Ten golden rules for restoration to secure resilient and just seagrass social-ecological systems

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ABSTRACT

It is unequivocal that the world has lost a significant proportion of its seagrass, and although glimmers of hope exist, losses continue with many ongoing negative trajectories. First and foremost, we need to put the world on a global pathway to seagrass net gain. Conservation of what remains must be a priority, but we need to increase coverage at rates unlikely to be achieved naturally; large-scale active restoration is required to fill this gap. Novel finance mechanisms aligned to the climate emergency and biodiversity crises are increasingly leading to larger-scale restoration projects. However, no clear framework exists for developing or prioritising approaches. With seagrass restoration expensive and unreliable, rigorous guidance is required to improve effectiveness and ensure it is cost-effective, so that projects can begin to transform whole coastlines. Building on current evidence from both terrestrial and marine sources, here we apply the '10 golden rules' concept, first outlined for reforestation and later applied to coral reefs, to seagrass restoration. In doing so, we follow the International Principles and Standards for the Practice of Ecological Restoration and view seagrass restoration in a broad context, whereby regeneration can be achieved by either planting or by enhancing and facilitating natural recovery. These rules somewhat differ from those on reforestation and coral reef restoration, principally due to the relative immaturity of seagrass restoration science compared to these comprehensively researched ecosystems. These 10 golden rules for seagrass restoration are placed within a coupled social-ecological systems (SES)

context and we present a framework for conservation more broadly, to achieve multiple goals pertaining to people, biodiversity and the planet.

INTRODUCTION

Seagrass meadows are social-ecological systems (SES) where human well-being is intricately intertwined with the resilience of a habitat-forming marine angiosperm. Humans are drivers of change, capable of both damaging and restorative actions. For seagrass, the balance has tipped to extensive damage, resulting in widespread net losses (Dunic et al., 2021). Now, growing interest in the value of seagrass for people, biodiversity and the planet (Unsworth et al., 2022) and the UN Decade of Ecosystem Restoration have galvanised enthusiasm for enhanced and extended restorative actions. Despite a relatively long history (earliest available data from 1935), examples of successful large-scale seagrass restoration are few (e.g., Orth et al., 2020;Hori and Sato, 2021), and there have been limited attempts to frame restoration in the context of coupled SES, which would leverage benefits of community-supported action (e.g., Levin et al., 2015;Hori and Sato, 2021).

The Society for Ecological Restoration (SER) defines ecological restoration as "*the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed*". Other definitions highlight the role of restoration in recovering biodiversity and improving human well-being (Gann et al., 2019). By definition, ecological restoration is not restricted to planting seeds or transplanting flora and fauna, but instead incorporates a broad range of actions to maximise ecosystem recovery (Gann et al., 2019). This contrasts with how seagrass restoration is commonly viewed as an applied physical process (e.g. planting seeds or transplanting plants). For example, a global synthesis of seagrass restoration focused solely on the ecological success of different planting methods (van Katwijk et al., 2016) without considering other restorative actions. Broader approaches to seagrass restoration, recognising and enhancing its positive social and ecological impacts, are needed to place seagrass on a trajectory of global net gain (Unsworth et al., 2022), rather than net decline (Dunic et al., 2021). Required is that we move beyond a singularised view of successful restoration, meaning new meadows are planted, to a combined view where damaged and fragmented meadows are rejuvenated, threatened and diminishing meadows are protected, and more meadows become resilient. Restoration toolboxes should include actions such as replacing swinging chain moorings with environmentally-sensitive Advanced Mooring Systems (AMS) (Luff et al., 2019), using sediment tubes to restore propellor scars (Furman et al., 2019;Price et al., 2023) or using bird perches to facilitate dispersal and recovery in nutrient-limited environments (Kenworthy et al., 2018). These approaches and others should go alongside re-planting meadows that have degraded or disappeared. We also need to consider and value community engagement and community-led approaches for restoration longevity and enhanced socio-economic benefits, with buy-in from local stakeholders monitoring and reinforcing existing and newly replanted areas (Elias et al., 2022).

Building on current evidence from both terrestrial and marine sources, here we apply the ‘10 golden rules’ concept first outlined for reforestation (Di Sacco et al., 2021), and later applied to coral reef restoration (Quigley et al., 2022), to seagrass restoration. In doing so, we follow the International Principles and Standards for the Practice of Ecological Restoration (Gann et al., 2019) and view seagrass restoration in a broad context, whereby seagrass regeneration can be achieved by either planting or by enhancing and facilitating natural recovery. While we have attempted to map our rules to those proposed for reforestation and coral reef restoration, they differ somewhat, largely due to the relative immaturity of seagrass restoration science. These 10 golden rules for seagrass restoration (see Figure 1) are placed within a coupled SES context and we present a framework for conservation more broadly, to achieve multiple goals pertaining to people, biodiversity and the planet.

1. PROTECT EXISTING SEAGRASS FIRST

Seagrass degradation and loss are issues of grave concern globally (Dunic et al., 2021). Since 1880, 19.1% of surveyed meadow area has been lost, and in some countries this may be as high as 92% (Green et al., 2021). Poor water quality and coastal development are the biggest drivers of losses (Unsworth et al., 2019;Turschwell et al., 2021). While significant progress has been made in some countries due to national or regional legislation/programmes (UNEP, 2020a), international action to halt decline has been minimal. In many countries, seagrass remains largely legally unprotected. As in other systems, planting *new* seagrass is not a simple solution to conservation concerns. It is slower, more difficult, and more expensive to re-plant meadows than it is to protect those that already exist. We, therefore, echo Quigley et al. (2022) in their first golden rule for coral reef restoration: “*No matter how compelling the evidence for the potential positive impact of restoration initiatives, there is no substitute for the protection of natural ecosystems*”.

While protection is complex, protection from some localised stressors can be achieved by implementing Marine Protected Areas (MPAs) or voluntary codes of conduct, and encouraging alternative low-impact livelihoods, tourism, and fishing practices (Cullen-Unsworth and Unsworth, 2016). However, given that large-scale stressors critical to achieving seagrass resilience originate from land (e.g. poor water quality), catchment-wide interventions are needed. Localised management is unlikely to be effective if stressors persist unmanaged, as examples from Kenya (Eklöf et al., 2009) and the Philippines (Quiros et al., 2017) demonstrate, where nutrient inputs from land remained unchanged following marine protection. In contrast, watershed restoration and management have led to indirect protection and recovery of submersed aquatic vegetation in Chesapeake Bay (Lefcheck et al., 2018) and Mumford Cove (Vaudrey et al., 2010) in the US, in Western Port, Australia (Dalby et al., 2023), and in Denmark (Riemann et al., 2016), Spain (Roca et al., 2015), and Portugal (Cardoso et al., 2010) amongst other places in Europe (de los Santos et al., 2019).

Where blanket protection measures are not possible, it may be necessary to prioritise *which* seagrass meadows to protect, in collaboration with stakeholders (rule #2). Decisions must consider predicted future climatic conditions, such as changing temperatures, sea level rise, land-use change and the gradual tropicalization of temperate systems (Hyndes et al., 2016), which may render a site unfavourable in the long term (rule #6). It is also worth considering that once degradation has reached a certain point, full ecosystem recovery may not be possible. It may be appropriate to adopt the framework of three management strategies (protect, restore, or transform) proposed by Darling et al. (2019), guided by social–environmental drivers. Seagrass meadows at low risk should be protected (protect). Where meadows are at intermediate risk, local stressors should be mitigated alongside targeted restoration to accelerate natural recovery (restore). And for meadows at highest risk, where investments needed are too high or unfeasible, it may be appropriate for meadows to be left to transition (transform). Vulnerability analysis (Grech et al., 2012) provides a means to collect and quantitatively synthesize opinion on the ecological effects of anthropogenic threats to seagrasses. The method uses a systematic standardized protocol (Halpern et al., 2007) allowing relevant actions to protect seagrass at local and regional scales.

Beyond the loss of habitat and associated Ecosystem Services (ES) (Unsworth et al., 2022), degradation of seagrass meadows can also be a direct cause of Greenhouse Gas (GHG) emissions (Salinas et al., 2020). When seagrass is lost, knowledge as to the fate of carbon they store is poor, but evidence indicates that carbon is remobilised from sediments and re-emitted into the atmosphere (Arias-Ortiz et al., 2018;Moksnes et al., 2021a). Likewise, eutrophication in seagrass systems likely leads to increased emissions of Nitrous Oxide (NOx) (Roughan et al., 2018), whilst disturbance may influence CH_4 emissions (Al-Haj and Fulweiler, 2020). Planting new seagrass is unlikely to stop, or even compensate for these emissions. Planting seagrass is not dissimilar to reforestation; the principle is not to plant an ecosystem, but individual plants that grow into a functional ecosystem over a long period of time. Some plants fail, and sometimes they collectively fail, even with the best supporting science (Hackney, 2000). Seagrass planting is expensive, with the average cost estimated at US$399,532 per hectare (Elisa et al., 2016), coupled with high chance of failure (68%) (van Katwijk et al., 2016) – both due to the relative scientific immaturity of the discipline with many knowledge gaps needing filling to bring down cost and improve reliability. Biological causes of failures are often ecological feedback systems preventing simple linear recovery and necessitating intensive and costly actions to overcome (Maxwell et al., 2017) (rule #5).

2. WORK TOGETHER

The recent Call To Action from the SER (Walder and Patel, 2023) to "*Inspire all of society to embrace ecological restoration*" recognises that restoration is collaborative and requires the involvement of multiple and diverse stakeholders, expertise and experience, echoing Sustainable Development Goal 17: Partnerships for the goals. Given that seagrass ecosystems are well-defined SES (Cullen-Unsworth et al., 2014), working together collaboratively and inclusively is key to success (Bennett, 2022).

Seagrass SES support diverse uses and livelihoods, from fishing and recreation to harvesting of raw plant material. Rights and equality are central, and stakeholders should be encouraged to continue activities, not just undisturbed, but enhanced by increased seagrass resilience. Finding ways to bring people together to co-design restoration projects (Gornish et al., 2021) will enhance the social capital of resulting habitats (Pretty and Smith, 2004), improve equality and is a positive process. Regulators and government agencies play important roles; in many cases, they have statutory responsibilities for granting legal permissions. Even when this is not the case, although their presence may complicate the involvement of some other stakeholders, their early involvement in projects can help reach wider networks and guide them towards greater long-term success. Projects create opportunities for communities to unite to participate in improving their local environment for wellbeing. This also provides opportunities to improve restoration through harnessing the correct skills and knowledge, as well as local experience and understanding. To ensure high-quality, effective restoration, we need to interweave expertise from multiple disciplines, from social to physical sciences: physical modelers to determine the most suitable restoration sites (and actions); biologists to conduct and ecologically monitor restoration efforts; local stakeholders for key site-level information and support; and social scientists to ensure delivery of the right socio-cultural benefits. A key challenge when engaging is to ensure all community voices are heard so that a more accurate picture of local knowledge can be understood. Traditional owners, indigenous communities, marginalised communities, and local resource users often hold knowledge of site ecology or environmental conditions that can only be gained from repeated observation and engagement over time (Aswani et al., 2018). Inclusion of such groups and their diverse perspectives and knowledge not only facilitates equity but provides intelligence that cannot be accessed through conventional scientific methods.

If restoration projects fail to integrate stakeholders effectively, there is a real risk of failure – either at the outset in terms of securing permissions, or subsequently if unaddressed conflicts or opposition lead to lack of recognition, support or potentially sabotage. Furthermore, there remain few examples whereby habitat restoration is a totally mechanized process. Protection and restoration usually require significant human capital input, even in the largest applied restoration project (Marion and Orth, 2010). Volunteers have become invaluable attributes to achieving the required human capital – collecting seeds or transplants, installing mooring systems, processing materials, and monitoring outcomes. And for now, beyond the timeframes of specific grants or funded projects, we need commitment from local stakeholders to ensure longevity. Without working together, long-term seagrass restoration at scale is simply not possible.

3. CREATE A BIODIVERSE ECOSYSTEM WITH MULTIPLE FUNCTIONS FOR PEOPLE AND PLANET

The overarching aim of seagrass restoration – as in other ecosystems – should be to maximise the biomass and biodiversity of meadows such that they support diverse and resilient ecosystem functioning and services for people and planet (Perring et al., 2015;Higgs et al., 2018a;Aronson et al., 2020). Nature-based Solutions (NbS) policies are increasingly driving seagrass restoration for delivery of specific ES, e.g. trapping carbon dioxide and reducing GHG emissions, supporting specific (e.g. charismatic) species, nutrient cycling and/or wave attenuation. Unless care is taken, this approach can overlook the fact that natural systems simultaneously produce multiple ES that interrelate in complex and dynamic ways (Bennett et al., 2009) creating mechanisms for unintended consequences. An overly narrow focus on a limited set of ES can lead to regime shifts with unfavourable and unexpected sudden loss of other services (Gordon et al., 2008). Furthermore, it can lead to stakeholder conflicts surrounding the perceived benefits and disbenefits of restoration. The danger of focusing on a single ES creates a greater risk of project failure. Increasingly we see deep uncertainty in the carbon store and sequestration role of forest ecosystems (Wells et al., 2023), and with it a greater appreciation for the weakness in the value of associated financial credits. We should learn lessons here and not make the same mistakes made in forests within the rapidly expanding field of seagrass restoration (rule #10).

The suite of ES benefits from biodiverse seagrass meadows is irrefutable but our understanding of their inter-relationships remains limited. They may have no relationship, they may have synergies, or their delivery may have trade-offs (Bennett et al., 2009). Services rarely correlate, and one can rarely be considered a surrogate for another (Bennett et al., 2009). They also rarely share the same drivers and when they do these may act in different directions (e.g. elevated nitrogen could increase system productivity and biodiversity but could also lead to increased nitrous oxide emissions). There are currently no examples where creating seagrass meadows high in stored carbon have led to unintended consequences for other ES, but it is inherently possible (Jones et al., 2022). The high fisheries value of seagrass at subsistence to commercial scales (Unsworth et al., 2018) creates a particular potential for conflict as proponents of restoration for biodiversity or carbon capture/storage may have reservations about aims to deliver fisheries provisioning due to issues around disturbance. The complex nature of seagrass SES means that any one of a range of human activities (Cullen-Unsworth et al., 2014) could be perceived as a threat to restoration focused on only one or two ES in isolation. We need more holistic thinking around the wider ecosystem and the impact of actions to manage other factors. For example, there is increasing evidence that unregulated conservation of seagrass-associated green turtles may negatively affect seagrass itself, with unintended consequences for fisheries and other ES delivery (Jones et al., 2022).

Given the dearth of understanding of seagrass ES inter-relationships, it is unlikely that detailed knowledge of such is integrated into restoration projects. Interactions, however, should be considered at least based on the best available information so that potential unintended consequences can be considered. Monitoring programmes should then aim to understand the flow of ES from restored habitats to fill knowledge gaps. This is especially important given increasing interest in packaging seagrass ES (either by stacking or bundling) to improve the flow of funds into their conservation and restoration (rule #10). Having said that, biodiversity enhancement across its full definition provides the most robust motive for enhancing our natural world, and a more effective way of creating genuine environmental improvement. Biodiversity is not entirely about species diversity, but also about genetic, ecosystem- and landscape- (or seascape-) scale diversity – all factors intrinsic to realising diverse ES for people and planet (rule #7).

4. SELECT APPROPRIATE SITES FOR RESTORATION

There are no international organisations planning global- (or even regional-) scale seagrass restoration initiatives, such as there are for reforestation (Di Sacco et al., 2021). Most restoration site selection occurs at the local scale, while multi-scale planning would be more effective for considering the myriad environmental and socio-economic factors that should contribute to decision-making. Regional governments should consider collective approaches that link to marine spatial units, such as the Large Marine Ecosystem framework (Fanning et al., 2007), whereby creating targeted large-scale restoration projects may have a greater impact on an area than the sum of many small-scale projects (Walker et al., 2014).

Not all seagrass meadows can or should be restored (see rule #1); just because an area historically contained extensive and productive seagrass, does not mean that it can or should again. Physical, environmental and/or social changes can shift the social-ecological equilibrium of the system such that it becomes locked in an alternative stable state (Unsworth et al., 2015), often due to ecological feedbacks preventing a return to a seagrass-dominated system (Maxwell et al., 2017). A rigorous process of seagrass restoration site selection is required to maximise chances of success. This needs to commence with clear objectives (e.g. restoration needs, area of habitat restoration, intended benefits and beneficiaries) and plans that are flexible and open to the broad principles of ecological restoration (Higgs et al., 2018b).

When re-planting is the goal, Habitat Suitability Modelling (HSM) is one tool for initiating the process to direct efforts to where consideration and detailed survey work should be targeted. Currently, HSM is unable to inform detailed site-level choices due to limited availability of high-resolution environmental data in many parts of the world, and the challenges associated with modelling the wave climate (and other variables) in shallow waters (Bertelli et al., 2023). Nevertheless, HSM can identify potential suitable areas according to the data currently available. Detailed ground-truthing is then required to calibrate and fill data gaps and provide local-scale resolution. Environmental factors such as sediment movement, hydrodynamics, light availability and nutrients should be considered for site suitability, alongside biological parameters such as the density of bioturbators, algae and grazers (Suykerbuyk et al., 2016), all of which may interfere with restoration, but may sometimes have positive effects (Pereda-Briones et al., 2018). These parameters can also vary in order of their importance, depending on other factors. For example, water movement in the form of tidal currents may have more effect on seagrass within an archipelago where meadows are sheltered from prevailing wave action, while wave height may be more important on open coasts.

Presence of existing seagrass would have a significant impact on model outputs, indicating that a site is suitable for it to grow; confirmation of seagrass extent can validate and improve existing HSMs. However, care should be taken to assess the condition of existing seagrass, along with any evidence of chronic or acute stressors acting at sites. If threats are not addressed, restorative actions may fail. Whilst a meadow develops over an extended period, there are many external threats that cannot be managed at a local scale, such as climate change, that bring additional risks to a project. Extreme weather events and marine heatwaves have the potential to decimate the most resilient meadows. The only way to avert these longer-term risks is to incorporate predictions for long-term resilience in site selection. Better ecological modelling is required to understand how and where to restore seagrass with ecological, biophysical and seascape features that confer resilience (Unsworth et al., 2015).

Not all the required information for rigorous site selection will be readily available; difficult decisions with limited information may necessitate different forms of inquiry. Local knowledge may also be helpful (rule #2) for understanding factors such as local hydrology, habitat preferences of fish, and the impact of prior human interventions (Mamun, 2010). In addition, the information of expert witnesses who have worked in these systems for many years may become helpful guidance and may either outperform or complement models (Sánchez-Carnero et al., 2016).

Finally, seagrass restoration site selection is not just a biological process. Decision-making clearly needs to be additionally based on social attitudes, opportunities and costs so that projects can be of benefit to all, primarily local communities and stakeholders, who will often need to become the long-term custodians of the site (rule #2).

5. DETERMINE APPROPRIATE RESTORATION METHODS

A common set of guidelines setting out the parameters for seagrass restoration success is not yet possible, although guidance exists on certain tried-and-tested planting techniques (van Katwijk et al., 2009;van Katwijk et al., 2016;Moksnes et al., 2021b). As stressed above, seagrass restoration does not only refer to planting seeds or transplants but includes a range of measures fostering seagrass recovery. Without clear guidelines, restoration projects often necessitate unguided decisions about methods. Given the current high cost and uncertainty of planting approaches, indirect methods to remove pressures and promote natural recovery of degraded meadows may often be more suitable and successful. For example, evidence from the UK suggests that replacing traditional swinging boat moorings with AMS reduces seabed scour and could lead to recovery of at least 6 ha of seagrass nationwide (Unsworth et al., 2017). Data from the US reveals that as few as 60 moorings need to be replaced to restore 1 ha of seagrass (Seto et al., 2024). In Australia, Saunders et al. (2017) used a dynamic land- and sea-scape model to develop simple rules that govern which of four alternative conservation actions seagrass funds should be directed to: protection on land, protection in the ocean, restoration on land, or restoration in the ocean. Whilst highlighting the importance of restoration in the ocean, the authors recommended a combination – both on land and in the sea.

Where planting seagrass becomes the most appropriate and cost-effective method, difficult decisions may be necessary regarding how to plant most effectively (see Appendix 1). Literature explains numerous methods that have examples of both positive and negative outcomes. Method selection based on local convention may not always be appropriate, even if stipulated by local guidance. While regulators have a propensity to want a 'recipe book' of defined methods that should be used in a particular area, we stress the need to ensure a particular method is appropriate for the local environment; often this requires experimental testing and monitoring to de-risk major investment. We still have limited knowledge about why particular methods are more likely to succeed in some localities than others; our understanding largely points to environmental drivers (e.g. hydrodynamics), modulated through biological feedback processes. Since environmental variables can change over small spatial scales, the appropriateness of each method to control feedback might similarly be modified. A recent review of the bottlenecks to successful seed-based restoration (Unsworth et al., 2023) highlights many knowledge gaps that require filling to improve success.

In the 'perfect' environment – i.e. one in which there are no negative feedbacks driving failure, but positive feedbacks driving success – we hypothesise that seagrass restoration will be successful despite the method chosen, with propagule supply the only limiting factor. In a stable, high-light environment of perfect biogeochemical balance and suitable nutrient availability, seed germination will be high, seedling development rapid and survival prevalent. As hydrodynamic pressure and instability grows, the need for interventions to secure seedlings, prevent seed loss and ensure plant survival increases. This scenario extends to other biophysical feedbacks such as sulphide build-up, bioturbation, predation/herbivory, and sediment re-suspension (Maxwell et al., 2017). When methods prove unsuitable in a given location, practitioners should examine the drivers at play and the biological traits within a system that may expand with scale to overcome feedbacks (Temmink et al., 2020). There is a propensity for practitioners to focus on the inadequacy of a method rather than to try and understand the factors leading to its failure. There is increased interest in using seagrass-associated animals to improve the likelihood of planting success. Such multi-trophic restoration (i.e. not only focusing on seagrass) may enable recovery of other trophic levels to build resilience in meadows, e.g. mesograzers (Cronau et al., 2023) or to reduce feedbacks (Donaher et al., 2021). However, such methods should proceed with caution due to relatively limited data.

There will always be a trade-off between ease of planting and chances of success. With every additional methodological intervention, logistical complications increase, as do the resources required. We stress the need for practitioners to be flexible to maximise success. Methods may have to vary spatially or temporally to first establish populations before facilitating restoration at scale. Restoration plans also need to incorporate risk management with respect to the spread of non-native species, particularly given the methods-based risks associated with the movement of whole plants and sediments. Finally, the dominance of evidence relating to *Zostera marina* in the seagrass restoration literature means that many globally accepted norms for restoration are highly biased and likely inappropriate for other species. The gaps in our understanding surrounding restoration of different species with different life history traits (Kilminster et al., 2015), particularly those in the tropics, highlights the need to determine locally-effective and species-specific methods prior to investing in large-scale restoration.

6. USE RESILIENT PLANT MATERIAL AND FUTURE PROOF YOUR PROJECT

A rapidly changing climate is increasingly placing new stresses on seagrass and, in-turn, upon restoration projects. This is because the safe operating space for individual species and their capacity to recover and rebuild new resilient populations are already changing (Kendrick et al., 2022). This has major implications for the species and locations chosen (rule #4), methods used (rule #5), and the populations that might be re-introduced through restoration. Climate change is expected to lead to contracting, fragmenting, expanding, and shifting of marine species' ranges, which will lead to the reorganization of assemblages (Tittensor et al., 2019). This will not only lead to large-scale losses and shifts in seagrass, but also in key seagrass-associated species (Hyndes et al., 2016), with potentially functional significance (e.g. presence-absence of grazers). The long-term cost-benefit of planting new habitats for a species likely to disappear in the next decade due to a changing climate may need to be considered. For example, the southern range limit of *Zostera marina* on the US east coast is projected to migrate northwards between 1.41° and 6.48° by 2100, resulting in substantial losses along the eastern coast of the USA (Wilson and Lotze, 2019). For restoration to occur in such areas, an altered strategy might be needed that either includes mixed species (inclusion of more southerly species) or the sort of innovative interventions (e.g. supporting natural adaptation or using gene editing to enhance adaptation) necessary to facilitate future resilience on coral reefs (Anthony et al., 2020). Range shifts for individual seagrass species with respect to sea temperature are likely already widespread (Hensel et al., 2023). There are significant potential policy implications for such range shifts, as new 'non-native' species become recorded in new territories. These species may need to be rapidly integrated into policy for seagrass conservation, so that as native species become less resilient to new local conditions, arriving species can be facilitated to maintain their functional role. It may also be prudent to consider the benefits of early introduction of 'surrogate' species so that ecosystem functioning can be maintained without large-scale habitat loss (Sorte et al., 2010).

Climate stressors may act more aggressively on different life stages (e.g. seedling survival) and at different times of year, influencing when seeds can be collected and their abundance and viability. Sea-level rise will also accelerate over the coming decades, placing new pressure on shallow seabed within the environmental range of seagrass (Saunders et al., 2013), altering the windows of opportunity for meadows to exist, especially as freshwater environments increasingly experience greater saltwater incursions further into estuaries (Grenfell et al., 2016). As some viable restoration habitat areas are lost, there may exist new opportunities to undertake assisted colonisation of polar areas where shallow seabeds are becoming increasingly ice-free (Krause-Jensen et al., 2020). Practitioners need to consider how to integrate future climate projections into projects, by adapting methods based on long-term climate predictions (e.g. expected intensity of an El Nino event) and considering sea-level projections to model the environmental window for where different seagrasses may thrive into the future. Models of where future environments may lie for individual species is unlikely to be available for many locations, and the high level of uncertainty associated with such models (Ramarohetra et al., 2015) means that practitioners will be required to make tough data-limited decisions. Projects in such places will need to actively consider improving the resilience of the ecosystem (Unsworth et al., 2015) and its adaptive capacity (Frietsch et al., 2023) to changing temperatures, storminess, catchment pressures, and water depths, as the only real means of providing improved protection to seagrass.

To provide resilience to restoration sites, ensuring appropriate water quality is imperative, as evidence frequently finds organisms that are less stressed are more able to resist and recover from impact (Hughes et al., 2005;O'Brien et al., 2018). There is also good evidence that seagrass resilience is promoted through recovery of top predators and their influence cascading through the food web (Baden et al., 2010;Hughes et al., 2016). It may also be beneficial to enhance the genetic diversity of populations, as this has been shown in experiments on *Zostera marina* to have a positive impact on resilience to elevated temperature (Ehlers et al., 2008). This ultimately requires moving plants or seeds with different genetic provenances. Mixing provenances of terrestrial plants has long been conducted and is considered conceptually straightforward (Breed et al., 2019), but has rarely been undertaken in marine systems. There is growing interest in translocating corals to build reef resilience and much discussion of the risks and benefits involved. Alongside the legal, biological and ethical challenges, data from meta-analysis of seagrass restoration projects globally indicate that propagules from nearby meadows are more likely to succeed than those from further away (van Katwijk et al., 2016), indicating that such movements may in fact be quite challenging to establish ecologically.

Ensuring the resilience of seagrass restoration projects into the future will also necessitate the SES being resilient and having adaptive capacity, not just the biological community, to ensure that unintended consequences of environmental shocks to local communities do not lead to ecological breakdown of restored seagrass (Frietsch et al., 2023).

7. MAXIMISE THE POTENTAL OPPORTUNITY OF THE RESTORATION

Given the challenges of achieving successful seagrass restoration, resources must be maximised to achieve the greatest potential ecological benefit. Seagrass meadows present in many landscape patterns, from continuous large areas to isolated and fragmented patches. Sometimes, these patterns exist naturally due to physical processes and barriers, with the local environment at its maximum carrying capacity (e.g. propagule supply limiting recolonisation). Sometimes, however, patchiness is human-induced or ecological bottlenecks prevent meadow scaling (e.g. boat anchoring causing fragmentation). There is good evidence that fragmented seagrass meadows are less resilient to environmental change than large continuous meadows (Livernois et al., 2017). Using restoration to reconnect meadow patches, therefore, may contribute to system-wide benefits and resilience of the coastal seascape. Stimulating natural regeneration has proved successful at filling fragmented seagrass meadows damaged by boating activity (Rezek et al., 2019) and deserves consideration where propagules and seeds are not limited. In the Florida Keys, wild bird fertilisation (using bird perching stakes) and sediment modification (e.g. filling areas too deep for seagrass recruitment or scraping down upland/submerged sediments to a depth suitable for recruitment) (Rezek et al., 2019) has led to recovery of fragmented areas, particularly in disturbed and phosphate-limited sediments (Kenworthy et al., 2018).

By thinking of restoration in terms of biodiversity enhancement at a range of scales, we move towards improving the integrity of the whole seascape and progress towards rebuilding life in our oceans (Duarte et al., 2020). Restoring connected seagrass meadows provides corridors for movement of flora and fauna within and between habitats, improving seascape connectivity, productivity, and functionality, and ultimately improving the resilience and ES provision of the system as a whole (Pearson et al., 2021). There is increasing interest in the concept of seascape-scale restoration where the value of connectivity between habitats is appreciated, and increasingly efforts are made to enhance these interconnected relationships. Within a tropical context, the data is unequivocal as to the benefits of doing this from a seagrass, mangrove and coral perspective (Mumby et al., 2004;Dorenbosch et al., 2005;Unsworth et al., 2008), but our understanding is more limited in temperate systems. Targeted research is required to understand how temperate habitat connectivity can enhance the value of marine ecological restoration; this may necessitate catchment-scale thinking, whereby interventions on both land and at sea are needed (rule #4). Biodiversity in a seagrass system is key to its functioning, at the level of microbial root associations, the plant population, epiphytic grazing or predatory top-down control. All interactions ultimately contribute to increasing and improving seagrass meadow resilience (Unsworth et al., 2015). Focusing on biodiversity across its definition will improve many aspects of system resilience and help to overcome feedbacks (Maxwell et al., 2017), facilitating better and more reliable seagrass restoration (rule #3). Gene flow between separate meadows is an important means of ensuring genetic diversity within populations, potentially improving resilience, particularly in the context of a changing climate (Ehlers et al., 2008) (rule #6). It may also be beneficial, therefore, to genetically reconnect populations.

8. PLAN AHEAD FOR INFRASTRUCTURE, CAPACITY AND RESTORATION MATERIAL

Putting plans in place to protect seagrass from ongoing pressures first and foremost must be the start of any restoration project, otherwise successes will be limited. Strategic regional planning is needed to determine the best restoration approaches for local seagrass to ensure funds are invested wisely and necessary infrastructure is developed. With increasing interest in restoration, new government, business, and NGO targets are emerging, leading to new projects commencing, sometimes without the necessary infrastructure, expertise and legislation in place. Addressing these needs takes up a large portion of project windows, leaving reduced opportunity for preliminary experimental work required to de-risk major investment (rule #5), and to evaluate restoration outcomes subsequently. Creating a successful seagrass restoration project is more complex than many organisations and aspiring funders recognise, necessitating varied expertise that is not widespread, plus many specialist research, aquaria and marine equipment and facilities. Rezek et al. (2019) conclude in their review of the relative high success rates of Florida seagrass restoration that *“the institutional knowledge and experience gained by restoration contractors and government* *permitting agencies over decades appear to have fostered restoration effectiveness in Florida and may underlie the high levels of seagrass persistence".*

Before a planting-based restoration project begins it is essential to create a development period, whereby decisions about sites and methods can be made based on good science, local data and knowledge of the literature (Garmendia et al., 2023). Given the complex social-ecological nature of seagrass systems, a very early part of planning must be developing a stakeholder engagement plan and delivering it. Just as it is necessary to pick the right biological conditions for the seagrass, so too is it essential to ensure the right social governance structure for local community buy-in (rule #2). Stakeholder engagement is also necessary at the commercial end where development proposals may come into conflict with restoration activities. Understanding marine spatial plans, infrastructure master plans, major economic development processes and political aspirations can be helpful in planning for the future of your project. These sorts of major planning processes may not always be problematic as they could lead to inspiring stakeholders favouring works to help compliment other proposed actions.

An adequate development phase is also important for building capacity in the restoration team. Plant science and marine ecology are rarely taught together, and with a history of poor funding to seagrass science there are skills gaps in many localities within the employment market to recruit the necessary staff to deliver restoration projects. Targeted postgraduate programmes are required that fill these gaps, alongside vocational training placements. Aside from biological skillsets, a wide range of expertise is required (see rule #2). In particular, there is a strong need for sound understanding of the legislative and policy framework in which restoration sits. Legislation is a key bottleneck for seagrass restoration in some countries if practitioners are not used to managing such activities. Seagrass planting requires disturbing the seabed, collecting propagules or seeds from a protected species/habitat, and depositing planting materials onto the seafloor, all of which can generate onerous licencing obligations. Scaled-up restoration that can be fostered by local communities as well as professional outfits requires a licencing system that is fit for purpose. This will take significant long-term planning within governments.

Planning with flexible project management and a good project risk assessment is critical, as many seagrass restorations will result in unexpected outcomes and shocks. Birds overgrazing, poor seed development and therefore availability, or adverse weather are examples of common shocks that result in setbacks. Such issues may lead to changes in project workplans, timelines, costs, and ultimately delays. Funders need to understand that these sorts of issues are commonplace in projects. Ensuring that restoration methods are scalable within resource constraints is also important (Quigley et al., 2022), as in many localities the need to resource projects is restricted by the availability of a sustainable and permitted supply of seeds and/or propagules. Such a supply can potentially be supplemented by nursery sites where plants can be grown at scale (van Katwijk et al., 2021). For these, too, significant expertise, infrastructure and time is necessary to build facilities, conduct experimental design, and generate usable stocks of plants or seeds necessary for realistic restoration at scale.

9. DEVELOP REALISTIC INFORMED GOALS AND REPORTING

Seagrass restoration is at a critical juncture. As global environmental policy increasingly embraces NbS, the need to inform decision-makers, funders and the public about the effectiveness and uncertainty involved has never been greater. This is particularly true in the context of needing to urgently fund research to improve success levels. Failure in seagrass restoration is far more common than success, a trend mirrored in many ecological restoration projects (McCrackin et al., 2017;Bayraktarov et al., 2019;Ma et al., 2023). Facilitating more successful restoration requires better knowledge and understanding of what works and what does not. Biological reporting mostly focuses around success rather than failure (Unsworth et al., 2023). There are significant structural problems related to scientific publishing linked to the limited and largely absent reporting of experiments that produce so-called negative results, e.g. those that do not support the tabled hypothesis (Fanelli, 2012).

The 10 golden rules for reef and forest restoration (Di Sacco et al., 2021;Quigley et al., 2022) emphasise the need to ‘learn by doing’. While we advocate that there is much to be achieved from this approach, this needs to happen at the scale of the restoration community as a whole and of each project individually. Better social-ecological monitoring tied to scientific reporting of seagrass restoration results is needed. This philosophy needs to come from a top-down approach from funders and regulators stipulating those results are shared via open-access archives such as Pangaea. Within the academic discipline of Psychology, scientists are encouraged to go through a process of pre-registration of trials to share the details of their research in a public registry before conducting the study (APA, 2024). This process aims to improve the design and reporting of the study as well as improve the collective understanding that is developed from the work (APA, 2024).

Similar systems could help improve the discipline of ecological restoration. Many current opportunities also exist for better sharing of conservation outcomes. The ‘Conservation Evidence’ project is one such example that also presents a free, objective platform for summarising the evidence base for the effectiveness of different restoration actions, making it easily accessible to planners and decision-makers. Data-rich, statistically valid and peer-reviewed reporting is clearly the gold standard, but not all restoration groups have the capacity to write academic or detailed scientific reports. Where this is the case, diverse media (videos, audio diaries, before-and-after pictures) can be used to ensure as much of the data and knowledge collected are recorded and available for others to learn from.

Alongside appropriate monitoring and reporting of positive and negative results, strategies and mechanisms to learn from project outcomes need to be adopted within and between teams to facilitate adaptive learning from their own and others’ successes and failures (Suding, 2011). It is critical that projects set reasonable goals that are not beyond their scientific, regulatory, or financial resources (Cairns, 2000). Goals need to be defined that can be monitored in the long-term, considering the capacity of the project to provide appropriate measures of progress, along with biological and social success (Cairns, 2000). Increasingly, seagrass restoration projects have many aligned goals, some of which focus on seagrass and associated biodiversity metrics, but others relating to communication and people’s engagement with nature and restoration. The array of goals and the importance of different facets of restoration projects need to be clear in planning, paperwork and the project communications strategy. Project goals need to be clearly articulated to the funder and, where appropriate, the wider public, so that reporting can be fair and appropriate.

Considerable pressure exists to create goals that funders and regulators understand and consider suitably ambitious at a conservation management level. However, typical ‘hectare level’ goals are, within the timescales of most project funding, often unachievable, and the long-term ability of projects to monitor such goals is hampered by short-term funding cycles. Whilst such goals create publicity opportunities for funders, and excitement and credence for our ability to restore seagrass meadows, they mask the reality that chances of success remain low. Project funding timescales are mostly insufficient to fully determine if meadow-scale restoration (establishment of a resilient area of seagrass) has been successful; consideration needs to be given to securing funds or mechanisms for long-term project monitoring. Options for long-term monitoring could include citizen scientists, the training of whom could be included within the main project funding timetable. Funding periods are also unlikely to be appropriate to enable the required iterative nature of restoration planting and growth. We know from large-scale restoration in places like the Wadden Sea, Japan and the US, that project successes have resulted from many years of repeated restoration where the system eventually reaches thresholds of stability and expansion (Orth et al., 2020;Hori and Sato, 2021). Many projects have defined ‘exit strategies’, whereby groups seek, within the timescales of the original project and its deliverables, to gain funding for a second stage. Such strategies may be required to secure further funding for supplementary planting or long-term monitoring, allowing eventual realistic project evaluations. In an ideal world, however, funders would recognise the need for longer-term projects to avoid this additional administrative burden and increase confidence at the outset, as recently exemplified by the British Ecological Society’s call for long-term (10-year) research grants (BES, 2024).

10. MAKE IT PAY

Currently, US$174.52 billion per year is needed to conserve our oceans (Johansen and Vestvik, 2020). While the average cost to restore 1 ha of marine coastal habitat is US$1,600,000 (Elisa et al., 2016), the real total costs are likely to be two-to-four times higher. Seagrass restoration is expensive, and to date has been largely funded through philanthropic and government funding mechanisms (Elisa et al., 2016). Projects are mostly local and small-scale and typically focus on active restoration and favour the first tranche of seeds required, rather than the investments needed to facilitate long-term recovery. Finance is largely absent to facilitate long-term restoration along with the required monitoring and maintenance, plus measures to ensure stewardship and increase the chances of success. We need mechanisms to generate finance for seagrass protection and enhancement, as well as for improved chances of successful restoration projects. Seagrass protection and enhancement is a priority for restoration (rule #1) but funding is far easier to obtain for planting *new* areas as funders typically see excitement in creating and claiming something over the enhanced value of protecting something. What we need to ensure is net gain in seagrass cover and sadly, this needs a stronger driver and returns than investment in nature. Innovative financing solutions are required to turbo-charge ocean and coastal preservation and prevent further decline.

Despite its significant global-scale value, seagrass has largely been ignored, until recently, in the development of novel finance mechanisms. Restoration of healthy and resilient seagrass ecosystems contributing to sustainable ocean wealth feeds in directly to ‘the blue economy’, likely worth $3 trillion by 2030 (IFC, 2022). Integration of the blue economy into mainstream government and financing initiatives creates new opportunities for bringing major investment into large-scale seagrass restoration. This is most likely at national or regional scales through mechanisms such as ‘Green and Blue Bonds’, and environmentally related ‘Debt Swaps’. But whilst these sorts of opportunities are of major potential power at the top-down government level, they are largely out of reach of most restoration practitioners. There exists, however, potential to generate funds for seagrass restoration through other novel finance mechanisms. To avoid the demonstrated pitfalls of equivalent terrestrial projects, these mechanisms must be evidence-based with validation at their core, not suffer from unintended consequences (Jones et al., 2022), and be equitable for stakeholders who rely on ES from the seabed. Investment is required to support innovation to ensure these sorts of NbS ‘products’ can be brought to market in a way that is equitable and evidence-based, with development including the experience of all stakeholders such that ‘solutions’ contribute to achieving all dimensions of sustainability (Nesshöver et al., 2017). Investors also need to understand the risks involved in financing seagrass restoration projects, which are still in their infancy, with healthy and self-sustaining meadows taking multiple years to develop (do Amaral Camara Lima et al., 2023).

One means of raising novel finance at the practitioner level is to develop mechanisms for the Payment for Ecosystem Services (PES) provided by seagrass ecosystems (UNEP, 2020b). While PES frameworks have been successfully applied in mangrove restoration (Huxham et al., 2015), success across other terrestrial projects is limited (Erbaugh, 2022). Most, if not all the discussion around the use of PES in seagrass focuses on credits to facilitate seagrass restoration. This discussion has, to date, been based on improving knowledge of the biology in readiness to implement restoration initiatives at scale. Improved research effort is required to understand how delivery of such credit systems can become win-win mechanisms for coastal communities and, in some instances, facilitate poverty alleviation, whilst allowing businesses and funders to obtain recognition for associated environmental and societal benefits. Carbon credits are the most traded ES, but remain in their infancy in a seagrass context, and are arguably the most uncertain and difficult to accurately value. Data on long-term GhG drivers (sources) and removals (sinks) is often absent, restricting what can be expected from seagrass carbon credits (Ward et al., 2023). Despite concerns around knowledge gaps for seagrass Blue Carbon, various seagrass carbon codes are in development around the world, and some are in use, such as Verra’s VM0033 Methodology for Tidal Wetland and Seagrass Restoration, and the Yokohama carbon code based on IPCC guidelines (Kuwae et al., 2022). Irrespective of the challenges, all predictions indicate that the market for carbon credits will continue to grow rapidly, and with it, likely create opportunities for financing seagrass restoration. The seagrass restoration community needs to urgently use this as an opportunity to develop more holistic and equitable PES tools for protection and enhancement of all seagrass ES, and for protection of seagrass as a holistic SES.

To facilitate PES mechanisms that can be used to support conservation and restoration activities and create benefits that are more holistic and equitable to local communities, we suggest that ES with direct community benefits (e.g. coastal defence, tourism, fisheries) should be the focus of future activity. Knowledge is rapidly growing as to the physical role of seagrass in supporting coastal environments through wave attenuation and flood protection (Fonseca and Cahalan, 1992). Improved stakeholder engagement (including sectors such as the insurance industry and engineering entities, traditionally not accustomed to the role of vegetation for protecting coastlines) in managing these challenges for coastal environments is required as they create realistic opportunities for restoration to pay. Fisheries obtain enormous subsistence and economic benefits globally from seagrass (Unsworth et al., 2018); consequently many large companies take large financial profit from fish populations dependent upon seagrass. In some parts of the world, fishers at local levels have become highly involved with seagrass restoration, bringing pro bono rather than financial input to projects, with enormous success (Hori and Sato, 2021). Improved means are required of bringing fishers into seagrass restoration and conservation. This may promote improved knowledge sharing with these industries regarding the role of seagrass in supporting fish communities.

Biodiversity offsets and credits can also finance seagrass restoration. Offsets have, however, been controversial and in some instance may have negligible benefits (Ma et al., 2023). For instance, if a healthy natural seagrass meadow is destroyed by a development, and restoration undertaken elsewhere, there is no guarantee that the restoration will be successful. If it is, many years will be needed before the restored meadow is supporting the same level of biodiversity as the natural existing meadow, and if located elsewhere, local communities may lose ecosystem benefits (Niner et al., 2017;Shilland et al., 2021). Alternatively, biodiversity credits that meet certain standards, and as for carbon consider the entire social and ecological value of seagrass, show better potential (Ducros and Steele, 2022). Biodiversity credits are often traded on voluntary markets and, if used to restore new seagrass meadows rather than as compensation for damaged meadows, may provide finance to scale-up restoration.

Ultimately, there is potential for developing novel finance mechanisms to form a blended global finance model for seagrass restoration. Traditional donors are likely to continue to be needed for high start-up costs, yet PES mechanisms that include all services provided by seagrass ecosystems, as well as adhering to standards and having a community focus, have great potential to enhance and scale-up seagrass restoration globally.

CONCLUSIONS

It is unequivocal that the world has lost a significant proportion of its seagrass (Waycott et al., 2009;Dunic et al., 2021) and although glimmers of hope exist (McKenzie et al., 2021), losses continue with many ongoing negative trajectories (Turschwell et al., 2021). First and foremost, we need to put the world on a global pathway to seagrass net gain (Unsworth et al., 2022). Conservation of what remains must be a priority, but we also need to increase coverage at rates unlikely to be achieved naturally, through active restoration. As Quigley et al. (2022) rightly highlight, "*the Bonn Challenge aims to restore 350 million ha of forest, 10 times the size of the GBR, itself the size of Italy*". As we illustrate here, we are nowhere near achieving such goals, but working to the 10 golden rules outlined above will set us on a better footing towards such ambitions. To truly take this to the next level, strategic future thinking is needed to grapple with how seagrass restoration can set similar ambitious but realistic goals. The global seagrass community needs to embrace interdisciplinary thinking and use a broad range of skillsets to achieve this. This is vital to secure a future for seagrass and the hundreds of millions of people who depend upon its resources.

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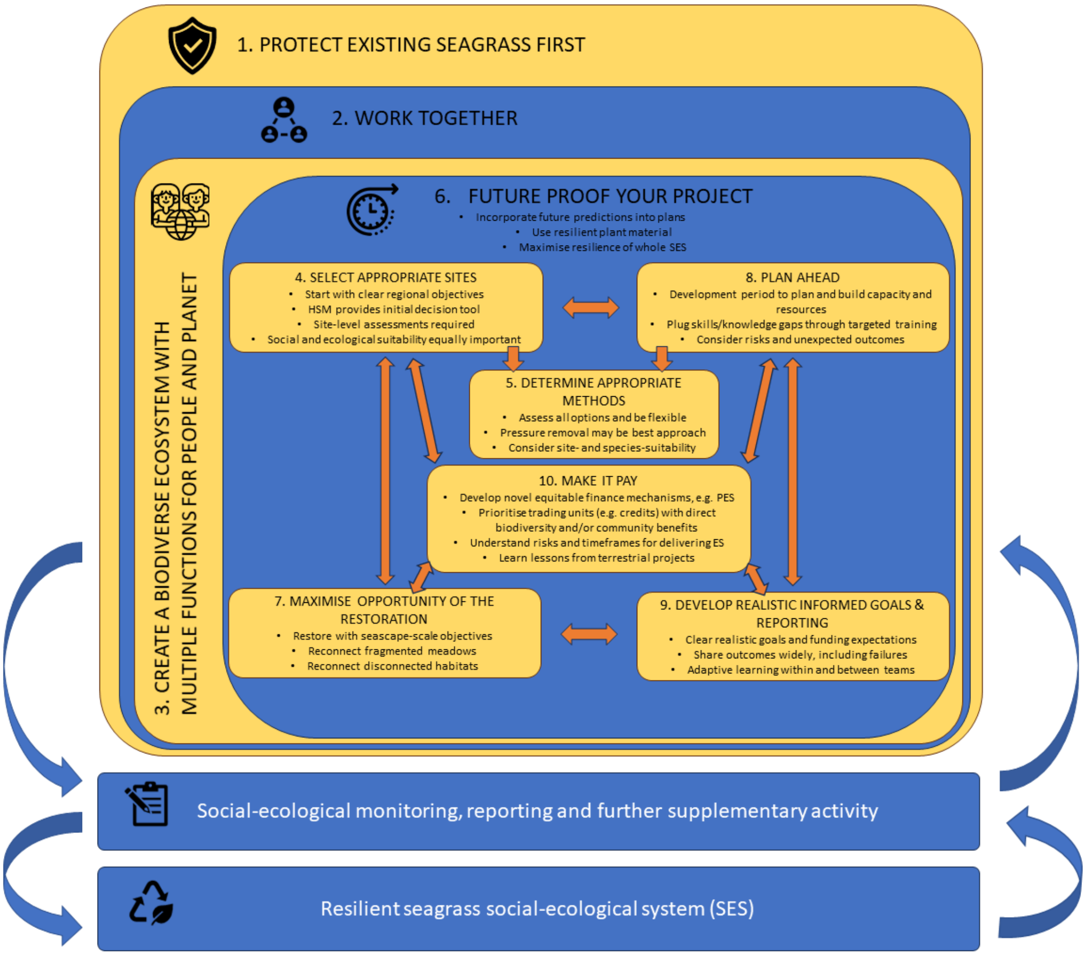
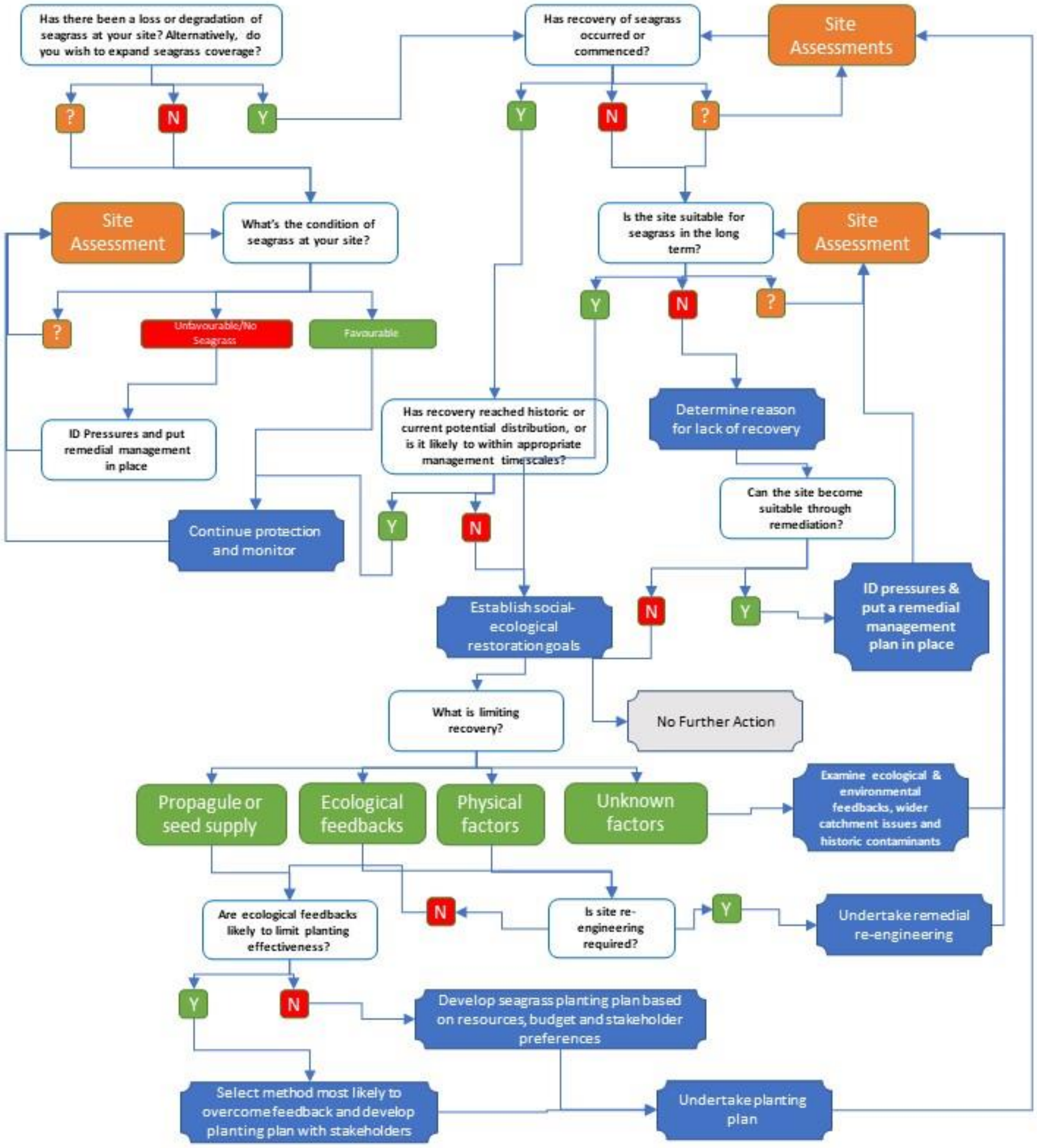


FIGURE 1. Ten golden rules to secure resilient and just seagrass social-ecological systems (SES). The rules are shown with four overarching principles (Rules 1, 2, 3 & 6) and illustrate how they are interdependent and need to be considered in parallel. Although not shown in the figure, two modifiers (space and time) are additional factors to consider as to how these processes operate. See text for details.



APPENDIX 1. Proposed decision tree to aid decision making as to the appropriate course for seagrass restoration during project planning