURE:

- Inappropriate site selection
- Uprooting of transplants due to strong flows, high wave energy or swell
- Sediment instability causing erosion or smothering & burial of seedlings
- Poor water quality (turbidity, eutrophication, low light)
- Algal blooms and/or excessive epiphyte growth
- Inadequate anchorage of transplants (washed away)
- Poor planning (no reversal of threats, lack of consideration for site selection)
- Too shallow (desiccation) or too deep (insufficient light)
- Excessive bioturbation (e.g. by polychaetes or stingrays) uprooting transplants
- (Over)grazing of transplants (e.g. by sea urchins or amphipods)
- Disease (e.g. fungal attack on seeds or seedlings)
- Too small-scale (poor resilience, insufficient self-facilitation)
- Lack of donor material or seed stock (e.g. no flowering)
- Damage from human activities, storms, floods or spills
- Largescale application of unproven technology (insufficient testing)
- Unrealistic expectations (re: costs, scale, duration, chances of success)

Hierarchy of approaches to seagrass restoration and management

For the most cost-effective and meaningful approach to seagrass restoration, the following hierarchy of considerations is recommended, in order of priority:

1. **Removing causes of further decline**: Prevent ongoing loss and reverse degradation of seagrasses by addressing the drivers of decline. This may include a variety of approaches, such as: establishment of marine protected areas, imposing boating access-restrictions, banning the use of trawling and other destructive fishing gear in seagrass areas, installation of anti-trawler devices, improving watershed- and catchment management practices, investing in waste-water treatment systems to reduce eutrophication (e.g. Greening and Janicki, 2006; Vaudrey et al., 2010), adopting a thorough EIA process and avoiding seagrass areas in site selection for ports, reclamation, industry, aquaculture, pipelines and other infrastructure.

2. **Assisting natural recovery**: Active approaches to create/restore conducive conditions that will facilitate & support or speed up natural recovery of seagrass vegetation and its associated ecosystem functions and biodiversity. This may include hessian bags or geotextile applications (to stabilise the substrate, trap recruits and facilitate successful establishment), restoration of tidal exchange (when restricted or blocked), management of freshwater inflow (e.g. in hypersaline estuaries), hybrid engineering measures such as bunds, sand bars, mussel ridges or oyster reefs (to create calmer conditions), or infilling of larger and deeper excavated injuries from boat groundings or propeller scars through regrading with sediment-filled biodegradable geotextile tubes.

3. **Overcoming recruitment bottlenecks**: If there is evidence of recruitment limitation (e.g. barriers to connectivity, lack of seed banks, near-total loss of vegetation over large areas with very limited or no remaining local sources to replenish from, or if sexual reproduction in the dominant seagrass species is a very rare event, there is need for intervention to overcome the bottlenecks to recruitment (Erftemeijer et al., 2008; Statton et al., 2017). Such interventions may include seed-based methodologies and efforts to restore connectivity (e.g. installation of culverts, establishment of marine protected area networks, re-opening of dammed estuaries). Other approaches that could be considered include the prohibition (or strict management) of significant disturbances (e.g. dredging) during sensitive reproductive periods (such as flowering or seed germination of key seagrass species). Interventions to overcome bottlenecks to successful seedling establishment, such as sediment instability caused by excessive bioturbation (e.g. by altering the sediment composition of the top layer or by shell armouring) would also fall into this category.

4. **Active restoration by planting** (‘gardening’): When approaches 1-3 have been implemented and natural recovery is still slow or unsuccessful, manual transplanting of shoots/fragments or relocation of plugs, sods or excavated mats of seagrass may be considered. Manual planting is also often carried out in

compliance with off-set requirements for unavoidable damage (footprint) as part of permit approvals for major coastal developments or port expansions. Planting of seagrasses may also be conducted to establish demonstration projects (for education or research purposes), as proof-of-concept, to reintroduce a species lost from an area, for blue carbon farming, or to engage local communities to enhance environmental awareness.

4. RESTORATION METHODS

A plethora of methods for seagrass restoration have been developed and tested over the past few decades. Seagrass restoration is relatively young discipline with new methods, innovative ideas and approaches being developed all the time. There are several excellent manuals, guidelines and reviews that describe and review a wide range of seagrass restoration methods in detail. Particular mention deserve the work by Mark Fonseca (Fonseca, 1994; Fonseca et al., 1998; Fonseca et al., 2002), Bob Orth (Orth and Marion, 2007; Orth et al., 2007), and the late Robin R.R. Lewis III (Lewis, 1987; Treat and Lewis, 2006). Useful recent reviews include: Calumpong and Fonseca (2001) and Van Katwijk et al. (2016).

Development and implementation of appropriate methods requires experience and familiarity with species' growth habits and life histories. Numerous methods have been shown to establish seagrass successfully; however, familiarity with handling and planting methods, as well as the ability to work in or under the water, are requisite. Most experience with these methods has been gained on temperate seagrass species, esp. in the USA and Australia. By comparison, seagrass restoration in tropical regions is still in its beginning stages (apart from some great work in Florida and earlier pilots in the Caribbean) and certainly has not yet been done successfully on a large scale. Seagrass restoration in the WIO region is still in its infancy, but some first small-scale trials have been initiated recently in Kenya, Madagascar and Mozambique.

MANUAL TRANSPLANTING

Planting methods in deeper waters will require the use of SCUBA equipment, experienced boat operators and trained SCUBA divers. Shallow waters may allow for the restoration works to be carried out by snorkelling, provided that the water depth is shallow enough to allow a snorkelling person to reach the bottom while holding his/her breath. Intertidal areas are often easily accessible on foot during low tide (provided they are not extremely muddy) and may as such offer the least logistical challenges to the planting activities. In all cases, it is important to clearly mark the planting areas, so its boundaries are clearly visible (e.g. poles, buoys).

All planting methods require available 'wild stock' as a source and are labour-intensive. While this can easily translate in high costs (per area, ha) - especially in western economies, where labour-costs are typically high - this may not necessarily be so in major parts of the WIO region or in restoration programs that involve local communities and/or volunteers.

Planting projects typically involve either sediment-free seagrass units, seagrass sods with sediment and intact rhizome/root systems, or seeds/fruits.

Sediment-free methods:

SEDIMENT-FREE METHODS

Advantages: Sediment-free methods have the advantage that they reduce the burden of carrying (heavy) associated sediment

Disadvantages: The main disadvantage of this approach is its labour-intensiveness (thus limiting the spatial scale of the restoration) and the use of metal staples, which is sometimes criticised, but these can be removed later (and re-used) or substituted for a biodegradable alternative (e.g. bamboo skewers)

For most sediment-free methods, plants are dug up using a shovel (or other device), the sediment is shaken off from the roots and rhizomes and the plants are placed in flowing seawater tanks, floating pens or similar, for holding until made into 'planting units'. It is important to ensure the presence of growing rhizome apical meristems in individual planting units as these provide a source of new shoots and horizontal growth, a means of colonizing of new areas. For vegetative stocks, a minimum of at least one apical shoot per planting unit is recommended. However, benefits can be derived from the clonal nature of the plant if a larger number of short shoots per length of rhizome is preserved (e.g. preferably three shoots per rhizome fragment in *Thalassia*). Plants should be collected and planted on the same day, kept in water with the same ambient temperature and salinity, and kept as moist as possible when out of the water. In a few cases, artificial seagrass mimics have been used with the aim of temporarily creating more stable conditions to allow for the establishment and recovery of natural seagrass plants in between the mimics.



Seagrass should be planted either directly into the bed (as sprigs) or anchored using one of a variety of devices such as rods, pegs, rings, nails, stones, shells, rebar, skewers or staples. U-shaped metal staples or robust wire hooks (e.g. wire for fencing horses) are the most common anchoring devices that have been used successfully in sediment-free seagrass planting programs to date. Plants are attached to the staples by inserting the rhizome-root portion of the plant fragments under the 'bridge' of the staple and securing the plants with a paper- (not plastic-) coated metal twist-tie. The twist-tie is secured around the plants at the meristem so that the leaves will extend from under the staple up into the water column when planted. A small strip of paper has been used to protect the rhizomes from the twist-tie by wrapping the group of plants with the paper and then inserted into the sediment so that the roots and rhizomes are buried. Loosening the sediment with a utensil such as a dive knife facilitates placing the roots into the sediment. Consideration of the orientation of the plants and angle of the staples or wire hooks can be important in high energy environments so that the plants are not displaced by the dominant current flow.

One person can lay out the planting units beforehand at the desired spacing, while a second person follows and installs them. The step of attaching plants to staples can be prepared beforehand but is time consuming. In areas with low wave energy and current velocity, groups of plants may be stapled to the bottom without attaching them to the staples beforehand. When negative buoyancy is not required, the metal staples may be substituted by bamboo skewers (bent into a ‘V’). The staples or wire hooks can be retrieved once plants have established themselves successfully, and then be reused again for further planting (e.g. in the next year).

Plants have also been woven into biodegradable mesh fabric (e.g. hessian bags[4]) that is attached to the sediment surface as a planting unit. This method has been applied successfully to restore seagrasses in mooring scars in Western Australia and degraded meadows in Kenya (see Case Study 9).

[4] Alternatively, sediment-filled hessian bags can be placed as ‘mattresses’ along the edge of healthy seagrass systems and left for natural colonization by surrounding seagrasses. Once the mattresses have an even and dense seagrass coverage, they can be transferred to a restoration site. Trials of this method - though not ‘sediment-free’ - to relocate *Halophila ovalis* and *Halodule uninervis* in Dubai showed potential.

In a recent, more innovative technique developed in the USA, plants were tied with paper strings (leaves up, roots down) to the bottom of cage-deployed frame systems (TERF units) that can be deployed from small boats in deeper waters without the use of divers. The cages help to protect the plantings from biological disturbance and are held down at the bottom with bricks and marked at the surface with buoys. Later, the cage systems can be removed once the plants have successfully rooted and their paper ties have decomposed.

Seagrass-with-sediment methods:

SEAGRASS-WITH-SEDIMENT METHODS

Advantages: Relatively easy, generally less labour-intensive (per area) and yielding higher survival than sediment-free methods

Disadvantages: The main disadvantage of these methods is the logistical challenge posed by the weight of the sods/plugs, which can be quite heavy to carry around (depending on their size) over longer distances, especially with deeply rooted species or when the donor bed is far away from the planting site

The sod or turf method consists of planting a shovel-full of seagrass with sediment (including benthic fauna) and rhizomes+roots intact. The only equipment needed are shovels and some sort of (large) basins to hold the sods. However, if the donor site is far away, transporting the sods may present a logistical problem as the weight of the material can be a physical burden. Deeply rooted species, such as *Enhalus acoroides* and *Thalassia hemprichii*, may require removal of a tremendous amount of sediment to harvest the below-ground plant structures intact. Furthermore, harvesting an entire sod may constitute a significant perturbation in the donor meadow, which may inhibit its recovery.

The plug method utilises tubes as coring devices to extract the plants with the sediment and rhizomes intact. The core tubes can be made of any diameter PVC plastic pipe with caps for both ends to initially create a vacuum and keep sediments from washing out the bottom. The tube is inserted into the sediment, capped (which creates a vacuum), pulled from the sediment and capped at the other end to avoid losing the plug. This is relatively easy in soft but cohesive sediments with smaller, thinner-leaves seagrass species, but becomes more challenging in coarser substrates with tougher seagrasses with dense root systems and taller, tougher leaves (care must be taken to avoid excessive leaf shearing). When the donor bed is far away from the planting site, many tubes are needed which adds to the cost and logistical burden (due to the combined weight).

Various modifications to these sod and plug methods have been made by different restoration programs to suit site- and project-specific conditions, scales and ambitions. Sod pluggers have been tried to extrude 3x3 inch plugs of seagrass into peat pots (transported on floating trays) for ease of sod planting, a method that showed some potential for shorter-leaves species (in high density) such as *Halodule, Halophila* and possibly *Ruppia* species, although there can be some challenges with squeezing out air trapped in the peat pots underneath the sods and with the ripping down the sides of the peat pots once at the bottom (to allow rhizome spread). In Qatar, a large seagrass relocation program near a major port development used metal trays to salvage 50x50cm sods of *Halodule uninervis* (harvested by snorkelers from meadows on fine muddy sediments) that were transported on self-made floating barges (constructed of pallets and old car tires) pulled behind a small boat between the donor site and the relocation site, where they were placed in similarly-sized depressions in the sediment (made with the same metal trays), a program that had some (albeit limited) success.

Seed-based methods:

SEED-BASED METHODS

Advantages: Relatively easy, suitable for large-scale application

Disadvantages: Dependency on seed-availability (and its timing), and the generally low %survival. The latter can, however, be easily compensated for by broadcasting (very) large numbers of seeds (as available)

Seed-based restoration techniques hold great promise for large-scale restoration of some seagrass species, especially in low-energy areas where seeds can settle and germinate and seedlings successfully establish without being washed away. Particular success in seed-based restoration has been achieved with eelgrass (*Zostera marina*) in Chesapeake Bay (USA), where approximately 100 hectares have been restored using seeds using a variety of techniques. Seed-based techniques have also been tested successfully for some other seagrass species, including *Posidonia* spp. in the Mediterranean and Australia (see Case Study 3 in the Appendix) and *Ruppia* spp. in the USA and South Australia (see Case Study 5 in the Appendix). Direct broadcasting of seagrass seeds appears to be the easiest and most cost-effective method. The major cost in this method is obtaining and storing the seeds. This is done through collection of fertile (seed-containing) shoots or mature fruits shortly before they would be released. The collected shoots are then maintained alive in large seawater tanks for several weeks until most seeds have been released (see Case Study 1 in the Appendix), and then the seeds are separated from other organic debris by winnowing and sieving, and stored until required for a restoration project.

An alternative approach in species that produce seeds contained within spathes on flowering shoots (e.g. Zosteraceae), is to harvest of large quantities of fertile shoots prior to seed release and to place these in mesh nets (suspended from buoys) - also referred to as buoy-deployed seed bags (BUDs) - anchored at the restoration site, allowing for natural seed release with time as the seeds ripen, falling out of the nets onto the seafloor and germinating. While this method may be suitable for community-based restoration projects in areas without access to facilities required to separate seeds from other plant material, the method is more costly and time consuming because of the large number of buoys, nets and anchoring devices required.

Irrespective of the methodology used for seed-collection and broadcasting, the percentage of broadcasted seeds that survive and become established as seedlings is generally low (<10%) and sometimes very low (1-2%). However, in areas where it takes little effort to collect seeds during the reproductive season (for seagrass species in which mass flowering and fruiting is common), it is quite easy to broadcast very large numbers of seeds to compensate for this low survival. For the smaller seagrass species, in order to obtain a few hundred seedlings per m^2, it is generally required to broadcast several thousands of seeds per m^2. Impacts on the donor meadows from harvesting such large quantities of seeds, however, has rarely shown to be significant. To enhance the success of seed germination and seedling establishment on dynamic intertidal flats, innovative seed-injecting devices have been developed for use in an eelgrass restoration program in the Dutch Waddensea.

A disadvantage of seed-based approaches is their dependence on the availability of seeds, which may be low or poorly understood. This is potentially an issue in parts of the WIO region, where the timing, intensity and frequency of flowering and seed production for most seagrass species are still largely unknown.

MECHANICAL TRANSPLANTING

MECHANICAL METHODS

Advantages: Potentially suitable for large-scale application

Disadvantages: High initial investment costs, (high-tech) operational and maintenance requirements, not always cost-effective

In an effort to scale up restoration efforts and reduce costs on a per hectare basis, a number of mechanical methods have been developed that make use of heavy equipment or machinery for collection of plant material & seeds or for planting. Examples of these include a modified mechanical plant harvester operated behind a boat used to harvest reproductive eelgrass shoots for seed collection from Chesapeake Bay (USA), a modified backhoe device to salvage and relocate sods of intertidal *Zostera noltii* in the Dutch Westerschelde (see Case Study 6 in the Appendix), a submarine mechanical device ('Ecosub') used to cut and plant sods of *Posidonia* spp. and *Amphibolis* spp. at deep sites of high wave energy near Cockburn Sound in Western Australia, a 'giga unit sod' transplanting machine used to salvage and relocate sods of tropical seagrasses from Tampa Bay in Florida, USA (see Case Study 3 in the Appendix), and the 'Safebent' method with a marinized transplanter (Model Optimal 880) equipped with a very long arm shovel operated from a jackup that was used for the mechanical relocation of *Posidonia oceanica* sods in Monaco. Due to the high investment costs and some project operational challenges, the relevance of these mechanical seagrass restoration methods for application in the WIO region is questionable.

Different restoration methods may be more or less suitable for different seagrass species, depending on their morphology and life history strategy (Table 2), though the suitability and effectiveness of most of these restoration methods have not yet been tested for most species in the WIO region to date.

Table 2. Suitability of different seagrass restoration methods by species. [Legend: tick marks (√) indicate that a method has been tested on a species (or its sister species); question marks (?) indicate that a method has not yet been tried but is potentially suitable for that species. Shading indicate that a method has shown to be particularly suitable (green) or unsuitable (red) when tested for a species].

	Thalassia hemprichii	*Thalassodendron ciliatum*	*Enhalus acoroides*	*Cymodocea rotundata*	*Cymodocea serrulata*	*Syringodium isoetifolium*	*Halodule uninervis*	*Halophila ovalis*	*Halophila minor*	*Halophila stipulacea*	*Zostera capensis*	*Ruppia maritima*
	T.h.	***T.c.***	***E.a.***	***C.r.***	***C.s.***	***S.i.***	***H.u.***	***H.o.***	***H.m.***	***H.s.***	***Z.c.***	***R.m.***
Passive restoration:												
Removal of threats (anchors, fishing, etc.)	✓	?	?	?	?	?	✓	✓	?	?	✓	✓
Sediment-free methods:												
Sprigs planted (shoot-method)	?		✓	?	?	✓	✓	✓		?	✓	?
Sprigs anchored (staple method)	✓		✓	?	?	?	✓	✓		?	✓	?
Sprigs on mats or frames (TERFs)	✓			?	?	?	?	✓		?	✓	?
Seagrass with sediment methods:												
Plugs (by cores)	?	✓		?	?	✓	✓	✓	?	?	?	✓
Sods (by shovel)	?	?		?	?	✓	✓	?	?	?	?	?
Sods (by trays)							✓	?	?	?	?	?
Sods (in peat pots)							✓	✓	?	?	✓	?
Seed-based methods:												
Manual broadcast	?		?					?			✓	?
Fertile shoots (BUDs-method)						?	?				✓	?
Seeds in bags with sediment								?	?	?		✓
Seedlings:												
Wrack-collected or lab-reared	✓	?	✓	✓	✓	?	?	✓		?	?	?
Mechanical methods:												
Mechanical seed harvester											✓	
Mechanical shoot planter*												
Mechanical sod harvester/planter	✓						✓				✓	

* tried in Western Australia on *Posidonia coriacea* and *Amphibolis* spp. with inconclusive results

5. RESTORATION SITE IDENTIFICATION

Inappropriate site selection is by far the most important cause of failure of seagrass restoration projects worldwide. If there is no seagrass (or just sparse seagrass) at a proposed restoration site, you have to ask yourself: why? Simply transplanting seagrasses to such sites (regardless of the method applied), or even attempting the use of seeds, will not, in and of itself, ensure the successful establishment of a new seagrass bed as long as the initial stressors (e.g. poor water quality, excessive bioturbation, heavy sea urchin grazing, beach seine fishing, boat traffic, high waves or currents, etcetera) are not clearly identified and ameliorated. Ameliorating such stressors can be expensive, but without it, seagrass restoration is unlikely to produce any significant successful results at such sites.

Important aspects to consider when selecting suitable sites for seagrass restoration include: habitat suitability (environmental conditions conducive to seagrass growth), level of (human) disturbance (from activities and/or developments that can affect seagrass health and survival), previous experience (success at similar sites), advice from local area specialists (people that know the area well), practical considerations (e.g. access, distance, as well as logistical, institutional and legal considerations), proximity to existing seagrass meadows, evidence of historical seagrass presence at the site, recent incidental sightings of seagrass colonisation in or near the area, and the nearby presence of other habitats (nearby) that are known to facilitate stability and offer positive feedback (e.g. reefs, mangroves, oyster beds) and that would help sustain successful seagrass restoration in the longer term.

Habitat suitability for seagrasses is largely determined by the tolerance limits of the individual seagrass species for environmental variables such as water temperature, salinity, light availability (a function of water depth and turbidity), flow velocity, wave exposure, low tide exposure to air (desiccation) and substrate conditions (composition and stability). This may require specialist advice based on a review of specific literature and in situ assessment and/or modelling of environmental conditions. However, most seagrass species will probably do well in relatively shallow subtidal waters of ‘normal’ salinity (~30-35 ppt), low turbidity, adequate light (~15-20% of Surface Irradiance), on stable sediments, in non-polluted areas, sheltered from excessive wave energy or extreme flow conditions.

It is not advisable to plant seagrasses in areas with no history of seagrass growth or in areas where the underlying causes of seagrass degradation and loss have not been addressed. Similarly, there will be a low probability of success in areas where seagrass loss has caused ‘irreversible’ negative feedback resulting in an alternative stable state (Suykerbuyk et al., 2016). Seagrass restoration sites should have similar depths to nearby healthy meadows and not be subject to chronic storm damage. Sites that undergo rapid and extensive natural recolonization by seagrasses should not be selected for restoration.

Seagrass restoration is sometimes required as compensatory mitigation for damage to seagrass beds, e.g. from pipeline trenching or port expansion. Other sites that are sometimes considered for restoration include injuries to seagrass meadows from boating activities, such as propeller scars, anchor damage and boat groundings.

Planting areas for compensatory mitigation may be classified as either on-site or off-site. On-site plantings are conducted within the area of disturbance on impacted sites, whereas off-site plantings are conducted at some distance from the impacted sites. There are usually few (if any) off-site locations available (unless newly engineered as part of an integrated design for a development) that can support seagrass growth or involve habitat substitution, i.e. replacing one (existing) habitat type with another (i.e. seagrass).

Checklist of criteria for site selection

Restoration sites:

- Historical seagrass distribution (aerial photography, maps, datasets, literature)
- Current seagrass distribution (mapping, fieldwork, evidence of loss/decline/scars/injuries)
- Proximity to natural seagrass beds (donor sites or source of natural recruitment)
- Restoration of sites with evidence of a high likelihood of natural recovery should be avoided (e.g. presence of viable seedbank, high numbers of seedlings, significant rhizome expansion from adjacent seagrass areas)
- Has the cause of seagrass decline been reversed?
- Seagrass restoration has been successful previously at similar sites (pilots?)
- Substrate / sediment composition/thickness (suitable for seagrass?)
- Sediment stability (significant erosion or burial that could hamper restoration)
- Bioturbation (high levels of bioturbation could frustrate restoration success)
- Water depth and tidal characteristics (similar to nearby natural seagrass beds)
- Light availability (meeting minimum light requirements)
- Water quality (turbidity / transparency / secchi, nutrients[5], organic matter, pollutants, phytoplankton and epiphyte loads)
- Salinity and temperature (within tolerance limits of target species)
- Wave / storm exposure (not exceeding tolerance limits of seagrasses)
- Tidal elevation (risk of desiccation during low tide exposure)
- Legal issues (permission)
- Constraints imposed by structures, dredged channels or human activities

Donor sites:

- Extensive enough (for the harvesting of sufficient plant material or seeds
- In good health condition (to offer high quality material/viable seeds)
- Located within the same biogeographical area
- Nearby (to minimise transportation costs and logistical constraints)

[5] A few studies suggest that addition of nutrients in the sediment (slow-release fertiliser) can sometimes help to stimulate healthy growth of transplanted seagrasses (e.g. in fine-grained carbonate silt environments in Caribbean and Florida). Addition of fertiliser showed no beneficial effects in most other studies worldwide.

Relatively simple GIS applications can further assist in site selection, for example by:

- *Exclusion mapping*: mapping of areas that are not suitable, inaccessible, earmarked for development, having potential user conflicts, or currently already covered by seagrass meadows or other valuable ecosystems;
- *Suitability mapping*: model-assisted mapping of habitat suitability for seagrasses based on environmental conditions such as light availability, depth, substrate type, water quality, current velocity, wave exposure, salinity and temperature; and
- *Logistical mapping*: considering practical considerations, such as road access, proximity to a jetty or marina, travel distances, proximity between donor and restoration site, need for SCUBA or boat etc.)

6. PRINCIPLES OF BEST PRACTICE - A RESTORATION PROTOCOL

Guiding principles for restoration planning

The following principles emerged over the past few decades of seagrass restoration practice worldwide as critical considerations to guide any successful seagrass restoration approach (see Treat & Lewis, 2006; Van Katwijk et al., 2016):

- **Large scale approach:** Many seagrass restoration projects in the past have been unsuccessful because their spatial scale was too small. One of the problems with a small-scale approach is that the (re)planted seagrass patches are too small to sustain themselves over time. Research suggests that restored seagrass patches of one hectare or larger are better able to withstand adverse conditions, overcome negative ecological feedbacks and survive over longer time scales than smaller patches or groups of small patches (Van Katwijk et al., 2016; Paolo et al., 2019). This seems at least in part to be due to self-facilitation through substrate stabilisation and self-seeding. Simply put: for successful restoration, it is better to think in terms of scales of hectares rather than square metres.

- **Working with nature:** Unlike the small scale at which active human effort - through 'gardening' approaches - is capable of restoring seagrass meadows, nature itself is able to recover at much larger scales through natural regeneration within relatively short time-frames over large areas. For this, two requirements will have to be met: [1] environmental conditions have to match (again) the ecological requirements of the seagrass species, and [2] natural recruitment (from a persistent seed bank, through seed dispersal, or through inflow of viable seedlings or plant fragments from nearby unaffected seagrass areas) should be sufficient to enable recolonization. Restoration approaches would benefit from capitalising on this 'free-of-charge' service that nature provides, through focusing their main effort on restoring environmental conditions and recruitment, and then letting 'mother nature' and 'father time' do the rest (a.k.a. '*working with nature*').

- **Site selection:** Inappropriate site selection is by far the most important cause of failure of seagrass restoration projects worldwide. Important aspects to consider include: suitability of environmental conditions (meeting the requirements for healthy seagrass growth, notably emersion and desiccation effects, nutrient limitation or overload, light requirements and site turbidity, currents, wave exposure, salinity and temperature tolerances, and substrate stability), level of disturbance or developments that can affect seagrass survival, local area specialists' advice, logistical considerations (site access, distances), nearby presence of existing seagrass meadows, evidence of historical seagrass presence, and recent sightings of seagrass colonisation nearby. Donor sites to harvest plant material or seeds need to be extensive enough and in good health, and located within the same biogeographical region, preferably in close proximity to minimise transportation costs and logistical constraints.

- **Spreading of risk:** To maximise chances of restoration success, it is often necessary to spread the risk of poor survival or loss of transplants by spreading the restoration efforts in space and time. Loss of seedlings, transplants and seeds is likely to be higher at dynamic sites that are exposed to strong currents, waves or tidal flows or experience excessive bioturbation, but these can be important areas to revegetate if the project goal is to improve sediment stability. Mortality and loss of seedlings and transplants can also occur due to storms, desiccation (intertidal) and seasonal fluctuations in salinity and temperature. The origin of donor material may also contribute to variability in success. Other (unknown) factors and the complexity of processes involved may further contribute to the unpredictability of success in seagrass transplantation. The effect of all these factors can be reduced by spreading and replicating the timing and location of the restoration activities over different sites and at different times, and by using source material from different donor locations (which also helps to maintain genetic diversity and resilience). Simply put: to minimise risks, it is better not to collect and plant all material at one time and at one location, but to vary and repeat restoration activities in space and time. Another way of spreading risk is to use multiple species of seagrass in the restoration (rather than just one), particularly in regions with high biodiversity. In a recent seagrass restoration experiment in Sulawesi (Indonesia), transplant survival and coverage at restoration sites increased with the number of species transplanted (Williams et al., 2017), achieving better results with transplanting multiple species together than with a single target species.

- **Keeping costs (per unit area) low:** It is of critical importance that the limited financial means that are available for restoration of sensitive marine environmental assets (especially in the WIO region) are used as effectively and efficiently as possible on successful projects (Treat & Lewis, 2006). There is general scepticism and perception worldwide that ecosystem restoration projects are costly and often have only minimal success. In order to achieve an as high as possible return for investment (of both labour and costs), it is therefore of paramount importance to keep the costs for each and every step of the restoration process as low as practically and technically feasible. This will allow for an as large as possible restoration outcome (in terms of hectares). However, a comprehensive feasibility study and thorough site selection prior to any restoration project remain essential to increase the success rate of any restoration project. Where possible, close collaboration with existing research and monitoring programs can help to reduce overall costs of ancillary investigations.

- **Minimising impacts on donor sites and avoiding species introductions:** If the seagrass restoration approach involves the use of donor material from elsewhere, it is critical that proper consideration is given to minimise impacts from the harvesting of the material (whether seeds, plants or sods) at the donor sites and to avoid the unintentional introduction of exotic or invasive species (plants and animals) at the restoration site.

Other practical considerations:

- Choice of species & donor material: The obvious consideration would intuitively be to plant the same species (or mixture of species) as what was lost from the site, which applies to most restoration projects. However, it may sometimes be better to plant a different species if site conditions have changed to an alternative state. A different species (e.g. a pioneer or opportunist) may then be better adapted to the changed conditions than the species that originally dominated the site. Donor material would ideally come from within the same biogeographical area or region. The use of material from multiple donor sites is sometimes considered to enhance and/or preserve genetic diversity. By all means, plant material should always be handled with extreme care and kept wet at all times, as most seagrasses have very little resistance to desiccation.

- Selection of restoration method: A plethora of restoration methods & techniques have been developed over the past few decades, and quite frankly most of them probably work well for most seagrass species on which they have been tested, provided that site-selection has been given adequately consideration. The desired scale of the restoration outcome and costs (versus available budget) can be important considerations in selecting the method of choice. In the end, practical logistics, convenience with regards to the local conditions at the site and familiarity and/or preference of the practitioner add further to the choice considerations.

- Community participation: Community-based projects are projects that take place in community settings with the involvement of local coastal communities from design to implementation. Such projects recognise local knowledge and other contributions made by community partners (or other local stakeholders) to project success. Effective community participation can greatly contribute to achieving local ownership and long-term sustainability of the outcome of a seagrass restoration project beyond the initial intervention. This will be particularly so when the community is (made) aware of the values of the restored seagrass ecosystem as fish habitat and coastal protection and thus its contribution to securing a better livelihood and future. It can also play a factor when weighing skill and experience against costs for the implementation of restoration objectives. Similar considerations apply to the decision to involve citizen volunteers. In all cases, there is need to carefully manage realistic expectations of the outcome of the restoration efforts and maintain transparent communication.

- Stakeholder engagement and the role of government: In most projects, it can be beneficial to engage stakeholders in the planning and implementation of a seagrass restoration project (in addition to community participation). Examples include NGOs, CBOs, local businesses, dive operators, MPA park rangers, port authorities, tourism and hotel industry and so forth. The contribution of non-governmental and community-based organisations can be particularly valuable and important in the WIO region. Municipalities and other local authorities and government representatives should be contacted for necessary permits and may be able to facilitate access and offer data and logistical support.

- Multidisciplinary approach: It can sometimes be valuable to seek the advice and/or involvement of experts from different disciplines (e.g. geologists, engineers), as a multi-disciplinary approach may sometimes be required to address the complex challenges at a project location in order to accomplish restoration success.

- Spacing of planting units: The choice of appropriate spacing of planting units will depend on the method and species. Practical experience with eelgrass restoration in the USA suggests that optimal spacing generally ranges between 0.5 and 2 m on centre. Obviously, the closer planting units are together, the more rapidly they will close up the gap over time (or attain a desired %cover or patchiness similar to what was there before). However, the benefit of increased rate of coalescence is soon offset by the substantially higher costs due to the number of planting units involved. For example, a 100m x 100m (1 ha) planting area planted on 2.0, 1.0 or 0.5 m centres would require 2500, 10000 or 40000 planting units respectively. Similar considerations apply for seed-based techniques, but the relatively low percentages of successful germination and seedling survival reported for such methods) need to be kept in mind.

- When to seed/transplant: When planning for the restoration, seasonal changes in weather (e.g. avoid periods of heavy rainfall or disturbance by storm waves) and site conditions (e.g. water quality) that may affect growth and survival of the planting units (or seedlings) and thus restoration success. When working on intertidal flats, timing of the fieldwork should consider the tidal conditions as this will determine accessibility and could pose safety issues for participating community members and volunteers. Availability of donor material may also vary seasonally, especially in the case of seeds (or fertile shoots) for species with distinct reproductive seasonality.

- Realistic timeframes: It is important to set realistic timeframes for successful seagrass restoration projects. Proper planning before implementation (incl. site selection and permits) will often take more time (months) than initially realised, but it always pays off in the end. Depending on the methodology and scale, the restoration work itself can take up several days or weeks (or more) and may be repeated multiple times, either within the same year or in consecutive years. Evaluating success should not be done too soon after initial planting. It is best practice to monitor the success, growth and survival of the transplanted seagrass for a period of several years following planting (five years, as used in the USA, is a good yard stick, but this can be reduced for fast-growing pioneer species (e.g. *Halophila* spp.) or may need to be extended for seagrass species that grow and spread very slowly). Recovering a reasonable vegetation cover may be accomplished within a few years (or even sooner in fast-growing species), but the full recovery of ecosystem functions is likely to take much longer.

- Planning a restoration schedule: Careful and thoughtful planning is crucial to the success of any seagrass restoration project and generally involve most of the following steps/considerations: damage assessment (size/scale and cause of seagrass damage / loss), determine adequate remediation approach (which first and foremost will involve measures to reverse habitat degradation), cost-benefit analysis of potential intervention options and scale considerations, seasonal perspectives and species life history characteristics, selection of planting stock, pre-planting site surveys at donor and restoration sites, assessment of pre-injury species composition and cover/distribution/extent and other historical perspectives, identify restoration goals and performance criteria, evaluate permit requirements and other legal considerations, site selection, obtain transplant stock (plants, sods or seeds), choice of planting method, species and spacing, evaluation of the best timing for the transplanting (or seed-broadcasting), developing success criteria and indicators, implementation of the actual restoration works, monitoring of plantings (plant performance & survival), remedial planting and site maintenance (this may include interventions to address substrate instability by reducing bioturbation or reducing wave and current scour, as required), interpretation of results, evaluation of success, sharing of lessons learnt.

- <u>Cost considerations:</u> Seagrass restoration is expensive. However, if successful, regained ecosystem services may compensate and eventually surpass these initial investment costs. True costs of any seagrass restoration project include the costs of mapping & ground-truthing, planting (sprigs or sods) or sowing (seeds), monitoring, community participation, contractor involvement and government oversight. Typical (all-inclusive) costs for seagrass restoration worldwide range from <590,000 to >910,000 US$ per hectare, but community-based projects in the WIO region (depending on their scale) are likely to be much cheaper. Seed-based restoration, projects assisting natural recovery, and restoration initiatives involving local communities or citizen volunteers are generally the cheapest, while projects involving site remodification, engineering measures (e.g. substrate modification) and/or those involving the use of SCUBA (in deeper waters) or heavy equipment (e.g. modified backhoe and seed harvesting or sod planting/relocation machines) are generally more expensive (up to >1 million US$ per hectare). It is highly recommended to include a thorough cost-benefit analysis prior to any decision about a restoration project, weighing the costs of different restoration methods (as well as those of additional habitat enhancements and other mitigating measures) against the benefits of increased scale of success.

- <u>Monitoring & evaluating success:</u> Monitoring of the progress and success of the restoration (although labour-intensive and expensive) is an essential component of any seagrass restoration project. Appropriate and sufficiently robust monitoring is critical to ensure that any contracted work was performed to specifications and was in compliance with regulatory permit requirements (where applicable). In any situation, monitoring of planting performance using standard methods provides the basis for ‘mid-course’ corrections (e.g. remedial plantings and/or other project modifications) and to derive lessons learnt for improved planning of subsequent projects elsewhere. There is general consensus that seagrass restoration monitoring programs should run for at least five years, with quarterly monitoring in the first year, followed by bi-annual (and eventually annual) monitoring in the remaining years.

7. RESTORATION MONITORING

Implementing a systematic monitoring plan to document the progress, challenges, effect of remedial measures and ultimate degree of success of the restoration is an essential component of any seagrass restoration project.

Although monitoring can be labour-intensive and expensive, a systematic and statistically robust monitoring program using standard methodologies is indispensable to ensure that any contracted work was performed to specifications and was in compliance with regulatory permit requirements (where applicable). In any situation, appropriate monitoring of planting performance provides the basis for 'mid-course' corrections (e.g. remedial planting, site modifications). It is also critical for deriving valuable lessons for improved planning of future seagrass restoration initiatives elsewhere.

Monitoring of performance of plantings and restoration success should always be linked to agreed standards and pre-defined metrics. Success should be evaluated against clearly defined success criteria that are preferably quantitative and scientifically valid. Success criteria can be as simple as the extent of restored area (in hectares) or a desired percent seafloor coverage (%cover or shoot density) of the vegetation and its persistence over time, but (especially in more recent projects) they often also include measures and indicators of the functional attributes (e.g. fauna colonisation, associated biodiversity, role in sediment stabilisation, nursery function, carbon burial etc.) of the restored habitat in comparison with similar natural (local) reference sites. It is important to consider to including measurements of some general environmental variables (e.g. temperature, salinity and turbidity, which may help to explain and attribute a disappointing outcome of the restoration efforts at certain locations to environmental conditions that are beyond control of the restoration team (such as severe rainfall, river floods, heat waves, frost, major storms or even cyclones).

Seagrass restoration monitoring programs is best run for a duration of at least five years, with quarterly monitoring in the first year, followed by bi-annual (and eventually annual) monitoring in the remaining years. The timing of monitoring events should be selected with consideration of the spring-neap tidal cycle and seasonality of weather (e.g. monsoons, rainy season, summer-winter). In the case of once-a-year monitoring, it is best to select the time of year when the seagrass is at the peak of its growth and development (maximum standing crop). The results of the monitoring during the first year (which should always be done quarterly) will help to define the best timing of monitoring in subsequent years. This may also be helpful in selecting the best timing for aerial photography or drone-assisted monitoring (as appropriate, e.g. in areas where access is more difficult), for follow-up monitoring of the long-term persistence of the restored areas in subsequent years.

Monitoring specifications typically include most (or some) of the following indicators:

- ***Survival:*** %-age of the number of transplanted sprigs, sods or broadcasted seeds that survived;

- ***Aerial coverage:*** a random sample of the surface area (in m^2) covered per planting unit should be recorded until coalescence (when individual planting units have grown together and become indistinguishable). By counting the total number of surviving planting units, they may then be multiplied by the average area per planting unit to determine the total area covered at the restoration site.

- ***Shoot density:*** a random assessment should be done of the density of shoots (by counting). Alternatively, a visual estimate can be made of the %cover of the replanted patches, which can then be compared against known shoot densities of a reference series of samples taken within the same general area to estimate shoot density. Early stage planting units may show an artificially high shoot density when expressed per m^2 when they are still associated with the anchor (or staple), but eventually planted patches spread out more naturally in a way that is more similar to natural colonisation. Shoot density is recommended in addition to aerial cover, because it is a more accurate means of assessing the asexual reproductive vigour of the plantings (how well they have established and spread). Shoot density can vary quite significantly between locations (as a function of site suitability) and seasonally (which needs to be taken into consideration when interpreting monitoring data in comparison with those from reference sites or against data from previous monitoring campaigns).

- **Photography/video:** repeated photography of restoration plots (best from standardised positions) and video transects of restored areas can be an additional (attractive) way of providing useful and potentially semi-quantitative records of progress of any seagrass restoration project.

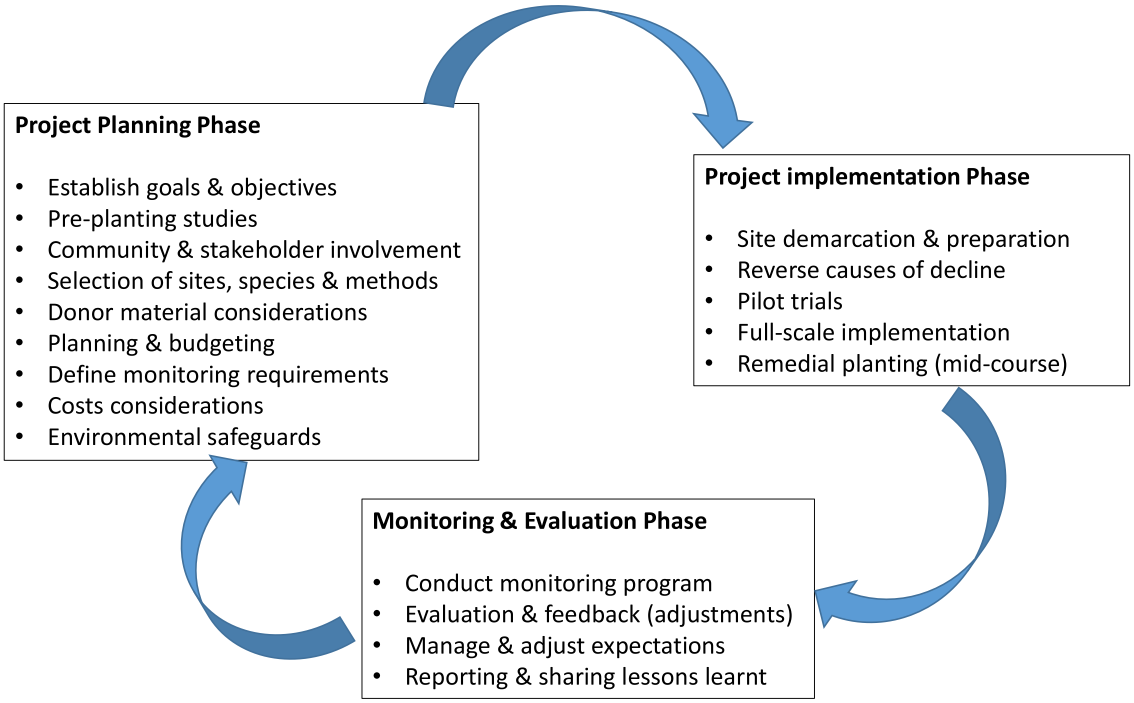
- **Ecosystem functions:** Where desirable and identified as intrinsically valuable indicators of project success, quantitative measures of selected ecosystem functions (as predefined at the onset of the restoration), such as associated biodiversity, ambient water quality, sediment stability, use as nursery ground, fish densities, carbon storage, etcetera) can be incorporated in the monitoring program as appropriate.

Monitoring reports should (as a minimum) contain the following information:

- Dates, times and geographic (GPS) locations of monitoring activities
- Observations of weather, sea state and tide at the time of monitoring
- Quantitative data on the measured attributes (% survival, aerial coverage, shoot density, photographs/videos and ecosystem functions) for each of the transplantation plots/sites
- Data of the environmental variables and weather for the monitoring period
- Interpretation of the data, supported by statistical analysis (as appropriate)

8. SEAGRASS RESTORATION MANAGEMENT PLAN

Seagrass restoration is unlikely to succeed if it simply means transplanting seagrasses without adequate site assessment and consideration of the underlying causes of seagrass loss at the site. To ensure a successful seagrass restoration project, a generalised planning protocol should be followed which would generally include the following basic steps and considerations:



PROJECT PLANNING PHASE:

- ***Goals and objectives:*** Establish clear goals and objectives for the restoration project prior to initiating any restoration activities.

- ***Pre-planting studies:*** Mapping of seagrass distribution and delineation of degraded areas in need of restoration. Study the potential sites to be restored and determine: seagrass bed history (species composition, cause of loss), exposure to environmental stressors (esp. air, waves and currents), substrate type, evidence of significant siltation or erosion, presence of bioturbation and other animal disturbances. For seed-based restoration approaches, phenological studies may be required to identify the timing of flowering and seed production of the different species and/or the presence of seed banks.

- ***Community and stakeholder involvement:*** Involvement and participation of local communities, stakeholders and/or citizen volunteers in seagrass restoration projects should be considered. It can help reduce costs, offer a source of local labour, contribute to ensuring long-term persistence and sustainability of the restored seagrass areas, and improve the success of the restoration efforts by offering an opportunity to incorporate local (traditional) knowledge of the area into the planning and design of the restoration approach. Early engagement of the community is critical in achieving their meaningful and effective participation, which should be sustained throughout all phases of the restoration project.

- ***Selection of sites, species and planting method:*** Site selection for seagrass restoration should consider the suitability of environmental conditions in meeting the requirements for healthy seagrass growth. Species selected for the restoration should be derived from the historical community composition and be well-adapted to current site conditions. The selection of planting methods should be based on an assessment of their suitability to the species and conditions at the site, the goals and desired outcome and spatial scale of the project, and a thorough (participatory) cost-benefit analysis of different options.

- ***Donor material:*** Locate a donor bed that satisfies the requirements for the collection of appropriate quantities of seagrass material for transplanting into the restoration site. For vegetative methods, this should be near enough for transplanting of the plants or sods on the same day (and not more than that). For sediment-free plant material and/or seed-based methods, consideration should be given to meet the needs for storage of the material (in moving seawater at ambient temperature and salinity). Efforts should always be made to minimise disturbance of the donor sites as it can be extremely frustrating for all persons involved in the restoration effort if there is significant (new) damage to a healthy donor bed due to the harvesting of material for the restoration, especially if the restoration is ultimately unsuccessful. Fortunately, in most projects impacts to donor beds are generally small in scale and usually show rapid recovery.

- ***Planning and budgeting:*** Determine time-frame and budget by evaluating typical staffing and equipment requirements. A minimum of seven to nine people is generally required for intertidal and shallow subtidal sediment-free planting. Time for planning, pre-trip preparations and mobilisation and demobilisation (incl. travel) should also be incorporated in planning and budgeting. Time and resources required for monitoring and reporting of restoration success should also be budgeted for.

- ***Monitoring requirements:*** Define methods, success criteria and frequency (and duration in years) for long-term monitoring. Include donor population monitoring (to determine recovery from impacts of harvesting of plant material for the restoration)

- ***Costs:*** Consider all the before-mentioned potential project costs, including site delineation, reports, mobilisation and demobilisation, planting operations, monitoring, remedial planting, overheads (perhaps incl. insurance), mapping, staffing, transport and food/drinks for volunteers, and so forth. Think of long-term sustainable financing options that could ensure sufficient funds to cover all works, including the monitoring and evaluation phase.

- ***Environmental safeguards:*** Assess potential environmental impacts of the restoration works, both at the donor site and the restoration site (including the risk of introducing invasive species if donor material is brought in from elsewhere) and consider practical ways in which these can be minimised.

PROJECT IMPLEMENTATION PHASE:

- ***Site demarcation & preparation:*** Carefully delineate the plots to facilitate both the transplanting and the monitoring of the restoration areas. This phase may also include some modifications to site conditions (as appropriate and feasible) to prepare the site for restoration and enhance chances of its success.

- ***Reversal of causes of decline:*** Make every effort to ensure that local threats (bioturbation, herbivory, sediment instability, adverse human activities) and known causes of decline and degradation to the seagrasses at the restoration site are understood and reversed (reduced to a level low as reasonably practical).

- ***Pilot trials:*** Initiate with small-scale or pilot restoration trials first, prior to engaging in large-scale restoration projects. Small pilot projects can help to test the suitability of different methods (incl. anchoring techniques and site remedial measures, such as sediment conditioning or creation of engineered sand-bars or shell reefs) for the species and conditions of the local site, and to get familiar with the handling of the plant material and equipment, time requirements, practical aspects, logistics and challenges) before scaling up the project for application at larger spatial scales (Tanner et al., 2014).

- ***Full-scale implementation:*** A large scale may eventually be necessary because a critical mass of plants/area planted is often required to ensure longer-term persistence of the restored areas. Spread the trials over different sites and times of the year to accommodate unforeseen circumstances, poor understanding of site complexities, and other unpredictable factors that may affect performance and success (Suykerbuyk et al., 2016).

- ***Remedial planting:*** Corrective measures (mitigation of unwanted developments or local interferences) may sometimes be necessary at a certain stage during on ongoing restoration project. This may include remedial planting as ‘mid-course’ correction, based on observations made during the monitoring program (e.g. unexpected or below expectation levels of survival of transplants). Sometimes, this may include interventions that help to modify site conditions (as appropriate and feasible) to improve chances of a successful outcome of the restoration.

PROJECT MONITORING & EVALUATION PHASE:

- ***Monitoring:*** Conduct thorough monitoring (see previous chapter) and be prepared to conduct site modification and remedial planting if survival is below expectation.

- ***Managing and adjusting expectations:*** It is important to manage realistic expectations of the outcome of the restoration efforts. To achieve this a clear communication strategy is critical. As long as a restoration pilot is viewed as it is, i.e. an experiment and learning process (to be scaled up and modified as we go along, with transparent sharing and learning of failures and unexpected developments along the way to determine what works and what doesn't), with no guarantee of success, it should be worth pursuing. Expectations may be too high if people are too quick to expect and conclude that a particular restoration approach will be successful without any prior learning experience and/or proven demonstration of success under similar circumstances (or from earlier pilot trials at the site).

- ***Reporting and sharing of lessons learnt:*** Publication of the results and sharing of experiences is essential, and offers an opportunity for others to accommodate the lessons learnt into the planning and design of new restoration projects at other locations in the future.

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Glossary

apical	- arising from superior, distal or extreme end (tip)
benthic	- living in or on the seafloor (sediment)
bioturbation	- physical disruption of the seafloor by animal activity
biogeographical region	- area of animal and plant distribution of similar or shared characteristics (distinct from other such regions)
blue carbon	- carbon captured by the world's oceans and coastal eco-systems (stored in the biomass and sediments)
cohesive sediment	- sediment containing a significant proportion of fine clay particles, which causes the sediment to bind together
compensatory mitigation	- creation or restoration of a wetland or seagrass area for the purposes of offsetting a permitted loss of a similar wetland or seagrass area
demersal	- living near or at the seafloor
herbivory	- consumption/grazing of living plant tissue by animals
life history (strategies)	- characteristic aspects of an organism's reproductive development and behavior, as well as it’s demographic characteristics such as generation time and life span, population density and population dynamics
meristem	- portion of a plant that contains tissue which divides and gives rise to similar cells or plant structures (e.g. tissues, organs, rhizome, roots, leaves)
mitigation	- the restoration, creation or enhancement of a seagrass area to compensate for permitted seagrass loss
monospecific	- consisting of a single species
opportunist	- a species that is able to colonise, reproduce and gain significant, persisting biomass when conditions are good but also has the ability to rapidly recover from seed when necessary
peat pot	- technique where by plugs of seagrass are removed and placed into commercially viable, small cups or pots (constructed of compressed peat) for ease of stacking, handling, transportation and outplanting
pelagic	- living in the water column of the open sea
pioneer (species)	- species of seagrass with a growth strategy that enables it to rapidly colonise unvegetated seafloor, usually with high investment in sexual reproduction, low resistance to disturbance but able to recover rapidly from seed bank
rehabilitation	- efforts that aim to improve conditions but not necessarily returning seagrass of the same species,

	abundance or equivalent ecosystem function
relocation	- salvage operations to rescue seagrass patches that would otherwise be lost under the footprint of planned developments and move them to other areas
remediation	- action of remedying something, in particular of reversing or stopping environmental damage or otherwise unwanted change
remedial planting	- corrective action of planting new seagrass planting units during a restoration program to replace previously planted units that died
resilience	- capacity of an ecosystem to respond to a perturbation or disturbance by resisting damage and recovering quickly
restoration	- any process that aims to return a seagrass system to a pre-existing condition (whether or not pristine)
rhizome	- underground stem, usually growing horizontally
salvage	- rescuing seagrass from an area where activities are planned that will destroy that seagrass
secchi (disk)	- a circular, white or coloured disk lowered into a body of water to estimate the clarity of the water by measuring the depth at which it disappears
secondary succession	- plant community which develops on sites from which a previous community has been removed
seedbank	- an accumulation of dormant seeds in the sediment which may germinate at a later time
seedling	- young plant that has germinated from a seed
shoot	- a single plant unit that arises from the rhizome
sod(s)	- section of seagrass-covered sediment held together by it's roots & rhizomes (also referred to as terfs or plugs), excavated for the purpose of transplanting
spathes	- bract at the base of a seagrass flower that will contain the ripening seeds after fertilisation (can break off and floats to aid in seed dispersal)
sprigs	- a seagrass fragment (or stem) bearing leaves, rhizome and roots, taken from a seagrass meadow with the purpose of restoration
tidal elevation	- relative elevation or bathymetric position where plants are found in relation to the fluctuating water levels caused by the tide
transplantation	- planting of seagrass shoots or sods derived from another seagrass area into a restoration site

Abbreviations

BUDs	-	Buoy-Deployed Seeding devices (for seed-based restoration)
CBO	-	Community-Based Organisation
EIA	-	Environmental Impact Assessment
GPS	-	Global Positioning System
NGO	-	Non-Governmental Organisation
PVC	-	Polyvinyl chloride
SCUBA	-	Self-Contained Underwater Breathing Apparatus
SER	-	Seagrass Ecosystem Restoration
TERFs	-	Transplanting Eelgrass Remotely with FrameS
WIO	-	Western Indian Ocean
WIOSAP	-	‘Strategic Action Programme for the protection of the Western Indian Ocean from land-based sources and activities’

Appendix: Case Studies

Case study 1: Eelgrass restoration in Chesapeake Bay using adult plants and seeds

Over the past four decades, a large-scale eelgrass (*Zostera marina*) restoration program has been implemented in Chesapeake Bay and adjacent coastal bays of Delmarva Peninsula (USA). Restoration was first initiated in 1978 following widespread seagrass loss and degradation in the bay due to ongoing deterioration of water quality. Major efforts were made to improve water quality through the installation of waste water treatment plants and improved watershed management. While eelgrass showed good recovery in Chesapeake Bay itself, there was no recovery in the adjacent coastal bays. Both manual and mechanized techniques were used in efforts to restore eelgrass at a number of different locations using either adult plants or seeds, highlighting the importance of the timing of transplanting, labour requirements and initial success. Much of the earliest transplant work was conducted in a variety of locations with different vegetation histories and water quality characteristics to address questions related to habitat requirements.

Figure A1: Buoy-deployed seed bag method (incl. assemblage and deployment), one of the methods used to restore eelgrasses at Chesapeake Bay (USA). (Photo credits: Bob Orth)

Planting eelgrass in fall rather than spring was optimal, offering the plants a longer growing period to become established. Techniques utilizing adult plants (e.g. mesh mats with bare rooted shoots, sods and cores of seagrass and sediment, bundles of bare root shoots with anchors, single shoots without anchors) were generally successful, with the manually planted single shoot method being both successful and requiring the least time. Mechanized planting with a planting boat had lower initial planting unit survivorship and did not result in significant savings of time.

Techniques using seeds (e.g. manual seed broadcasting from a small boat, use of burlap bags to protect seeds, and buoy-deployed seed bags or BUDs) rather than adult plants had varying degrees of success with highest seedling establishment noted where seeds were protected in burlap bags. Current issues with seeds deal primarily with the low survival rate of seeds (generally between 5 and 10% of seeds establishing as seedlings in field experiments) and seed treatment and storage conditions affecting their viability.

Figure A2. Mechanical harvesting of seed stock from donor areas, seed processing in tanks at the lab, and manual broadcasting of seeds from a small boat. (Photo credits: Bob Orth)

Despite having some of its own challenges, broadcast of seeds is one of the least labour-intensive techniques used to date in the program and is currently proving highly successful in restoring eelgrass to Virginia's seaside coastal bays that have been un-vegetated since the 1930s. For the past 20 years, over 72 million seeds were broadcasted into 215 hectares of seaside bays. This natural enhancement of these environments is simple, fast, and effective. Their 215 hectares of seeded plots have since spread naturally into ~3,640 hectares of eelgrass throughout the seaside bays.

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Marion, S.R. and R.J. Orth, 2010. Innovative techniques for large-scale seagrass restoration using *Zostera marina* (eelgrass) seeds. Restoration Ecology 18(4): 514-526.

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Orth, R.J., K.A. Moore, S.R. Marion, D.J. Wilcox and D.B. Parrish, 2012. Seed addition facilitates eelgrass recovery in a coastal bay system. Marine Ecology Progress Series 448: 177-195.

Case study 2: Facilitating *Amphibolis* seedling recruitment with artificial substrates

The coastal waters off Adelaide (South Australia) have seen a significant loss of >6,000 ha of seagrasses since 1949, primarily due to overgrowth by epiphytic algae resulting from anthropogenic nutrient inputs, and turbidity. Despite substantial improvements in water quality since the late 1990's, natural recovery of seagrasses (especially of *Amphibolis antarctica*) has been slow, with high levels of sand movement hampering the successful establishment of seedlings. Initial restoration efforts focused on adapting techniques used elsewhere, such as transplantation of shoots, sprigs and laboratory-reared seedlings, but the success and scale of these efforts was limited. During these initial studies, hessian matting was used around the transplants to stabilize the sediment. While ultimately unsuccessful in this goal, it was observed that seedlings of the seagrass *Amphibolis antarctica,* which have a miniature 'grappling hook' on their base, naturally became entangled in the hessian material, thus facilitating their establishment. Following this observation, a range of techniques were tested using hessian and other materials to entangle *Amphibolis antarctica* recruits and allow them to become established. Standard hessian sacks filled with sand were eventually selected for subsequent work. These bags can simply be dropped off a boat and do not require any further manipulation by divers.

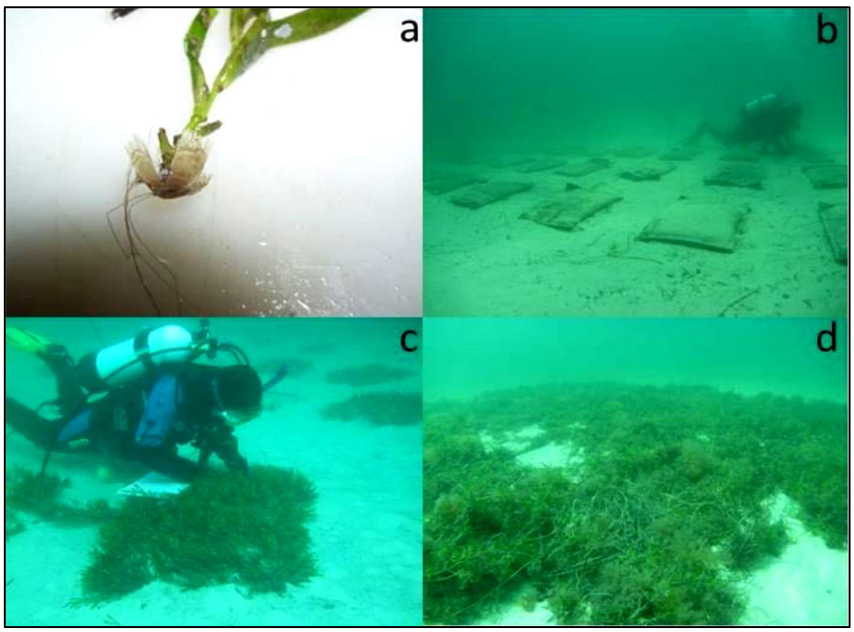

Figure A2: *Amphibolis antarctica* recruitment facilitation approach showing: (a) *Amphibolis* seedling with close-up of grappling hook to assist anchorage; (b) recently deployed sand bags laid out for monitoring; (c) 6-month old deployment covered in *Amphibolis* seedlings; (d) restored *Amphibolis* patch showing coalescence from ~40 bags. (Photo Credits: Jason Tanner and Andrew Irving)

May to August was shown to be the best period for bag deployment to coincide with the natural dispersal of seedlings and maximise recruitment success. *Amphibolis antarctica*'s structural characteristics (stem density and length) were similar to those in natural meadows five years after bag deployment. Early deployments started to coalesce into larger patches by 2013 and have now formed several larger patches where the locations of individual bags can no longer be distinguished (Tanner et al. 2014). Deterioration of hessian bags before seedlings have become established can be a challenge. Following the success of these proof-of-concept pilot studies, the focus is now on upscaling the approach to a series of 1 ha trials, and treatment of the hessian bags prior to deployment to prolong their integrity.

References: Irving, A.D. et al. (2014). Rehabilitating seagrass by facilitating recruitment: Improving chances for success. Restoration Ecology 22: 134-141.

Tanner, J.E. et al. (2014). Seagrass rehabilitation off metropolitan Adelaide: a case study of loss, action, failure and success. Ecological Management and Restoration 15: 168-179.

Case study 3: 'Seeds for Snapper': Collection, processing and broadcast delivery of *Posidonia australis* seeds

Cockburn Sound is a natural embayment approximately 16 km long and 7 km wide, SW of Perth, Western Australia. Cockburn Sound has seen a 77% decline in seagrass cover (~2000 ha) since 1967, largely due to the effects of eutrophication, industrial development and sand mining. In small, localised areas, natural recruitment has been successful, but many other parts have not been able to recruit and recover naturally. A number of techniques have been trialled in an attempt to develop efficient and cost-effective methods to regenerate seagrass meadows, including transplanting large sods, cores, transplanting sprigs and seedlings. However, cost and labour-intensiveness has been a prohibitive factor for many of these methods to be applied at larger scales, while availability of plant material and impact on existing meadows has proven prohibitive for others.

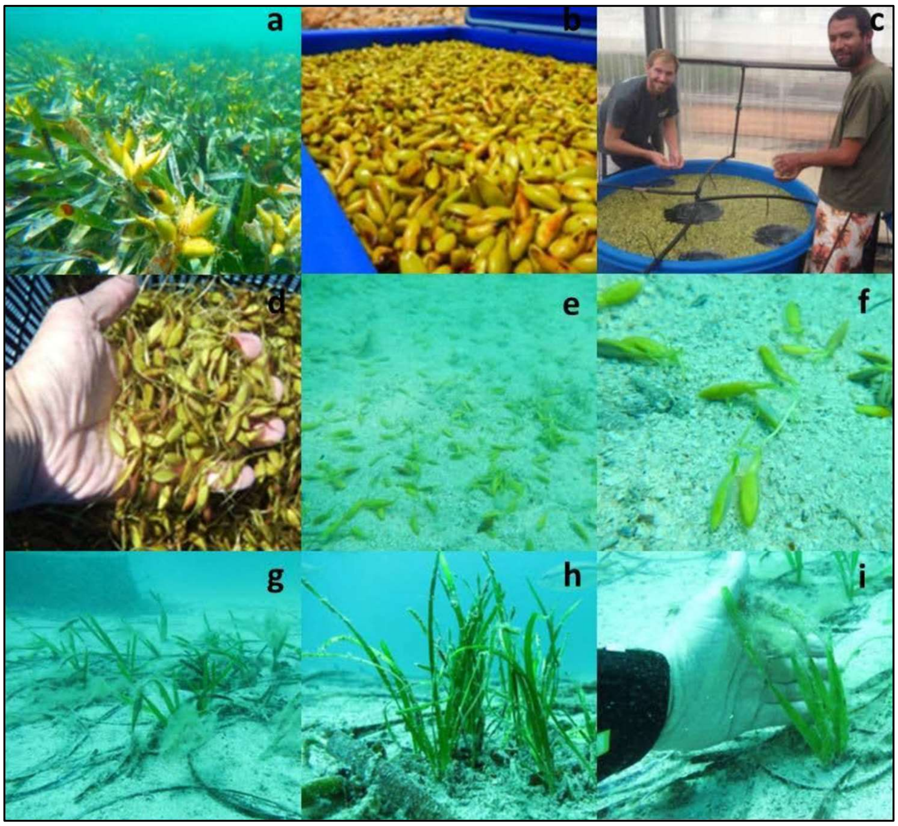

Figure A4: (a) Mature *Posidonia australis* fruit prior to collection; (b) fruit in 100 L cooler for transport back to lab; (c) processing fruit after collection; (d) after processing, seeds are clean and ready for delivery to field sites; (e) seeds scattered on surface of sediment (200 seeds m^{-2}); (f) close up of seeds settled on the sea floor; (g) 1 year old established seedlings; (h) seedlings established in high density; (i) two year old seedling with multiple shoots. (Photo credits: John Statton)

Many species of seagrass produce an abundance of seed (100's-10 000's m^{-2}) that offer a significant source of planting units, which like seed collection in terrestrial environments and unlike clonal material, can be obtained without direct negative impact on the donor vegetation. The overall objective of this case study was to develop a large-scale collection, processing and remote seafloor delivery process for the restoration of *Posidonia australis*, a seagrass species with non-dormant, directly developing seeds.

To address this objective, the following more specific aims for this species were pursued by developing technologies to (1) collect fruit at maturity from source meadows using purpose built nets, (2) process collected fruit to obtain pure seeds in temperature controlled holding tanks by agitation via aeration to obtain large quantities of seed material that settle on the bottom of the holding tank, and (3) trial approaches to effectively and efficiently deliver seeds to the restoration site, which included; a) diver assisted, precision seeding by scattering seeds close to the sea-floor, and (b) remote, broadcast seeding from a boat. One of the major benefits of using the broadcast seeding method, as opposed to transplanting sprigs and shoots, is that seeds are negatively buoyant and naturally fall to the seafloor. Hence, there is no requirement for expensive and labour-intensive diving operations, especially when considering deeper sites or when there is low water visibility.

Pilot scale trials have shown good success. *Posidonia australis* was seeded at densities of 200 seeds m^{-2} into three 25 m^2 replicate plots at four locations in Cockburn Sound. Seedling establishment success varied from 1% (2 seedlings m^{-2}) to 10% (20 seedlings m^{-2}) after 2 years. At 18 months, seedlings have begun to produce new shoots and by 24 months, established seedlings had 3-5 shoots and had begun horizontal expansion over the sea-floor. The initial success of this approach is now being scaled up in an innovative community-based approach by enlisting the help and involvement of local recreational fishermen in a program known as 'Seeds for Snapper'. In this program, 40-50 local recreational fishers have volunteered to release one million seagrass seeds (collected and provided by scientists) back into the sea in a massive effort to restore the lost seagrass meadows of Cockburn Sound. This will increase the scale of seeding and ability to restore locations that are difficult to access (deep, turbid, turbulent, or diver-restricted locations), and identify and overcome critical environmental factors limiting seedling establishment. Preliminary assessments show that establishment success is around 14 - 38 seedlings m^{-2}.

References:

https://ozfish.org.au/seeds-for-snapper/

Statton, J. L.R. Montoya, R.J. Orth, K.W. Dixon and G.A. Kendrick, 2017. Identifying critical recruitment bottlenecks limiting seedling establishment in a degraded seagrass ecosystem. Scientific Reports, 2017; 7 (1) DOI: 10.1038/s41598-017-13833-y.

Case study 4: Seagrass Restoration at Port Manatee, Florida (USA)

Restricting boating access from certain areas (damaged by propeller scarring) in Tampa Bay, Forida through regulatory measures and installation of demarcation buoys (prohibiting all entry, transit, anchoring or drifting within the restricted areas) resulted in significant (4.5 ha) and successful seagrass recovery (through 'passive' restoration) at relatively low costs (US$ 300,000/= for buoys and three years of enforcement patrols & maintenance), which by far exceeded the disappointing results (very low or no survival) of a simultaneous (~US$5 million) mechanical seagrass relocation approach using a 'giga-unit sod' transplanting machine that salvaged and relocated ~11,000 large sods from a port expansion zone into a nearby ~4 ha relocation site. Whilst capable in relocating viable plant material along with suitable sediments, the condition of the donor material and the poor suitability of the receiving habitat (marginal) contributed to the overall poor success of the mechanical approach. This case demonstrates that – where feasible – reversal of seagrass degradation by addressing the root cause in order to facilitate natural recovery can be one of the most cost-effective approach for large scale seagrass restoration.

Figure A4. Seagrass salvage and restoration work at Tampa Bay (Florida): Top: 'Giga-unit sod' transplanting machine. Bottom (left): intertidal area from where 1x1 m seagrass sods have been removed with the 'giga-sod' machine (see frame for reference of scale). Bottom (right): demarcation buoys used to prohibit all entry, transit, anchoring or drifting within restricted areas to allow seagrass to recover from boating damage. (Photo credits: Paul Erftemeijer)

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Case study 5: Translocation of a *Ruppia tuberosa* seed bank in the Coorong

The ecological health of the Coorong, a coastal lagoon system in South Australia, was devastated by a long-term drought from 2006 to 2010 and upstream over-abstraction of water from the Murray River. Decreased water levels and extreme salinities resulted in a rapid decline of *Ruppia tuberosa*. Despite recent improvements in environmental conditions in the Coorong, *R. tuberosa* populations in the main lagoons of the Coorong have not naturally returned on a large scale, due to a severely exhausted seed bank. Lake Cantara, a small nearby saline lake within the Coorong National Park, has an established and healthy population of *R. tuberosa* that largely survived the drought and acted as the donor site for this seed bank translocation project. *R. tuberosa* seeds are about 1mm in size, black and tear-dropped shaped, and can be found in high densities in the top layer of the lake bed sediments. Seeds were collected in late summer and early autumn, when Lake Cantara was dry. A small excavator was used to scrape off the top 15mm of sediment, containing the seeds. Track mats were used to reduce the impact of the excavator. The seed was collected in strips, with even-width gaps to promote faster recovery of the *R. tuberosa* seed bank in Lake Cantara.

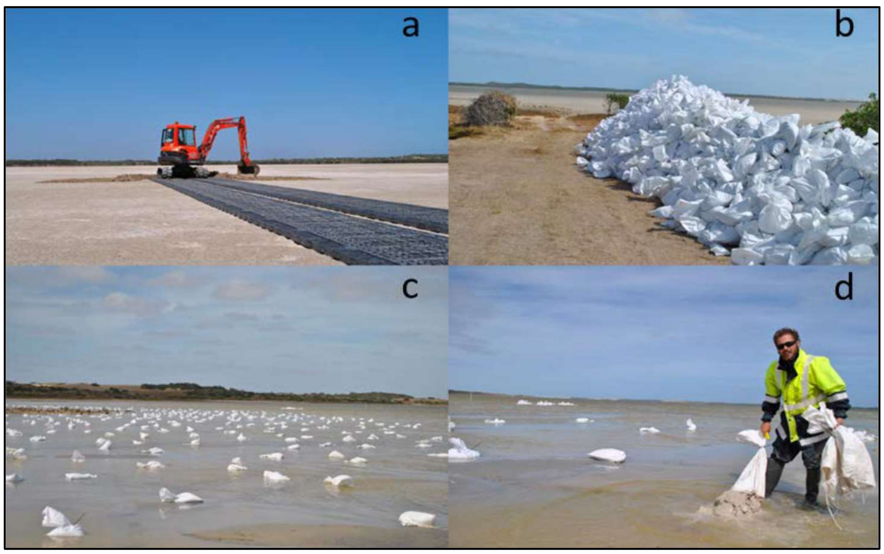


Figure A5. Stages in the *R. tuberosa* translocation action 2014/2015, (a) harvesting seeds in sediments at Lake Cantara, (b) stores of sediments containing seeds, (c), placement of stored sediments and (d), spreading actions. (Photo credits: KorJent van Dijk and Michelle Waycott)

The sediment was transported in bags to translocation sites in the Coorong. 'Planting' was carried out during exposure of the mudflats along the Coorong South Lagoon when water levels were low. Planting sites were chosen based on water level predictions, as *R. tuberosa* in the Coorong is known to grow best at water depths between 30cm and 100cm. Planting involved lightly agitating the mudflat surface, scattering the seed sediment, and then pressing it into the soil. Deeper sections of mudflats had shallow water cover even at planting time, so the seed sediment was scattered directly into the water and local wave action kept it in place. A total of 280 tonnes (14,080 bags) and 450 tonnes (30,100 bags) of sediment were translocated in 2013 and 2014 respectively. An estimated area of ~20 ha and ~41 ha were restored during the two years. The restoration efforts were successful in that *R. tuberosa* did recolonise the areas transplanted. While the restoration helped recovery in the South lagoon, water levels have not been high enough to complete the reproductive cycle at revegetated sites. Densities of seeds and turions (wintering buds that remain dormant at the lake bottom) remained low compared to historical values.

Reference: Collier, C., K.K. van Dijk, P.L.A. Erftemeijer, N. Foster, M. Hipsey, E. O'Loughlin, K. Ticli and M. Waycott, 2017. Optimising Coorong *Ruppia* habitat. Strategies to improve habitat conditions for *Ruppia tuberosa* in the Coorong (South Australia) based on literature review, manipulative experiments and predictive modelling. CLLMM Management Action 15, Technical Report, University of Adelaide, Adelaide SA, 163 pp.

Case study 6: Relocation of large sods of intertidal *Zostera noltii* seagrass using a modified backhoe

Seagrass relocation at the Eastern Scheldt, The Netherlands, involved the use of a modified excavator driven onto the intertidal mudflats along the dikes that 'scraped off' large sods (~2 m^2) of dwarf eelgrass (*Zostera noltii*) with soft (muddy) sediment (top-layer) that were stored, transported and re-instated in comparable habitats further away. The seagrass vegetation along the dikes was salvaged to make way for major dike renovations along a particularly vulnerable stretch of coast, in coping with sea level rise. The harvested sods of seagrass were relocated to eight recipient sites located further away from the dikes. In total, 2600 m^2 of seagrass sods were mechanically transplanted to six intertidal flats over the course of five years (2007-12).

Figure A6. Photographic impression of the sod relocation method at the intertidal sites in the Eastern Scheldt, showing the modified backhoe scraping technique and transplant relocation. (Photo Credits: Wim Giesen)

This project had some promising results, achieving mixed successes with the relocation, depending on location, with an overall survival of 43% of the sod transplants after 5 years, at an overall total cost (incl. monitoring) of about 770 Euro per m^2 (~US$8.6M per hectare). At four of the six intertidal flats, transplants showed low survival and gradually decreased in size over time. The lack of success at those sites may partly be attributed to site conditions at the receiving habitat, notably local desiccation patterns, but may partly be unpredictable due to natural variability, as the researchers showed. The other two sites showed extensive seagrass colonization around the sod transplant areas (in some years), which are still surviving and healthy up to the present day.

Reference:

Suykerbuyk, W. et al. (2016). Unpredictability in seagrass restoration: analysing the role of positive feedback and environmental stress on *Zostera noltii* transplants. Journal of Applied Ecology 53: 774–784.

Case study 7: Seagrass *Zostera capensis* restoration experiment using a 'plug' method on tidal flats in Maputo Bay (Mozambique)

The aim of this seagrass restoration study was to assess effects of sediment digging for clam collection on *Zostera capensis* recovery and compare survival of experimentally transplanted seagrass plugs using PVC tubes to restore disturbed areas. The study was conducted on tidal flats in Maputo Bay, Mozambique. Seagrass community structure, shoot density, fauna abundance, epiphytes and grain size was investigated at t=0 (before digging) and at 14, 45, 75 and 175 days after digging. The effectiveness of replanting *Zostera capensis* was tested by means of the plug method using PVC tubes with two different diameters (7.5 cm and 4.5 cm). A total of 160 plugs were transplanted in eight plots (80 plugs with the 4.5 cm tube and 80 plugs with the 7.5 cm tube), and monitored for survival, shoot density and epiphyte abundance.

Figure A7. Photographic impression of the ongoing seagrass restoration project at Maputo Bay (Mozambique) using cores of seagrass for the transplantation of *Zostera capensis* on intertidal flats affected by clam digging. (Photo credits: Salomao Bandeira)

Seagrass at donor sites recovered rapidly (% cover restored within ~2 weeks and other ecological attributes in subsequent weeks). After 3 months, survival of planted seagrass differed significantly between the plug method, being high for 7.5cm diameter PVC tubes (60%) and low (<10%) for 4,5cm tubes. While *Zostera capensis* recovered rapidly from the disturbance caused by clam harvesting, this species is impacted by a range of other pressures in Maputo Bay. A wider seagrass restoration plan for Maputo Bay should therefore be developed in participation with local communities. Initial results of the experiment are promising and indicate that the use of PVC corers (7.5cm not 4.5cm) to relocate seagrass plugs may prove to be appropriate for (small-scale) *Zostera capensis* restoration in Maputo Bay.

Reference: Mabuto, M.A. et al. (2018). Response of Seagrass *Zostera capensis* to physical disturbance (clam collection) and evaluation of replanting experiment using plug method. Extended abstract, presented at a regional conference.

Case Study 8: Community-based seagrass restoration trial at Beravy, Tuliara (Madagascar)

This ongoing seagrass restoration trail was initiated in February 2019 by Reef Doctor, an NGO based in Ifaty, south-west Madagascar. It is part of a project by the local community of Beravy in partnership with Vezo Miaro (Young Fishermen Association). Seagrass beds in Beravy have been in decline primarily due to sediment run-off from land, which consequently smothered the seagrasses. The land-to-sea runoff of sediment was caused by deforestation of nearby mangroves and agricultural activities on adjacent land, uses that are also being addressed in the project. The ultimate goal is to restore seagrass areas degraded by sedimentation to contribute to long-term sustainability of coastal ecosystems and support community development in the Bay of Ranobe.

Each month, 1,200 patches of seagrass are transplanted into damaged and degraded areas in the tidal zone of the bay using sods (30 x 30cm) dug out by spade from a healthy nearby seagrass beds of *Cymodocea serrulata*, *Cymodocea rotundata* and *Halodule uninervis*. As of May 31, 2019, seagrasses have been transplanted into two sites with a combined total area of 0.2 ha. The ultimate target is to have transplanted 36,000 patches of seagrass.

Figure A8. Photographic impression of the ongoing seagrass restoration project at Beravy, Tuliara (Madagascar) using spades for the excavation of seagrass sods for transplantation into degraded areas. (Photo credits: Leah Pettitt and Emma Gibbons, Reef Doctor)

Survival of the transplanted seagrass patches is being monitored to assess the success of the methodology. The percentage cover of selected patches are being surveyed every three months, as well as the overall survival rate across all transplants. Initial results are encouraging. Evaluation of these regular monitoring results allows for adaptation of the restoration approach and methodology along the way and for the establishment of an optimal transplantation method.

Reference: Reef Doctor, 2019. Seagrass transplanting in Beravy to create healthy ecosystems in Ranobe, in order to support local fisheries. Initial Report, May 2019, 11 pp.

Case Study 9: Community-based seagrass bed restoration at Wasini Island, Kenya

A number of preliminary seagrass restoration studies and small-scale pilots were initiated along the Kenyan coast beginning in 2007. The experimental trials of seagrass restoration were conducted following incidences of seagrass decline due to excessive sea urchin herbivory at Diani. This first seagrass transplantation trial off Diani Beach was conducted using the sod method and the climax species *Thalassodendron ciliatum* and *Thalassia hemprichii*. Although this trail did not bear strong results it provided insights into restoration processes and yielded good indicators for follow-up and lessons learnt on site selection and optimization of transplantation techniques.

Further experimental work in a research project using artificial seagrass mimics provided insight in the process of (meio-) faunal colonisation, sediment trapping and establishment of pioneer seagrass seedlings within the restoration plots.

Figure A9. Photographic impression of the ongoing community-based seagrass restoration project at Wasini Island, involving the planting of seagrass seedlings and the use of hessian bags for anchorage and sediment stabilisation (right), after advance consultation and planning by the local community (left). (Photo credits: Jacqueline Uku, Lilian Daudi and Charles Muthama, KMFRI)

In April 2015, a promising community-based seagrass restoration project was started at Wasini Island to restore degraded seagrass areas. A major component of this project focused on training of local community members in seagrass restoration. The training included an overview of importance of coastal ecosystems to ocean health and local community livelihoods, the reasons for seagrass restoration, procedures for restoration and practical training in restoration techniques.

The project successfully trained 30 local community members and implemented mapping of healthy and degraded seagrass areas at Wasini Island. Approximately 2.3 ha of seagrass habitat was restored using *Thalassia hemprichii* shoots and seedlings collected from a nearby donor site. Seedlings were planted using hessian bags for anchoring and to stabilize the sediments at the site. The long-term growth, performance and survival of the restored seagrass areas is being monitored by the communities. The encouraging initial results of this trial and its methodology will be used for the planning of further participatory seagrass restoration activities along the Kenyan Coast.

References:

Mutisia, L.N.D. (2009). Restoration of Kenyan seagrass beds: a functional study of the associated fauna and flora. MSc Thesis, Free University of Brussels, 94 pp.

Uku, J.N. et al. (2017). Seagrass bed restoration in Wasini Island, Kenya. Unpublished report for the Kenya Coastal Development Project (KCDP). Kenya Marine and Fisheries Research Institute, 5 pp.

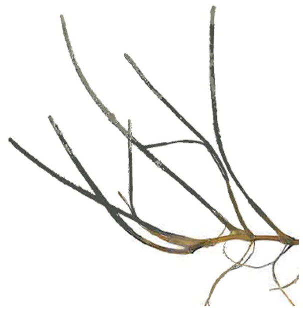
Seagrasses of the Western Indian Ocean region

Halophila ovalis

Halophila minor

Halophila stipulacea

Enhalus acoroides



Zostera capensis

Thalassodendron ciliatum

Ruppia maritima

Syringodium isoetifolium

Cymodocea rotundata

Halodu|le uninervis

Thalassia hemprichii

Cymodocea serrulata