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When nature needs a helping hand: Different levels of human intervention for mangrove (re-)establishment

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Protecting existing mangrove forests is a priority for global conservation because of the wide range of services that these coastal forests provide to humankind. Despite the recent reduction in global rates of mangrove loss, high historical loss rates mean that there are at least 800,000 ha globally that are potentially suitable for mangrove re-establishment. Recently deposited mud banks or intertidal, previously terrestrial, land might provide additional habitat for expanding mangrove areas locally. There is a long history of mangrove rehabilitation. However, despite numerous good examples of, and growing expertise in, natural or assisted (re-)establishment activities, most mangrove planting efforts, for instance, either fail entirely or meet with only limited success. Exposed to waves and currents and subject to tidal inundation, mangroves differ from terrestrial forests, and approaches to, or tools for, terrestrial forest restoration cannot easily be transferred to mangrove forests. Successful mangrove (re-)establishment usually requires a robust understanding of the abiotic and biotic conditions of the chosen site, the ecological requirements of the mangrove species used or facilitated, the reasons for previous mangrove loss or degradation, as well as the barriers–both societal and ecological–that have prevented natural recovery to date. Because most mangrove forests are socio-ecological systems, with which local human populations are intimately engaged, (re-)establishment will normally require the support of, and engagement with, local communities and other local stakeholders. Here, we summarize where, when and why (re-)establishment of mangroves is needed and how to assess this need. We discuss a range of potential aims and goals of mangrove (re-)establishment along with potential pitfalls along the way from conceiving the initial idea to its realization. We compare different technical and conceptual approaches to mangrove (re-)establishment, their challenges and opportunities, and their design and financial requirements, as well as potential solutions. We ground our final outlook and recommendations on examples of successful efforts and the factors that rendered (re-)establishment successful in the past.

KEYWORDS

mangrove forest, restoration, rehabilitation, afforestation, Ecosystem Design, reforestation, ecosystem services, stakeholder-engagement

Introduction

Despite the many ecosystem services that mangrove forests provide, notably their valuable contributions to the livelihoods and wellbeing of local stakeholders and societies, we have witnessed a drastic decrease in mangrove areas worldwide. While there has been a reduction in rates of loss between the late 20th and early 21st centuries (Friess et al., 2020), mangroves continue to be lost at a global average of 0.13% year^{-1} (Goldberg et al., 2020). Natural mangrove forests provide some ecosystem services more efficiently than re-established mangrove stands (Kathiresan and Rajendran, 2002; Su et al., 2021). Hence, protecting and conserving existing mangrove forests is of utmost importance.

Whilst, thus, halting the on-going loss of mature and old-growth mangrove forests remains the priority (Lee et al., 2019), there are also multiple opportunities for restoring, rehabilitating, reforesting or even afforesting mangroves worldwide, in order to help compensate for historical damage (see **Box 1** for definitions; we apply these definitions throughout this paper and use the generic term "mangrove (re-)establishment" to describe any approach that aims at the development of mangrove forests). Despite a plethora of guidelines and handbooks on mangrove restoration and rehabilitation (e.g., Primavera et al., 2012a; Lewis and Brown, 2014; Armah et al., 2016; UNEP-Nairobi Convention/USAID/WIOMSA, 2020; Teutli-Hernández et al., 2021), numerous rehabilitation and restoration efforts are still unsuccessful (Kodikara et al., 2017a; Wodehouse and Rayment, 2019) or may produce forests of poor structure or low diversity or sustainability (Dahdouh-Guebas et al., 2021). Often, mangrove (re-)establishment activities suffer from a lack of clear aims and goals, making it difficult to both properly plan the activity and monitor its success.

Here, we review pertinent literature and use unpublished knowledge on mangrove (re-)establishment to: (1) describe the main rationale for mangrove (re-)establishment; (2) compare different approaches, along with probable pitfalls and potential solutions; (3) provide an assessment of what has made (re-)establishment efforts successful in the past, in order to (4) come up with an outlook and recommendations for future interventions. Even though multiple mangrove re-establishment efforts, following different approaches, have been undertaken worldwide, there is a clear bias in the scientific literature toward reports of re-establishment activities, their success or failure, or lessons learned from the Southeast Asian region. Thus, some of our analyses focus on this region, but Atlantic and Eastern Pacific mangrove regions are also considered where possible and reasonable. Rather than adding to the wealth of hands-on guides, we aim at guiding readers and practitioners through

BOX 1 Glossary.

Afforestation (also referred to as mangrove forest creation)–establishing a (mangrove) forest in an area where there had been none in recent times; this includes planting on newly deposited sediment banks or newly formed intertidal (e.g., following sea level-rise) previously terrestrial spaces

Biodiversity–diversity of life over all hierarchical levels, from intraspecific genetic diversity to interspecific diversity, to the diversity of higher taxonomic levels within a given ecosystem or set of ecosystems and beyond, comprising the diversity of ecosystems in a given region itself

Blue Carbon–atmospheric carbon (dioxide) captured and sequestered by marine and coastal vegetation, and stored in their biomass or as recalcitrant organic matter in the water body or sediments

Conservation (also referred to as protection)–protection and maintenance of natural habitats or ecosystems from potentially damaging effects of human activity

Ecosystem–entity of a biological community of interacting organisms in its physico-chemical environment (habitat)

Forest structure–integrative descriptor of measures that encompass the spatial density of trees (their distance to each other), their height and volume (stem diameter) and three-dimensional architecture (of the canopy and, in the case of mangroves, their aerial roots)

Functional distinctiveness/distinctness–measure for differences in functional traits among species in a given ecosystem, described by the distance spanned by distinct species in (part of) their trait space

Functional diversity–range of expressions of functional traits of species in a given ecosystem, potentially influencing ecosystem processes

Functional trait–any feature of an organism that contributes to its integrity in response to abiotic and biotic conditions and, thus, impacts individual fitness through effects on survival, growth or reproduction

Habitat–physico-chemical environment of a community of organisms

Nature-based solution–actions to counteract environmental effects or change through using natural or modified ecosystems that both address societal challenges effectively and adaptively and provide co-benefits to humankind in addition to those goals directly aimed at

Recovery–(natural) process of regaining something lost, e.g., a former ecosystem status [often referred to in the context of (human) health]

(Re-)establishment–generic term, inclusively encompassing the many different approaches to (re-)establishing an ecosystem, either in an area where a similar ecosystem had been previously degraded (re-establishment), or in a new suitable place (establishment)

Reforestation–renewing forest cover following forest area loss, be it through human-driven habitat degradation (e.g., forestry extraction, land use-change) or through natural processes

(Natural) Regeneration–(natural) restructuring or renewal of a structure, e.g., of an ecosystem (more often referred to in the context of organ or limb regeneration)

Rehabilitation (also referred to as **Ecological Restoration**)–re-establishing (some of) the conditions and ecological processes in a degraded ecosystem or its habitat in order to initiate a trajectory toward recovery of near-to-previous conditions (recognizing that complete restoration may be impossible within a short- or medium term).

Restoration–returning a degraded ecosystem back to its former natural state or condition (this may take place after a very long period only)

Species richness–number of species present in an ecosystem and as a simple count of species, richness does not take into account the (relative) abundances of species, unlike other measures or indices of taxonomic diversity

Taxonomic diversity–diversity of taxa (species or higher taxonomic levels), taking into account the relative abundance of all taxa for calculating a variety of indices that describe different aspects of biodiversity.

considerations and pragmatic planning to support successful mangrove (re-)establishment.

When and why to (re-)establish

Effective protection of mature mangrove forests as providers of numerous ecosystem services to local communities and humankind worldwide remains the most important global management goal. Upon advanced degradation of existing mangrove forests, however, ecosystem service provisioning will be severely hampered, and conservation of the *status quo* might not be an option anymore. Disturbances and stressors are considered drivers of mangrove degradation. The term "disturbance" is defined in mangrove studies (as well as generally in ecology) as any factor that destroys mangrove plant biomass which has already been formed, while "stressors" are environmental conditions that reduce plant growth and yield (Cramer et al., 2011). Accordingly, grazing, trampling, herbivory by crabs, snails, insects or mammals, and algal accumulation

(Dahdouh-Guebas et al., 2011; Van Nedervelde et al., 2015; Jenoh et al., 2016; Kodikara et al., 2017a), have been identified as common disturbances. Extreme levels of light, prolonged drought or flooding, high salinities, high sedimentation rates (smothering), pollution, or hydro-mechanical forces (Pereira et al., 2016; Kodikara et al., 2017a,b; Madarasinghe et al., 2020) are considered major stressors. Under such conditions of continuous disturbance or stress, active intervention through one of the approaches discussed here could be a viable solution.

Restoration, reforestation and rehabilitation apply to degraded ecosystems (see **Box 1**). Hence, the major challenge here is to determine when a mangrove forest is so degraded that some form of active intervention is required (as opposed to cases where initial degradation of ecosystem integrity can still be halted through effective conservation measures). Yando et al. (2021) recently provided the Degradation Indicator Framework to assess the severity of mangrove degradation using multiple indicators and comparisons to reference sites. On the other hand, afforestation (see **Box 1**) can transform unvegetated coastal habitats into mangrove stands, e.g., on freshly deposited sediment banks to stabilize the sediment and to establish ecosystem service provisioning *de novo*.

The aims and goals of efforts to (re-)establish mangrove forests are manifold, and partly depend on the causes of mangrove loss or decline, as well as the needs and requirements of stakeholders. These goals and aims, in concert with the peculiarities of a particular location and socio-ecological setting, affect the approach to choose. The close involvement of local and regional stakeholders in co-designing (re-)establishment activities and the resulting definition of aims and goals will further drive the choice of approach.

The focus of mangrove re-establishment has changed over time. Before the early 1980s, the major aims were provisioning of timber for construction or fuelwood. More recently, goals included the removal of pollution, enhancement of fisheries or production of livestock fodder, or coastal protection. Lately, biodiversity conservation and aesthetics were added to this list of objectives, but the major focus now is on improving sequestration and storage of "blue carbon" for carbon-offsetting in the context of climate change-mitigation efforts (Taillardat et al., 2018).

How and where to (re-)establish

Each of the approaches of mangrove (re-)establishment has their advantages and pitfalls that mediate the decision on which one to choose (see also Ellison et al., 2020). Aims and goals may differ regionally, depending on both the structure and species composition of mangrove forests and their human use and management policies. Thus, the Indo-West Pacific (IWP) mangrove regions are species-rich and commonly characterized by highly diverse mixed mangrove forests. By contrast, mangrove forests of the Atlantic-East Pacific (AEP) are relatively species-poor and often develop monospecific stands on a small- to medium scale (c.f. Quadros et al., 2021). These ecological differences translate into the need for different approaches to, and aims of, mangrove management (Lugo, 2002, for conservation). Further, societal and legal peculiarities at the regional and national scale have to be taken into account in the planning and implementation of mangrove (re-)establishment programs. For instance, land ownership and management policies may differ markedly among different countries (Recio et al., 2016, for Central America) which, in turn, may affect aims and goals, and thus, the choice of approaches to mangrove (re-)establishment. Hence, while concepts and approaches of mangrove (re-)establishment are often generally applicable and transferable across regions, recommendations derived from them cannot necessarily be transferred one-by-one from one region to another but may require adjustment to regionally specific ecological, societal or legal conditions.

Approaches to mangrove (re-)establishment

Natural rehabilitation

Concept

Natural rehabilitation (also referred to as ecological restoration: SER and Policy Working Group, 2002) involves facilitating the natural processes of recruitment, settlement and establishment of mangrove propagules, taking advantage of local hydrodynamics for providing propagules to settle locally (Lewis, 2005). This approach produces a near-natural forest structure as in the original forest and may entail little costs. However, it requires essentially undisturbed hydrodynamics and topography (Otero et al., 2019). Under ideal conditions of hydrodynamic connectedness between existing mangrove stands and degraded areas, natural recruitment of seedlings and recovery of mangrove will occur over time, as soon as the disturbance or stress (direct or indirect human impact or natural processes) has been removed. Changes in the local hydrology or connectedness across ecosystems require the restoration of favorable hydrological conditions (Dahdouh-Guebas et al., 2011). For instance, road or rail construction has disconnected (previous) mangrove areas from the sea in many coastal areas. Thus, upon surveys of stakeholder needs and selection of appropriate sites, the restoration of suitable hydrological conditions and reconnection of the degraded site with existing mangrove forests may allow for natural recovery and structural regeneration.

Such restoration of hydrological conditions as basis for mangrove re-establishment is particularly important in the case of abandoned aquaculture ponds. These ponds are potentially ideal re-establishment sites, because they were once mangrove forests. However, aquaculture ponds often do not exhibit sufficient tidal connectedness and exchange, are surrounded by shorelines that were built up with too steep slopes or have water levels too deep for successful mangrove recolonization and establishment. Opening tidal channels, flattening pond walls or building up islands inside the ponds may be required here (Brown et al., 2014; Oh et al., 2017).

Hydrological restoration after disturbance by, e.g., road construction (c.f. Teutli-Hernández and Herrera-Silveira, 2018, in mangrove areas of Yucatán, Mexico; Krause et al., 2001, in mangrove areas of the Ajuruteua peninsula, Pará, Brazil) can be achieved, for instance, by implementing box culverts that reconnect both sides of the road hydrologically (Teutli-Hernández and Herrera-Silveira, 2018).

Natural rehabilitation has been successful following the excavation of filled mangrove channels or the re-grading of the slopes of mangrove sediments (Lewis, 1990; Lewis and Streever, 2000) or reconnecting impounded mangroves to normal tidal influence (Brockmeyer et al., 1997; Turner and Lewis, 1997). For instance, 60% of mangrove forests of the Ciénaga Grande de Santa Marta (Colombia) died due to increased sedimentation rates and decreased water levels because of human-induced disturbance of the natural hydrological conditions. Over the last years, mangroves were re-established, through reopening obstructed channels to allow for free flow of water to the area (Elster, 2000). A similar situation of mangrove re-establishment is also witnessed in mangrove lagoons along the west coast of central Africa, notably in the Republic of Congo, Benin, and Ghana, with sedimentation obstructing the mouths of lagoons (Ajonina et al., 2016), as well as in estuarine mangroves of Pichavaram, southeast coast of India (Kathiresan, 2000).

Assisted rehabilitation

Concept

When mangrove propagules are not available in sufficient quantities, or in areas with improper tidal flow, natural rehabilitation may not be successful. In such cases, active planting may be necessary. When reconnecting isolated stands to nearby forests is not feasible, propagules can be collected from adjacent productive mangrove stands (Primavera et al., 2012a) and planted or broadcasted onto an incoming neap tide to boost the supply. However, collecting and removing seedlings from spatially restricted areas of flourishing mangroves nearby, rather than relying on a natural supply of diverse seedlings through tidal deposition, bears the risks of (i) impoverishing the donor stand and (ii) diminishing both the species richness and the within-species genetic diversity in the recipient area (see § The role of genetic diversity in (re-)establishment).

Species selection and propagule preparation in nurseries

When active planting is deemed necessary, careful planning of each step is pivotal. Prior to the planting of propagules, seedlings or saplings, selection of appropriate species according to the local environmental conditions is essential. Thus, any introduction of species not native to the planting site should be avoided. For instance, the introduction of non-native mangrove species (the South Asian *Sonneratia apetala* and the American *Laguncularia racemosa*) in southern China (Lee et al., 2019), or of the Indo-Pacific mangrove palm *Nypa fruticans* in Nigeria, have reduced native species diversity, with rapid invasion of *N. fruticans* into the neighboring country of Cameroon (Moudingo et al., 2019).

Depending on the objective, e.g., near-natural recovery or fast forest development, the initial species choice can be different. Careful species selection will increase the success of sapling establishment, subsequent recruitment and, thus, of the entire action itself (Bosire et al., 2008). This selection should also reflect on information about natural succession of different mangrove species with different functional traits. Ideally, species should be selected based onsite elevation and their natural occurrence near the restoration site or in times prior to degradation (Kathiresan, 2015), which might also reflect successional stages of mangrove development (Zimmer, 2022). In some mangrove forests of Northern Brazil, the early successional *L. racemosa* is followed and outcompeted by *Avicennia germinans* that, in turn, will be replaced by *Rhizophora mangle* in late successional stages (Mehlig et al., 2010). In the Indo-Pacific realm, *Sonneratia alba*, *Avicennia alba*, and *Avicennia marina* are considered pioneer species that pave the way for late successional species. In this context, local ecological knowledge from the communities living in the vicinity provides additional useful input (Longépée et al., 2021).

In some cases, mono-specific plantations reflect natural conditions, such as in many Amazonian mangrove forests of Northern Brazil (e.g., Quadros et al., 2021), or in zones dominated by *S. alba* (Bosire et al., 2003) in Southeast Asia. Along the same line, monospecific restoration can perform better than mixed-species restoration for specific ecosystem services (Su et al., 2021). Further, monospecific mangrove plantations can naturally recruit non-planted but locally available species and develop into multi-specific stands over time (Bosire et al., 2006); this can occur when particularly robust species, such as *A. marina*, are used as pioneering “nurse plants” to facilitate ecological recovery in degraded sites (Huxham et al., 2018; **Figure 1**).

Depending on the selected species, the plantation approach might differ, Thus, large propagules of Rhizophoraceae (such as the genera *Rhizophora*, *Kandelia*, *Ceriops*, *Bruguiera*) may be planted directly, whereas small propagules or seeds (e.g., of the genera *Avicennia*, *Sonneratia*, *Xylocarpus*, or *Excoecaria*) should be grown out in a nursery (Kathiresan, 2015). However, nursery cultivation may be advantageous for large propagules too, even though this requires an investment in space and time, as it can reduce the number of non-viable seedlings planted out and increase the success rate of planted seedlings onsite, as long as they are deployed at suitable elevations relative to mean sea level.

FIGURE 1
Natural recruitment of the locally available *Aegialitis rotundifoilia* (smaller plants) after the planting of several robust *Rhizophora* spp. (larger plants with prop roots) by the local community (near Gwa, Rakhine State, Western Myanmar) (photograph credit: Jean Yong).

Many mangrove nurseries generally adopt terrestrial plant horticultural techniques to grow mangrove saplings. These terrestrial nurseries usually use freshwater to water the seeds and seedlings. Better success is achieved when the seedlings are progressively acclimatized physiologically to the local conditions (prevailing tidal influences, salinity, lower nutrient levels and local climatic conditions). Suitably "hardened" mangrove seedlings are more likely to survive when grown at lower nutrient levels and inoculated with suitable sources of "old" mangrove mud (possibly containing plant growth-promoting microbes of the reference site: Saravanakumar et al., 2013, 2016; Mai et al., 2021; **Figure 2**). More detailed studies are needed to ascertain these useful field and operational observations about mangrove seedling preparation and microbial sediment inocula (c.f. Holguin et al., 2001) prior to transplantation. Nevertheless, it is clear that identifying a site for a mangrove nursery (near the project site) with suitable tidal inundation to harden the mangrove seedlings supports the development of a successful mangrove planting project.

Site selection

One of the causes of poor survival rates of saplings is poor site selection, often in the lower intertidal to subtidal zones, where mangroves do not thrive, rather than the optimal middle to upper intertidal levels. These more suitable sites have in many regions been converted to aquaculture ponds, whereas the former are open access areas with no ownership problems. Hence many governments and non-governmental organizations still continue to invest in low tidal mudflat planting, despite the repeatedly documented very low survival rates. Not making this mistake, but rather planning properly, will significantly increase the chance of being successful. The tidal elevation of mangrove planting sites within the intertidal zone, between mean and high water levels (Primavera and Esteban, 2008), must be ecologically evaluated to match the eco-physiological traits and optimal growth ability of the planted species (e.g., Satyanarayana et al., 2009, Satyanarayana et al., 2018), and governments and practitioners must engage in realizing such ecological evaluation for successful (re-)establishment measures.

Besides the fact that habitats below the mid-tidal level are not suitable for mangroves, planting mangrove seedlings there can impair other valuable coastal ecosystems. Further, even in areas that had previously been occupied by mangrove forests, local conditions may have drastically changed, such as after the 2004 Indian Ocean tsunami (Nehru and Balasubramanian, 2018; Dahdouh-Guebas et al., 2021). Therefore, the presence of mangroves in historical aerial or satellite imagery does not necessarily prove the suitability of a location for mangrove (re-)establishment (Dahdouh-Guebas and Cannicci, 2021). On the other hand, the lack of mangroves on a given soft-sediment mudflat does not necessarily indicate its unsuitability as mangrove habitat, as such a stretch might be hydrologically (or spatially) isolated from (adjacent) mangrove stands or be too recent for natural mangrove establishment (see below).

Community-based ecological mangrove restoration

Concept

Community-based ecological mangrove restoration (CBEMR)[1] is based on Ecological Mangrove Restoration (Lewis, 2005; Lewis and Brown, 2014; and exemplified by Brown et al., 2014). The default objective of CBEMR is to facilitate

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[1] For more information on Mangrove Action Project's CBEMR technique, see https://mangroveactionproject.org/mangrove-restoration/

FIGURE 2
Ecologically sensitive mangrove plant acclimation strategy. The eco-physiological hardening of *Rhizophora stylosa* (left) and *Avicennia officinalis* (right) saplings (inoculated with "old" mud taken from suitable reference sites) by using natural tidal inundation for 1–2 months (Left: 2011, Singapore; Right: 2006, Sri Lanka) (photograph credits: Left: Chua Jit Chern and Jean Yong, Right: Farid Dahdouh-Guebas).

natural regeneration where sites are not propagule-limited, to encourage all local species back onsite, and follows a holistic approach that starts with engaging and empowering local communities and relevant stakeholders to resolve those issues that caused the initial mangrove loss and then to restore their own sites. Unless the objective is something other than full ecosystem restoration, planting is normally necessary only if the site is "propagule-limited". If this is the case, other methods can be used to introduce more propagules and seeds, for example, by broadcasting them onto an incoming neap tide. Only if even this does not provide the propagules necessary for natural recovery, CBEMR considers active planting a last resort.

Practitioners gain insight from communities' local knowledge and together study the biophysical parameters of the site and socio-ecological factors that might affect re-establishing the site in question and mangrove conservation in general. This process identifies the appropriate species that are living, or should live, on the proposed site, their ecology, physiological and ecological preferences and tolerances, method of reproduction, as well as their cultural and practical relevance for local human users. Other parameters include environmental conditions, such as salinity, sediment type, tidal amplitude, likely wave energy, elevation relative to sea level and hydrology (depth, duration and frequency of inundation). Data are collected onsite history (e.g., previous use), ownership and tenure, propagule availability, and current obstacles to natural recovery (Elliott et al., 2013). This ensures a clear understanding of what has changed on the site (e.g., environmental conditions), and therefore, what needs to be, and what can be, remediated (Johnson et al., 2016), knowing that sometimes the issue preventing natural recovery cannot be resolved, so another site, or a set of potential sites ranked for ease of re-establishment, should be considered. To complement this research, a concurrent study of a nearby reference mangrove forest of similar topography, hydrology and salinity is encouraged for planning the intervention and monitoring its success.

After selection of the appropriate site (for example, not below mean sea level on regularly inundated mudflats), the next stage is for all stakeholders to agree on the aims and goals of the intervention and to develop a detailed action plan, paying particular attention to removing natural recovery inhibitors and improving the hydrology. This might require varied activities of ecological engineering (Lewis, 2005) from improving the drainage and hydrology in a former aquaculture pond, to installing fencing to exclude grazing or trampling animals, offering alternative fuels for cooking, or establishing a community-based forest management group to reduce extraction pressure (like Eco-Development Committees at Coringa Wildlife Sanctuary[2]; Dahdouh-Guebas et al., 2006). All activities take place within the restrictions of budget, local labor skills and availability, and social agreements, such as supplementary livelihoods, need to become sustainable in their own right. For baseline data-acquisition, monitoring the project starts before the intervention and continues after the work is completed. During this, interventions, such as channel excavation or hydrological improvement, are amended as necessary.

For example, re-establishment of degraded mangrove stands has successfully been demonstrated by the M. S. Swaminathan Research Foundation with the involvement of 5,240 families by planting 6.8 million saplings along the east coast of India over an area of 1,475 ha. This participatory effort resulted in a 90% increase in mangrove forest cover in Pichavaram between 1986 and 2002 (e.g., Kathiresan, 2018), empowering the local people to implement poverty alleviation programs such as supplementary income-generating activities for firewood, fodder and house construction. In some cases, however, prior poverty alleviation through region- and case-specific measures is a pre-requisite for, rather than an outcome of, community engagement in mangrove conservation and re-establishment

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[2] https://eastgodavari.ap.gov.in/tourist-place/coringa-sanctuary/

projects, because local fisherfolks are too immersed in securing family income, food and security for spending time and energy in any mangrove (re-)establishment activity (Dahdouh-Guebas and Cannicci, 2021). Another example of this approach comes from Myanmar, where the NGO Mangrove Service Network (MSN) worked with village members of Jiro Pasig, east of Sittwe, to develop a mangrove greenbelt to reduce coastal erosion (previous to this project, the village had had to move the shorefront houses back three times due to erosion). In this case, as the site was propagule-limited, the community developed a nursery (located just above the restoration site to mitigate any transplanting shock) for appropriate low-zone pioneer species and grew them up for a year. Once planted out, the area was fenced off to exclude grazing or trampling animals, and the villagers were encouraged to reduce mangrove wood harvesting pressure. Planting these pioneer species was a success, and the corresponding mangrove stand[3] is now producing propagules, driving natural recovery along the coast.

Ecosystem design

Concept

An alternative approach to re-establishing degraded ecosystems toward high biodiversity aims to establish ecosystems (not necessarily with high biodiversity) that provide those ecosystem services that are most required by local and regional communities. Hence, Ecosystem Design (Zimmer, 2018) does not focus on ecosystem characteristics, such as biodiversity, but on the provisioning of services and natural resources for their (sustainable) use. The re-establishment of degraded ecosystems, or the establishment of *de novo* ecosystems in suitable areas will, according to this approach, thus be driven mainly by the needs of local and regional stakeholders.

Those needs might not require the (re-)establishment of high biodiversity or high (mangrove) species richness (but see Cannicci et al., 2021, on low functional redundancy of mangrove fauna). For example, Rahman et al. (2021) demonstrated that species richness or functional diversity of mangroves in the Sundarbans of Bangladesh are not the major drivers of carbon sequestration in above- or belowground biomass or in the sediment. The best predictor of carbon stocks in the Sundarbans mangrove forests was functional distinctiveness, i.e., a measure of how different and functionally distinct the mangrove species of the study sites were. Hence, planting only a few regionally dominant mangrove species may be sufficient for getting a newly established mangrove stand up and running. Along this line, fast-growing species, e.g., some species of the genus *Avicennia*, will result in positive effects in a shorter span of time (e.g., Kathiresan, 2015); generating benefits fast may be particularly important where the services are critical to health and wellbeing, for example in protecting against shoreline erosion and storm surges (Primavera et al., 2014). *Avicennia* spp. may also store larger amounts of carbon in their sediments than *Rhizophora* spp. in restored sites (Kathiresan et al., 2013, Eid et al., 2020). Hence, following the concept of Ecosystem Design, initially planting pure stands of *Avicennia* may be justified, if rapid provisioning of services such as coastal protection or carbon sequestration is prioritized by stakeholders. Beyond this societal aspect that is also covered by, e.g., CBEMR, Ecosystem Design has been suggested as a scientific field laboratory for testing and comparing different approaches and solutions for active interventions in degraded or newly established ecosystems (Ellison et al., 2020).

Ecosystem service-provisioning and biodiversity

Additional evidence supporting the notion that Ecosystem Design with limited species richness may be feasible is the fact that some species-poor mangrove forests of the AEP are (almost) as productive as species-rich forests of the IWP, which supports the notion that Ecosystem Design with limited numbers of (re-)established species may be justified. Quadros et al. (2021) recently explained this observation, which apparently contradicts the biodiversity-productivity paradigm, by noting that the two dominant species of many regions of the AEP (*R. mangle* and *A. germinans*) are very different from each other with respect to a suite of functional traits, while many species of IWP mangrove forests are more similar to each other. This conclusion concurs with the idea that a few, significantly different, species might be as efficient in providing particular ecosystem services as many, very similar species (c.f. Rahman et al., 2021). This hypothesis notwithstanding, biodiversity can be one of the multiple aims and goals of an intervention, and in many cases taxonomically or functionally diverse communities will provide services as well as explicitly designed communities of mangrove species. Genetic (intraspecific) diversity, on the other hand, might be low in naturally recovered mangrove forests, if the supply of propagules is limited, and active planting and designing communities, e.g., following the concept of assisted evolution (aiming at increased ecosystem resilience through enhancing evolutionary processes in key species: see § The role of genetic diversity in (re-)establishment), can be a solution against genetic impoverishment.

The sequestration and storage of organic carbon in the sediment of mangroves depends on many species-specific and environmental factors (e.g., Kathiresan et al., 2013; Zimmer and Helfer, 2020), and increases with ongoing development of the vegetation (e.g., Jimenez et al., 2021, in Northeast Brazil; but see Carnell et al., 2022). Any intervention that aims at improving the capacity for blue carbon storage will have to take these factors into account, and in this context, old-growth forests might not be the aim. For instance, the leaf litter of young (e.g., replanted) *Rhizophora apiculata* has been reported to decay about 40% faster than that of mature trees of the same species in the Matang Mangrove Forest of Malaysia (Pradisty et al., 2021).

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[3] visible at Lat 20.1723 Long 92.9132.

While, on one hand, this will release some CO_2 faster into the atmosphere and will leave less litter material to be buried and decomposed by the fauna, it will, on the other hand, release more processed litter material into the sediment porewater for being stored in a stable form (while still leaving recalcitrant litter material for being buried by crabs). Hence, dense cohorts of young saplings might contribute better to the sequestration of organic carbon into the sediment than naturally thinned-out stands of mature trees. For a practical examination of this idea, controlled small-scale harvesting of mangroves was recently suggested as a measure of nature-based climate solutions for climate change-mitigation (Murdiyarso et al., 2021), and this notion has been corroborated by the observation that carbon sequestration and storage rates do not increase continuously with stand age but level out upon stand maturation (Carnell et al., 2022). Following the rationale of Ecosystem Design, replanting of mangroves in the harvested areas would then have to target species with high CO_2-sequestration rates and efficient storage of organic carbon in their biomass (e.g., fast growth rates or high wood density) and in the sediment. Furthermore, under the rationale of Ecosystem Design, the intervention might not be limited in time but might require regular action (in this specific case: harvesting) to maximize carbon sequestration, if this aligns with the needs of the local stakeholders.

Components of mangrove forests other than the trees are often ignored in intervention efforts, with an assumption that the fauna and/or microbiota will follow the flora and establish itself once the trees have been planted or recruited (Martínez-Espinosa et al., 2020). As early as 2001, Holguin et al. stressed the importance and potential of utilizing tailor-made microbial communities in the process of mangrove rehabilitation. Ecosystem Design explicitly includes the implementation of animals (and microbes) that contribute to ecosystem service-provisioning through interacting with the vegetation in driving ecosystem processes when and where feasible. Thus, the aim of re-establishing a degraded ecosystem can be facilitated by colonizing the degraded or newly formed habitat with flora, fauna and microbiota. Alternatively, to-be-established sites can be selected to be nearby mangrove stands with suitable source populations for these biota (Dahdouh-Guebas and Cannicci, 2021).

In a broader sense, Ecosystem Design can be subsumed under Nature-based Solutions, aiming at solving societal challenges through natural drivers and processes. Nearshore infrastructure development and mangrove loss can cause severe erosion by disturbing the fine sediment balance and tidal flows. One approach to reduce erosion and mitigate wave action is “Building with Nature,” which involves combining both vegetation and hard engineering components in aquatic habitats (see, e.g., Albers et al., 2013, in Vietnam). Another example is the installation of two breakwaters made of rocks (therefore described as green-gray engineering) in Ajuy, Iloilo, Philippines, that reduced wave energy and increased sediment level by 50 cm over 6 years and created an accretion area of 4,000 m^2 (Furukawa et al., 2019). Regular yearly plantings of *A. marina* and *S. alba* seedlings survived only after three years when the sediments became firm enough to support mangrove establishment and high enough to drain sufficiently at low tide. Therefore, a community designed from these two species as early successional pioneers appears to be the best solution for implementing mangrove stands under these particular conditions and for this particular purpose.

The role of genetic diversity in (re-)establishment

An important but often neglected aspect of planting mangrove propagules from adjacent forests is their (intraspecific) genetic diversity. Genetic diversity in natural populations is a fundamental component of biodiversity that affects both the resilience of the population toward environmental change and the evolutionary potential of a population or species, i.e., its ability to adapt to changes in environmental conditions and community structure. Loss of genetic diversity increases the vulnerability of populations and their risk of extinction through the loss of adaptive traits (Amos and Balmford, 2001; Keller and Waller, 2002; Frankham, 2005; Ragavan et al., 2017). In addition, population viability is strongly related to effective population size (i.e., the number of individuals contributing their genes to the next generation), with small populations suffering from increased homozygosity and consequent accumulation of recessive deleterious alleles due to inbreeding, and potential fixation *via* genetic drift, which compromises the reproductive fitness of individuals (inbreeding depression).

The management of genetic diversity has a key role in promoting adaptive responses of forests to environmental changes and thereby mitigating deleterious effects of climate change (FAO, 2014; Cortés et al., 2020). In some instances, assisted gene flow (e.g., through active planting) or assisted evolution (which involves deliberately enhancing evolutionary processes leading to resilience, i.e., helping species to adapt to a changing environment more rapidly than through natural evolutionary processes) have been proposed as conservation approaches to aid species persistence and adaptation under climate change (see, e.g., Gaitán-Espitia and Hobday, 2021, and references therein). Management of genetic diversity encompasses both neutral and adaptive genetic diversity; their joint assessment is now facilitated by genomic approaches (Allendorf et al., 2010; Breed et al., 2019). While many terrestrial forest restoration programs incorporate genetic information to strengthen the resistance and resilience of forest ecosystems to environmental changes, restoration programs for marine ecosystems–including mangrove forests–have rarely done so, partly due to a lack of empirical data on genetic diversity and structure of the studied ecosystem, or to the complexity and costs of genetic/genomic approaches (Coleman et al., 2020). To the best of our knowledge, no mangrove (re-)establishment program have thus far considered genetic information in their planning phase (only in the monitoring phase; e.g., Granado et al., 2018), despite the increase in knowledge about genetic variation in mangrove ecosystems gained over the last two decades (e.g., Dodd et al., 2002; Triest, 2008; Wee et al., 2015; Hodel et al., 2018; Azman et al., 2020; Mantiquilla et al., 2021; Triest et al., 2021).

Active planting of propagules can be considered a special case of assisted gene flow (Vanderklift et al., 2020). In this context, it is essential to consider the genetic composition and diversity of the propagules deployed and adjust the choice of their origin based on the aims of the intervention (restore to historical baselines vs. redefine for new–current or future–conditions; Coleman et al., 2020).

We here recommend considering genetic aspects in mangrove management programs to ensure (i) the maintenance of a sufficient level of genetic diversity to sustain population viability and species evolutionary potential, and (ii) the use of propagules with appropriate genetic composition to favor adaptive traits for current and/or future environmental conditions while avoiding outbreeding depression in case of genetic exchange with neighboring populations (for newly established stands in afforestation programs) or remnant individuals from the former population (for re-established stands in reforestation programs). When direct assessment of neutral and adaptive genetic diversity is not possible due to financial constraints, the origin and quality of propagules should still be carefully considered, using indirect measures, such as number of parent trees or populations from which the propagules originated, environmental conditions in the populations of origin, or phenotypic characteristics (e.g., Melville and Burchett, 2002, for *Avicennia*; Ng et al., 2015, for *Rhizophora*; Guo et al., 2018, for *Lumnitzera*). Hands-on protocols that can be applied by practitioners onsite are urgently needed here.

When are mangrove (re-)establishment efforts successful?

To decide whether any specific mangrove (re-)establishment effort has been successful, "success" needs to be defined. The key measure of success is achieving the explicit aim of the intervention. Hence, the goals and aims of mangrove (re-)establishment need to be clearly identified and outlined by all stakeholders before starting the implementation, including an *a priori* definition of criteria of success based on the aims of the intervention (**Figure 3**).

Numerous factors drive the specific goals of individual interventions, such as the history of the degraded site, the cause(s) of local or regional mangrove loss, and the local status of mangrove stands and their protection. Most importantly, the needs, requirements and demands of local and regional communities, and their consideration in the implementation of aims and goals, will be decisive for the success or failure of the intervention.

Large-scale mangrove planting projects are often driven by high profile governmental (Wodehouse and Rayment, 2019) or international targets translated into quotas of numbers of hectares or seedlings to be planted within a given timeframe. Such quotas may incentivize poor choices of species and sites. For example, large-sized propagules that are easily procured and planted, such as of species of the genus *Rhizophora*, become the default choice within the low mangrove zone, instead of eco-physiologically more appropriate *Avicennia* spp. or *Sonneratia* spp. (in the Indo-Pacific region). Large areas of mudflats below mid-tidal level that can be rapidly planted are often chosen, regardless of their ecological unsuitability for mangrove growth (Primavera, 2005; Primavera and Esteban, 2008; Primavera et al., 2012b). In this context, the definition of success becomes the percentage of quota achieved during the implementation rather than the percentage of mangroves that survive beyond a suitable timeframe, while it is only long-term monitoring of (re-)established mangrove stands that allows for determining the ecological success. As a consequence, mangrove-planting efforts are often a failure. In Sri Lanka, more than 90% of planting attempts showed no success five years after implementation (Kodikara et al., 2017a). In the Philippines, the long-term survival of mangroves was as low as 10–20% (Primavera and Esteban, 2008). Out of 48 (re-)establishment sites in south Asian countries, 46%, with a total area of almost 128,000 hectares, show severe failure (Worthington and Spalding, 2018).

Stressors and disturbance

Many studies have demonstrated the importance of considering major disturbances and stressors that commonly appear in mangrove re-establishment sites (Mafi-Gholami et al., 2015a,b; Lewis et al., 2016; Duke et al., 2017, 2022; Kodikara et al., 2017a; Salmo et al., 2019). For instance, re-establishment sites along the Sri Lankan coast regularly experience cattle-trampling and -browsing, algal accumulation through flotsam collection or insect attacks (Kodikara et al., 2017a). Furthermore, the mouths of Sri Lankan (and South African: Adams et al., 2004) lagoons silt up and close during the dry season, resulting in water and run-off that is impounded at the start of the rainy season,

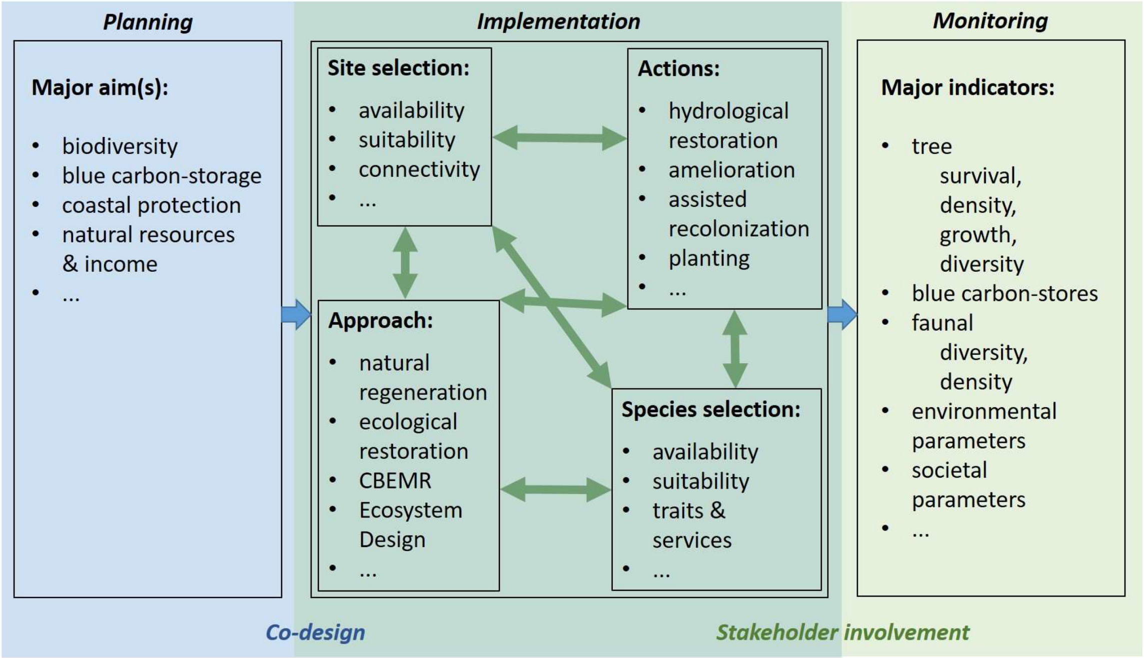

FIGURE 3
Conceptual scheme of major steps and decisions during planning, implementing, and monitoring the success of, mangrove (re-)establishment. Blue arrows depict the progress of action, green arrows show dependencies of decisions.

drowning the planted mangroves, before the lagoon mouths finally break open again. Therefore, along with continuous monitoring efforts (see § Monitoring), additional interventions such as supplementary planting when needed, removal of weeds, pests (e.g., barnacles) and trash, preventing cattle-grazing or -trampling and removing silt from channels, where necessary, might be necessary to increase the chances of success (Lewis and Brown, 2014). However, while disregarding such disturbances or stressors has reduced the restoration success (Kodikara et al., 2017a), mitigating these stressors might be difficult, impossible or inappropriately expensive. Hence, early assessment and identification of common disturbances and stressors at potential mangrove (re-)establishment sites is mandatory during the planning process, and taking agents of disturbance or stress for young seedlings into account is imperative: "the period between dispersal and recruitment to sapling stage" is critical for mangrove settlement success (Krauss et al., 2008; Van der Stocken et al., 2019). Their early detection, preferably during site research before any intervention has taken place, will help to alleviate much of this early seedling mortality. For instance, Gillis et al. (2019) provide evidence for hampered root development under conditions of high nutrient exposure (e.g., from aquaculture effluents). Poorly developed roots will result in reduced resistance of saplings to being uprooted by heavy wave action or storm surges. Allowing for the development of root structures in nurseries prior to planting might help overcome the consequences of elevated nutrient loads, but this additional step will not render measures to reduce nutrient input to mangrove habitats unnecessary. Another reason for increased risk of uprooting of seedlings or saplings may be connected to the density at which they are planted. Le Minor et al. (2019) used a numerical model of sediment dynamics around *Rhizophora* seedlings to show that under given conditions of water flow and sediment load, the distance among seedlings determines sediment dynamics (i.e., sediment accretion vs. removal) around seedlings. In some areas, for instance the Matang Mangrove Forest Reserve, different species are planted at different distances (*R. apiculata*: 1.2 m vs. *Rhizophora mucronata*: 1.8 m) (Arifin and Mustafa, 2013; Goessens et al., 2014). While these precautions seem to be based on experience rather than modeling sediment dynamics, any potential driver of (re-)establishment failure should be evaluated empirically or through modeling upfront.

Societal aspects

Beyond these rather technical issues, a central *sine-qua-non* for successful mangrove (re-)establishment is involvement of, and acceptance by, local actors and stakeholders. In a comprehensive literature review, Dale et al. (2014) identified a "gap in integration between human and ecological components" as a major driver of mangrove (re-)establishment failures. From the very first plans of actively intervening through the different phases of implementation (co-design, jointly with local and regional stakeholders, scientists and practitioners) to the final monitoring of the outcome of the implemented action(s), social and societal needs, requirements and demands are decisive (**Figure 3**). Convincing incentives and benefits to users of natural resources and other ecosystem services are essential for sustained stakeholder engagement. While this is surely accounted for by both CBEMR and Ecosystem Design, the relevance and importance of stakeholder involvement has started to be considered in mangrove (re-)establishment efforts only rather recently.

Local communities must be engaged and actively support the intervention for mangrove (re-)establishment to be successful. Even upon successful initial (re-)establishment of thriving mangrove stands, long-term survival will only be assured if local stakeholders engage in sustainable use and management of the ecosystem and its natural products and services (e.g., Goessens et al., 2014; Hugé et al., 2016; Martínez-Espinosa et al., 2020). Two of the many obstacles in this context are access- and usage-rights. Local stakeholders will most likely engage in mangrove (re-)establishment and subsequent management if they are assured of access rights and benefits, or if adequate and accepted alternatives for income and livelihood are offered. Thus, higher level policies and governance must be adjusted to the needs arising from combined sustainable management and wise use of (re-)established mangrove forests. Criteria for successful mangrove (re-)establishment on a societal level, hence, include employment, income and (alternative) livelihoods, raised awareness and developed capacities, particularly in the context of gender equality and equity.

Monitoring

The success of mangrove (re-)establishment can then be measured in several ways, e.g., through vegetation characteristics (Ellison, 2000), species diversity (Passell, 2000), ecosystem processes (Rhoades et al., 1998), such as organic matter turnover, or the societal aspect of ecosystem services (Huxham et al., 2017). Over the last decade or so, ecological processes in (re-)established as compared to natural mangrove forests were of high concern in estimating the success of the intervention (McKee and Faulkner, 2000; Lewis, 2005, 2009; Bosire et al., 2008; Lewis and Brown, 2014). Simple measures that can be obtained by monitoring the development of the (re-)established mangrove area include survival and growth of seedlings and saplings, canopy cover and closure, leaf area index or estimating aboveground biomass from forest structure surveys and the use of species- and region-specific allometric equations (e.g., Ong et al., 2004; Komiyama et al., 2008; Vikrant et al., 2011), as well as some of the many available diversity indices. However, monitoring should also incorporate the succession of the associated fauna, such as insects, crabs (Ashton et al., 2003; Salmo et al., 2019), snails, fish, shellfish, birds and mammals, as a recent functional analysis in some of these taxa reveals extremely low redundancy across mangrove forests worldwide (Cannicci et al., 2021). Rarely have the invertebrate infauna of the sediment been considered, as our knowledge on the taxonomy of this cryptic group is still in its infancy, and their investigation is time-consuming. Modern techniques of meta-barcoding or metagenomics of environmental DNA may soon render diversity assessment easier, provided that taxonomic and ecological knowledge about the infauna is further improved in parallel. The same applies to microbes (bacteria, archaea, fungi, microalgae, and protists) both in the sediment and the water body, where microbiome profiles provide insight into the development of (re-)established ecosystems. While recognized as essential players in numerous ecosystem processes, our understanding of this ecosystem component is still limited (Saravanakumar et al., 2016; Allard et al., 2020; Mai et al., 2021).

In addition to these biotic factors, changes in sediment characteristics, such as increasing sediment organic matter content, i.e., "blue carbon" storage, salinity and N- or P-content, are sometimes also suitable indicators of successful mangrove re-establishment (Grueters et al., 2021). For example, in the mangrove system of the Ciénaga Grande de Santa Marta, Colombia, which provides a model case-study of mangrove rehabilitation for the Americas, increased salinity due to anthropogenic interference with the natural hydrological conditions was a major cause of mangrove mortality. Accordingly, measures were taken to restore natural hydrological conditions with the aim to enable mangrove recovery (e.g., Perdomo Trujillo et al., 2020).

An early model of trajectories of mangrove attributes (Twilley et al., 1998) predicted that, depending on the timeframe of salinity amelioration toward suitable conditions, 50–75% of the values of basal area from a nearby reference sites would be reached within 40 years of active intervention. After about 30 years of intensive restoration activities in the Ciénaga Grande de Santa Marta, the management of hydrological conditions and their effects on salinity conditions (Jaramillo et al., 2018) proved to have affected both above- and belowground blue carbon stocks (Perdomo Trujillo et al., 2020). Along the same line, restoration efforts in karstic mangrove areas of Yucatán (Mexico) significantly reduced sediment salinity, resulting in successful regeneration of mangrove structure (Teutli-Hernández and Herrea-Silveira, 2016). Here, long-term monitoring and maintenance followed thorough planning, including selection of suitable sites, definition of goals and site-specific restoration action (see Zaldívar-Jiménez et al., 2010, for further details).

Thus, monitoring mangrove (re-)establishment success should encompass both floristic and faunistic surveys, as well as characterization of environmental conditions (Lewis and Brown, 2014; Ragavan et al., 2020). Most importantly, however, any monitoring of the development of (re-)established mangrove stands should include nearby reference sites of natural or old-growth mangrove forests (e.g., López-Portillo et al., 2017). Only by doing so it is possible to compare the processes in a (re-)established mangrove stand with what would be expected in a mangrove forest of a given species composition in a given region.

It takes several decades after establishment of a mangrove stand to reach forest maturity with respect to vegetation and sediment characteristics (Salmo et al., 2013, in the Philippines; Sillanpää et al., 2017, in Indonesia; Elwin et al., 2019, in Thailand; Twilley et al., 1998, in the Colombian Caribbean). While the mangrove vegetation in a *Kandelia obovata* stand in southern China attained a mature state with macro-benthic fauna at an age of about 20 years, younger mangrove forests seem to exhibit a higher richness of macro-benthic species than older ones (Chen et al., 2007), and the carbon storage capacity of restored mangrove forests increased with age during initial stages of establishment, but sequestration rates do not increase further upon maturation (Carnell et al., 2022, in Australia). Such observations need to be taken into account when monitoring the success of active interventions, and all parameters used as proxies for (re-)establishment success must be viewed in the light of comparison with nearby healthy and thriving mangrove forests as reference ecosystems (c.f. Dencer-Brown et al., 2020; Rog et al., 2020).

Whereas success is sometimes reached already when specific objectives of the project are met, (re-)establishment efforts can generally be considered successful if the provisioning of ecosystem services is similar to that of natural mangrove forests (Bosire et al., 2008). As many ecosystem processes, such as sediment-trapping, and nutrient- and organic matter-turnover (Bosire et al., 2008), depend on specific characteristics of the flora and fauna (Ellison, 2000), assessment of those parameters that help predict ecosystem service-provisioning by (re-)established mangroves is imperative. This kind of evaluation was conducted in several studies, for instance in the Matang Mangrove Forest Reserve (Malaysia) and in the Sundarbans (India) (e.g., Putz and Chan, 1986; Eong, 1995; Hussain, 1995) and following extensive planting in Gujarat, in part to protect and enhance local fisheries (Das, 2017). However, while monitoring is mandatory and should be considered during the very first steps of planning to make sure that local communities engage in it in the long-term, funding for mangrove (re-)establishment projects often does not cover a long enough time span for monitoring progress beyond a few years.

Outlook and recommendations

Protecting and conserving existing, old-growth and mature mangrove forests is of pivotal importance. Legislative protection of mangrove forests (despite the often poor enforcement) has prevented some areas from being lost and thereby has supported natural recovery of nearby degraded habitats. Laws and their enforcement should be improved, and monitoring implemented, for better protection of existing mangrove forests, their processes and the many services and benefits to humankind that they provide (Ragavan et al., 2020).

In addition to mangrove protection, active intervention is required, and sadly, decades of mangrove (re-)establishment efforts, with sometimes huge investment of money and time, have not reversed global mangrove area loss thus far. While our understanding of mangrove ecosystems, their processes and how their components interact, has improved greatly over the past decade, active interventions for mangrove (re-)establishment remain unsuccessful in many cases. We hold that the lack of thorough planning is one major reason for many of these failures. When there is no proper plan, mangrove (re-)establishment is pointless:

The decision to (re-)establish mangroves ("whether?") at a site needs a strong reason to do so ("why?") and a clear vision of aims and goals. Both are intimately linked to the decision about the approach ("how?") and the site ("where?"). Site selection for mangrove (re-)establishment must acknowledge the natural habitat of mangroves in the mid- to high-intertidal zone and the species-specific small-scale distribution within this zone. Planting below mid-tidal level is not only ecologically unsuitable for mangroves, but also potentially damages other valuable ecosystems (e.g., seagrass meadows). The range of suitable intertidal habitats with (muddy) soft sediment will in the future likely include open sediment stretches that are newly established due to relative sea level-rise or changed hydrodynamic conditions. While there is no clear guidance yet on limits for establishing mangroves in previously non-mangrove areas, we should not principally consider unvegetated areas off limits. Indeed, mangrove areas are shifting with climate change, but natural range shifts are sometimes prevented by human infrastructure and other disturbances, therefore resulting in mangrove area reduction; establishing mangrove in previously unvegetated areas could compensate for this reduction. If we did not proactively take future environmental conditions and settings into account when planning for mangrove (re-)establishment, we would potentially miss opportunities for increasing mangrove areas regionally. Ultimately, a coastal system that provides the ecosystem services needed locally or regionally might reflect a mosaic of ecological elements in balance. Judgment, based on historic and regional reference, or consideration of other ecosystem uniqueness and rarity, should be drawn upon when determining the extent and place of mangrove establishment.

Detailed analyses of the environmental and societal conditions of potentially appropriate sites will produce a higher chance of successful (re-)establishment. Favorable hydrological conditions are essential for any intervention to be successful, and restoring connectedness to adjacent ecosystems may render planting unnecessary in the long run. The choice of the approach to be used and the species to be (re-)established requires ecological consideration according to local (small-scale) environmental conditions and the availability of propagules, but should also take into account the needs of local communities for ecosystem services and species-specific contributions to the provisioning of these services. Hence, the involvement of local stakeholders from the very first steps of planning, as well as *a priori* clarification of property- and use-rights, and how the long-term protection and maintenance of the site is ensured, are crucial for successful intervention.

Long-term monitoring of the (re-)established mangrove stand and its various components and compartments, such as flora, fauna, microbiota and the sediment, in comparison to adjacent intact, healthy and mature mangrove forests is highly desirable. Such monitoring, in relation to clearly formulated aims and goals, is the only way to properly distinguish between successful and failed interventions. Lessons learned from such efforts will improve the success of future mangrove (re-)establishment efforts when translated properly according to local ecological and societal conditions.

This article provides recommendations for best practices–to be adapted to local peculiarities and conditions–to increase the probability that (re-)established mangroves stands will provide ecosystem services needed regionally and will be able to face challenges of global change in our changing world.

Author contributions

MZ and DW coordinated the author consortium. MZ and VH took responsibility for the manuscript revisions and final proof-reading. All authors contributed equally to the writing of the manuscript.

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Conflict of interest

SCo was employed by Silvestrum Climate Associates.

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