Ecosystem Design: When Mangrove Ecology Meets Human Needs

16

Martin Zimmer

Abstract

At least two thirds of all ecosystems worldwide have been impacted and changed severely by human activity (MEA Millennium ecosystem assessment – ecosystems and human well-being: biodiversity synthesis. World Resources Institute, Washington, DC, 2005), mostly without considering consequences for the structure, functioning or service-provisioning of these ecosystems. The societal challenges arising from this are twofold: conserving natural heritage and resources, and at the same time providing and sustaining valuable livelihood and well-being for mankind. Once we missed the chance of preserving an ecosystem from degradation through conservation, restoration is the attempt to repair (i.e., bringing back to a past state) or otherwise enhance (i.e., promoting remaining components and structures) the function of an ecosystem that has been impacted (Suding KN, Annu Rev Ecol Evol Syst 42:465–87, 2011) into a state that warrants historical continuity (Murcia C et al., Trends Ecol Evol 29:548–553, 2014) and closely resembles natural conditions. Nevertheless, most restoration efforts lack a clear aim, and monitoring is rarely considered. Hence, an evaluation of restoration success is difficult, if not impossible. As an alternative to restoration, a new five-step concept of directed design for novel ecosystems (sensu Hobbs RJ, Arico S, Aronson J, Baron JS, Bridgewater P, Cramer VA, Epstein PR, Ewel JJ, Klink CA, Lugo AE, Norton D, Ojima D, Richardson DM, Sanderson EW, Valladares F, Vilà M, Zamora R, Zobel M et al., Glob Ecol Biogeogr 15:1–7, 2006; Morse NB, Pellissier PA, Cianciola EN, Brereton RL, Sullivan MM, Shonka NK, Wheeler TB, McDowell WH et al., Ecol Soc 19:12–21, 2014) with defined functions and services is presented in this chapter. Recent advances in restoration ecology pledge for accepting unintended novel ecosystems as valuable providers of ecosystem services in restoration efforts (Perring MP, Standish RJ, Hobbs RJ et al., Ecol Process 2:18–25, 2013; Abelson A, Halpern B, Reed DC, Orth RJ, Kendrick GA, Beck MW, Belmaker J, Krause G, Edgar GJ, Airoldi L, Brokovich E, France R, Shashar N, De Blaeij A, Stambler N, Salameh P, Shechter M, Nelson PA et al., Bio Sci 66:156–163, 2016). Ecosystem Design develops this idea further to intendedly designing novel ecosystems with the aim of providing particular services that are locally or regionally required for the well-being of mankind. Thus, in contrast to conventional restoration, Ecosystem Design places humans and their needs in the center of action. For this, Ecosystem Design first assesses local and regional needs for ecosystem services to be provided. Second, Ecosystem Design defines a set of these services as goals for the establishment of a functioning ecosystem in a degraded area. In a third step, a toolbox of information on species characteristics and requirements, as well as on the species-specific contributions to service-provisioning, including interspecific interactions under the given environmental conditions, recommends a set of suitable species from the regionally available species pool. Such a toolbox requires trait-based models to determine which species assemblages are most effective (Laughlin DC, Ecol Lett 17:771–784, 2014) in providing the desired ecosystem services, and the choice of suitable and appropriate species would be facilitated by knowledge of previous community composition. The set of initial species will, in a fifth step, be installed in the degraded area, and subsequent natural succession will shape and fine-tune this novel designed ecosystem (unless this semi-natural development deviates from the aim of providing particular ecosystem services,

M. Zimmer (✉)
Department of Ecology, Leibniz Centre for Tropical Marine Research, Bremen, Germany

University of Bremen, Faculty 02 Biology/Chemistry, Bremen, Germany

IUCN-SSC Mangrove Specialist Group, Bremen, Germany
e-mail: martin.zimmer@leibniz-zmt.de; martin.zimmer@uni-bremen.de

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when counteraction to semi-natural succession will be required). Upon installation and subsequent development of the designed ecosystem, long-term monitoring in the sixth step will allow for evaluating the success of the design and intervention if needed, since clear aims and goals had been defined in the second step of Ecosystem Design. Whereas this approach may in cases contrast efforts to conserve or restore biodiversity on its own sake, Ecosystem Design aligns with the Sustainable Development Goals of the United Nations in warranting human well-being in times of increasing demands for ecosystem services, especially in tropical coastal areas with ever-growing population sizes.

Keywords
Ecosystem Services · Service-Providing Unit · Novel Ecosystems · Directed Ecosystem Restoration

16.1 Introduction

16.1.1 Mangrove Restoration

Once we missed the chance of preserving an ecosystem from degradation, rehabilitation is considered a valuable alternative to conservation. Whereas rehabilitation aims at the replacement of the initial structure and function of an ecosystem, restoration – a special case of rehabilitation – is the process of assisting the recovery of an ecosystem back to its original condition as nearly as possible (Field 1998; Ellison 2000; Alexander et al. 2011). To this end, restoration is the process of repairing damage caused by humans to the diversity and dynamics of indigenous systems (Fig. 16.1). Thus, the aim of restoration is a functional ecosystem providing similar services as the original ecosystem. It is common sense that, apart from biological considerations, restoration ecology should include historical, social, cultural, political, aesthetical and ethical aspects.

Mangroves, growing on soft-sediment shores along many tropical and subtropical coasts, are among the most productive ecosystems and provide numerous ecosystem services both to local human populations and to mankind worldwide. Mangrove area loss proceeds at a rate that exceeds area loss of most other ecosystems (Bradshaw et al. 2009; Wabnitz et al. 2010; Giri et al. 2011). However, recent attempts of mangrove reforestation or restoration largely failed, because most of them were not based on scientific knowledge about the ecology and (intertidal) distribution of regionally occurring mangrove species (e.g., Elster 2000; Primavera and Esteban 2008; Lewis 2009; Alexander et al. 2011): owing to practical problems of site-selection (Field 1998), many attempts of mangrove reforestation used the "wrong species" in the "wrong environment", without taking into account species-specific requirements for habitat characteristics and location along the intertidal gradient (see also: Elster 2000; Lewis 2005; Matsui et al. 2010, with respect to habitat hydrology). Another important environmental factor that drives mangrove species distribution, both regionally and along the intertidal gradient, that should be taken into account for restoration efforts is the geomorphological settings (Balke and Friess 2015). More generally speaking, successful active restoration that is based on plantation has to consider species-specific response traits (Hedberg et al. 2013; Laughlin 2014) that determine whether a particular species can cope with, and dwell under, given environmental conditions. Thus, the framework of response- and effect-traits (Lavorel and Garnier 2002) is essential for selecting appropriate sets of species with respect to the prevailing environmental conditions of the degraded and to-be-rehabilitated or-restored ecosystem. Alternatively, providing environmental conditions –e.g., elevation above sea level and inundation regime, or hydrology and hydrodynamics – that will support the settlement success of particular species seems pivotal in cases where the abiotic environment had been changed beyond thresholds (Lewis 2005; Matsui et al. 2010) – this, in turn, requires at least basic knowledge on species-specific response traits.

As comparably little information is available on successful versus failed mangrove restoration attempts, many of these programs seem to have been carried out without any reference to lessons that might be learnt from other similar programs, contributing to the overall little success worldwide. Notwithstanding the potential of rehabilitation or even restoration of degraded ecosystem, the long-lasting

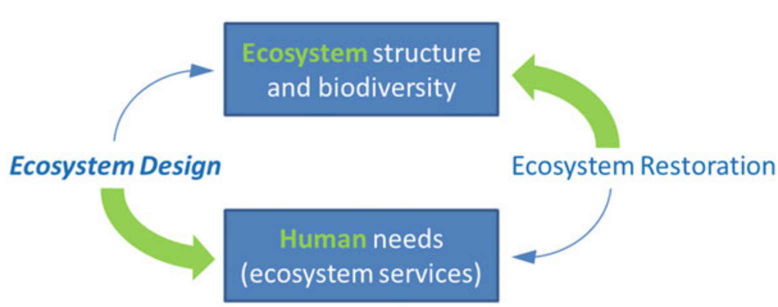

Fig. 16.1 Conceptual difference between ecosystem restoration, focusing on the ecosystem, and *Ecosystem Design*, focusing on human needs

aftereffects of mangrove degradation underscore the importance of eliminating its causes, since once sites are cleared of mangroves, it is difficult for them to recover without knowledge-driven intervention. Hence, planning mangrove reforestation or restoration should be based on scientifically sound knowledge, and any rehabilitation effort must be accompanied and monitored in the long term accordingly (c.f., Bosire et al. 2008; Alexander et al. 2011).

Unsuccessful restoration is a waste of time, money and human resources (c.f. Primavera and Esteban 2008). Hundreds of volunteers that invested time and energy in large-scale restoration campaigns must have been frustrated to see their efforts being washed away by tides and storm surges within months after having been planted. However, successful or promising examples have been implemented (c.f. Primavera and Esteban 2008; Alexander et al. 2011), e.g., through the community-based ecological mangrove restoration concept (CBEMR) of MAP (http://mangroveactionproject.org/).

Not surprisingly, naturally recovering mangroves (c.f., Kamali and Hashim 2011) might be more diverse than those restored through human action, and planting of mixed-species forests is recommended to maximize biodiversity (Alongi 2011). However, plant and crab biomass or density seem to be higher upon assisted than through natural restoration (Ferreira et al. 2015) and in reforested than in natural stands (Bosire et al. 2008; but see: Walton et al. 2007). Along the same line, protected mangroves exhibit much higher crab diversity than reforested mangroves in the Philippines, mostly owing to differences in sediment characteristics among the studied sites (Bandibas and Hilomen 2016). This leads to the question as to when rehabilitation is successful (c.f., McKee and Faulkner 2000; Ruiz-Jaen and Aide 2005). According to the aim of rehabilitation (as defined above), the answer lies in the successful re-establishment of ecosystem service-provision, and the performance of ecological processes has been suggested as one measure of restoration success (Ruiz-Jaen and Aide 2005; Walton et al. 2007; Vovides et al. 2010): regrown plantations might dwell, but a desired service might not be provided (i.e., restoration has failed: McKee and Faulkner 2000), possibly because most ecosystem services are not provided by a single species but by a community or at least a set of species, including microbial key players (c.f., Holguin et al. 2001; Berry and Widder 2014) that interact to drive underlying ecosystem processes. Interestingly, the success of mangrove restoration has rarely been estimated based on components other than the vegetation itself (but see: Macintosh et al. 2002; Bosire et al. 2008; Bandibas and Hilomen 2016), but if we include ecological processes driven by the fauna or microbiota, we will be able to better judge whether restoration was successful or not.

Along this line of how to best achieve a “functioning ecosystem” (whatever that is) upon restoration, the controversial discussion on whether coral reef restoration should be performed through artificial reef structures as hard substrate for settlement or by transplanting stocks from another, healthy reef is ongoing (Abelson 2006). The former is well-perceived in the public but has only weak scientific background, whereas the latter proves efficient and is based on a strong scientific background but is controversially perceived by the public. Obolski et al. (2016) suggest the re-establishment of grazing fish along with corals to support coral reef restoration, and Halpern et al. (2007), more generally pledge for considering (positive) ecological interactions in restoration-planning and -activities.

16.1.2 Novel Ecosystems

Human action inadvertently, or even deliberately, changes the ecosystems that surround us and are used by us. Hence, “novel ecosystems” (sensu Hobbs et al. 2006; Perring et al. 2013; Morse et al. 2014; Miller and Bestelmeyer 2016) have been established since humans started actively changing their environment by cutting forests and creating arable land. Forestry and agriculture act as designers of novel ecosystems with clear definition of goals. Similarly, fisheries management has since long ago adopted approaches of manipulating community composition in desired directions. Most human activities, however, intervene with natural systems without predicted or even predictable direction and result in undirected and unsupervised creation of novel ecosystems without clear goals and with uncertain outcome. It is interesting to note that these are widely accepted, whereas the **active design of a novel ecosystem** commonly encounters resistance, and the designers of such ecosystems have to face the reproach of acting as “playing god”. Novel ecosystems bear the chance of new species combinations that will result in the potential for changes in ecosystem processes and services (Hobbs et al. 2006). If a clear goal (with respect to ecosystem processes and services) is defined, it will be possible to actively use this potential and design communities and ecosystems that drive those processes that underlie the desired services (Perring et al. 2013), particularly where it is difficult –or even impossible– or costly to return to previous ecosystem states which is the aim of classical restoration (Hobbs et al. 2006; Fig. 16.1). As recently outlined by Miller and Bestelmeyer (2016), some recommendations even include that such considerations should be made regardless of the origin of the species that drive a given process, meaning that non-native species might also contribute to ecosystem service-provisioning. Contrarily, immigration of non-native species into degraded ecosystems is considered one of the reasons for unsuccessful restoration efforts

(Suding 2011). The primary aim of **ecosystem design**, however, should clearly be to rely on the native regional species pool and to (re-)establish those species that naturally occur and would naturally colonize the to-be-designed area, if supply was guaranteed. This, actually, is also one of the most promising approaches to undirected ("community-based") rehabilitation of mangroves (Primavera and Agbayani 1997; Lewis 2009), proposing that planting mangrove seedlings or treelings will be unnecessary, if suitable conditions for natural recruitment (e.g., in terms of hydrology and shore topography) are re-implemented (Kamali and Hashim 2011).

16.2 Service-Providing Units as Target of Ecosystem-Manipulation

16.2.1 The Rationale

Forestry and Agriculture are illustrative examples of novel ecosystems that have been created in a directed approach for centuries, aiming at growing plants that provide clearly defined ecosystem services (food). Aquaculture ponds are built (also on cost of previously existing ecosystems, such as mangroves) to produce fish or shrimp for human consumption and commerce.

A less essential need of many people is covered by gardening. Several, partly contrasting, services are expected from private gardens, such as small-scale production of fruit and vegetables, provision of a quite space for leisure and recreation, and/or provision of a small-scale habitat for birds and insects within an urban area. Depending on which service the individual gardener desires or requires, they will choose the species of garden plants and the design of the garden. Wild herbs or pest species will be removed and fought from vegetable plantations but maybe not from intended insect- or bird-habitats; flowering plants with either beautiful flowers or rich in nectar for insects and nutritious fruits for birds will be chosen for the insect- and bird-habitat, whereas breeds that promise high yield will be preferred for fruit- and vegetable-production. Contrasting services can be achieved by compromising designs of the garden or spatial partitioning and compartmentalization.

16.2.2 Plants

It becomes obvious from the above that many ecosystems are already shaped by human activity to support those plant species (and breeds) that best provide services of different qualities. Thus, natural forests, including mangroves, had been (and still are being) replaced by plantations of fast-growing producers of wood for construction, furniture or charcoal, or other products. Along this line, mangroves have been clear-cut for giving space to, e.g., oil palm-plantations, even though the particular conditions under which mangroves grow are suboptimal for oil palms, and their yield is way below the value local people might gain from sustainable use of mangroves. Notwithstanding that most of the new designation of previous mangrove areas will provide money and income to either local people or companies, most corresponding management plans do not seem to take into account the related loss of valuable and irreplaceable services provided by intact and functioning mangrove forests.

Green land (and forests) had been (are still being) turned into arable land and plantations, resulting in artificial ecosystems with extremely low species diversity that, however, highly efficiently provide the desired ecosystem service of feed- and food-production. For this aim, human society has since long accepted to loose local and regional biodiversity and the provisioning of services of natural ecosystems. As for gardening, we even accept the use of highly toxic pesticides and the introduction of non-native, potentially invasive, species; the long-term consequences are only recently begun being understood. Interestingly, and in contrast to the concept of novel ecosystems or ecosystem design, society is willing to invest time, energy and money into maintaining these artificial ecosystems in a stage that guarantees (close-to-)optimal productivity and production, without even considering –potentially irreversible– ecological side-effects of their intervention.

Along this line, it seems only logical to base restoration efforts of degraded ecosystems on those plant species that most reliably and effectively provide those ecosystem services that are needed under particular circumstances. This concept is being practiced when it comes to constructed artificial wetlands for treating municipal or industrial wastewater. If, for instance, the aim of such wetland, be it designed as freshwater swamp, or in coastal areas as saltmarsh or mangrove, is the extraction of excessive nutrients from aquaculture, the best results (i.e. the cleanest water) will be obtained by using plant species that are most efficient in nutrient-uptake (and -storage).

16.2.3 Animals

The management of fish stocks is clear intervention in a natural community with the aim of (ideally sustainably) providing income and food to local populations and mankind worldwide. The concept of understanding fisheries in the light of directly changing ecosystems becomes even clearer, when looking at aquaculture rather than wild catches of fish. Here, a single species (or, if "integrated multitrophic aquaculture", IMTA, is implemented, few species) that optimally provide(s) a service is/are introduced into a novel ecosystem and its service (food production) is used to gain income.

Huge areas of mangroves have been lost through clear-cutting for the implementation of land-based aquaculture, in particular for shrimp ponds. This has happened almost all around the world, but a strong regional focus lies on South-East Asia. When shrimp ponds have to be abandoned due to decreasing productivity (and income for the owner and workers) or disease, new mangrove areas will be clear-cut to give space to new ponds. Restoring ponds into functional mangroves is possible but tedious and time-consuming.

Alternatively, we could imagine to (re-)implement those abiotic and biotic environmental conditions that will support those animal species (e.g., crabs, shrimps or fish) in a degraded mangrove area that are desired by local societies to be used for subsistence fisheries or sustainable commercial fisheries. The targeted species would, in this case, not be the implemented one, but restoration of a mangrove ecosystem would aim at those mangrove species that best provide habitat for the target species of subsequent sustainable fisheries.

16.2.4 Microbes

Microbes are being used for producing numerous medical products and food (supplements), since microbiology has provided insight into the plethora of capabilities of bacterial or fungal strains. For instance, building a fermenter for the production of food is designing an artificial single- (or few-) species ecosystem.

Much less is known about specific contributions of microbes to ecosystem processes or even the provision of ecosystem services. The knowledge of microbial physiology has proven helpful in utilizing them for habitat-amelioration and -enhancement. For instance, introducing certain strains of bacteria into seawater that has been polluted by oil spills might be the most efficient way to fight long-term aftereffects of such spills (Dombrowski and Baker 2016). Doing so is clearly aim-oriented in that the service of oil-breakdown provided by these bacteria drives the decision on which species to introduce into a degrading ecosystem.

In the case of mangrove, the pivotal role of the sediment microbiota as driver of plant-nutrient interactions has been stressed with respect to mangrove conservation (Bashan and Holguin 2002). Along the same line, mangrove restoration could be assisted by ameliorating and improving habitat quality through establishing suitable microbial communities (Holguin et al. 2001; Gomes et al. 2010). Doing so in degraded previous mangrove areas would create an inhabitable environment for recolonization by mangroves, be it aided or natural. Assuming species-specific microbial communities of the rhizosphere of (c.f. Ramírez-Elías et al. 2014), or the sediment around (Selvam and Kathiresan 2010), mangrove trees, designing a sediment microbiota by selecting certain microbial species and strains might even be used to promote mangrove species that provide particular services better than others during re-colonization processes.

16.2.5 So What?

What humans have done for centuries is undirected and unsupervised alteration of ecosystems with unpredictable, and thus unforeseen, consequences for our natural environment. It is about time to take responsibility for what we are doing and supervise changes we pose on ecosystems in a desired direction. Why not take a step further and design communities of naturally occurring plant and animal species to provide particular ecosystem services that are required (or desired) in a particular area by re-implementing regionally natural ecosystems?

16.3 Ecosystem Design

16.3.1 The Concept

"Enhancing ecosystem services (. . .) are exciting new directions" in restoration practice (Suding 2011), but the role of ecosystem services is often ignored in management decisions which may cause continued degradation and destruction of mangroves (Barbier et al. 2011). As any effort of improving ecosystem service-provisioning upon restoration of degraded ecosystems has to encompass social-ecological as well as socio-economic considerations (Abelson et al. 2016), clearly defined services should be included as restoration goals and be measured as criterion of success. Meeting the goals of REDD+ of reducing greenhouse gas emissions and storing carbon in forest ecosystems (including mangroves!), for instance, requires science-based restoration-planning (Alexander et al. 2011), and choosing explicitly those species that are best at driving or providing any of these services might be promising.

One step beyond trying to restore previously degraded ecosystems with the aim of possibly re-gaining a handful of previously provided ecosystem services, I propose the even more promising approach to design novel functioning ecosystems in degraded areas from scratch, according to the services locally or regionally required (Fig. 16.1), taking into account local habitat peculiarities and other environmental conditions (be they natural or man-made) as well as the pool of regionally available native species as service-providing units (SPUs: see above). From this pool, we should re-establish a minimum set of species that, according to our understanding of ecosystem service-provisioning, are necessary to drive the designed ecosystem to providing the required service(s). Upon the initial establishment of foundation species, we can expect further species to immigrate from a regional pool and trigger the development of a more natural community (for review, see Ellison 2000; Matsui et al. 2010), and taking interspecific interactions (Halpern et al. 2007) into account, might even facilitate ecosystem design and planning which species to implement. Depending on such interactions of immigrating species with initially (re-)implemented species and their interference with the desired ecosystem process (es), such natural succession may, however, be counterproductive at some stage until further species establishment will stabilize ecosystem performance and functioning (with respect to service-provision), or "gardening intervention" (see above) will become necessary.

Thus, the choice of mangrove species to be (re-) implemented in a degraded coastal area, serving as foundation species (sensu Dayton 1971) and ecosystem engineers (sensu Jones et al. 1994), must not only be based on the regional pool of native species but should be made according to the ecosystem service(s) that are sought to be provided. For instance, not all mangroves accumulate carbon, and rates of forest floor accretion are directly linked to the frequency of tidal inundation, and thus, to the composition of the mangrove community (Alongi 2011). Even though this has never been actually measured in the field, there seems to be common agreement that *Rhizophora* prop roots are more effective in capturing sediment than *Avicennia* pencil roots, as it has recently been demonstrated for particular detritus being trapped amongst mangrove roots (Gillis et al. 2016). Similarly, the sequestration of detritus-derived organic matter in anoxic mangrove sediments upon decomposition of mangrove detritus results in climate-change mitigation through huge amounts of carbon and nitrogen being stored in stable compounds in a stable environment. The structure of the sediment organic matter, however, differs among mangrove species (V. Helfer and M. Zimmer, unpublished data), as well as does the composition of the microbial community that thrives on mangrove-derived organic matter in the sediment (Holguin et al. 2001). Thus, not all mangrove species might be equally suited for restoring sedimentary C- or N-stores (c.f. Matsui et al. 2010; Alexander et al. 2011; Vovides et al. 2011).

Whereas relatively few mangrove species have been used in rehabilitation projects (Field 1998; Primavera and Esteban 2008), selecting other species than the most commonly used ones might proof a better choice, both in terms of success and benefit. However, local and regional geomorphic settings, hydrology, currents and sedimentation patterns must be taken into account (Elster 2000; Lewis 2005; Primavera and Esteban 2008; Matsui et al. 2010; Kamali and Hashim 2011; Balke and Friess 2015), when selecting the species to be used for mangrove restoration. Pre-conditioning the newly designed habitat by introducing sediment microbes with particular traits and specific interactions with mangroves might be necessary, or at least helpful and advantageous, too. Along the same line, different tree species may be associated with different mangrove crab communities that, in turn, seem to depend on the presence of habitat-mediating trees (Dahdouh-Guebas et al. 2002). Some burrowing crab species (*Ucides* spp. and *Uca* spp.), but probably not all, act in reducing sediment salinity (Pülmanns et al. 2015), particularly during dry seasons (Pestana et al. 2017), or have an effect on other sediment characteristics such as organic matter content or redox conditions.

Ecosystem design, as proposed above, requires (Fig. 16.2)

- Basic knowledge of previous and current presence of species (flora, fauna, microbiota) with potential relevance for mangrove performance: e.g., metabarcoding of environmental DNA from sediments provides a useful tool for the rapid assessment of the composition of past and present communities (Taberlet et al. 2012; Thomsen and Willerslev 2015).
- Sound knowledge of environmental requirements of species: e.g., niche-modelling and knowledge of geophysical processes of coastal environments and climatic conditions can predict mangrove recovery under given environmental conditions (Twilley et al. 1998; Balke and Friess 2015).
- Detailed understanding of interspecific interactions and mutual dependencies: e.g., the re-establishment of mangrove trees might be promoted by inoculation of seedlings or saplings with appropriate growth-promoting microbes (Holguin et al. 2001) potentially serving as initiator of microbe-based interactions of ecosystem relevance (c.f., Berry and Widder 2014).
- Reliable predictability of how consortia of species and their interactions will drive service-relevant ecosystem processes, and how environmental conditions may act mediating: e.g., successful recovery of mangrove forests may be accompanied by reduced organic carbon content of the sediment due to reduced water content (Matsui et al. 2010); along this line, high-throughput assessment of sediment organic matter structure through, e.g., pyrolysis-GC/MS (py-)GC/MS) or Near Infrared Reflectance Spectrometry (NIRS) (Fuentes et al. 2012; Gerber et al. 2012; Kleinebecker et al. 2013; Tolu et al. 2015) may help predicting the spatial distribution of ecosystem processes that relate to C- and N-sequestration as it depends on the community composition and environmental conditions.

Provided that we have this basic information at hand, the five steps of Ecosystem Design can be implemented:

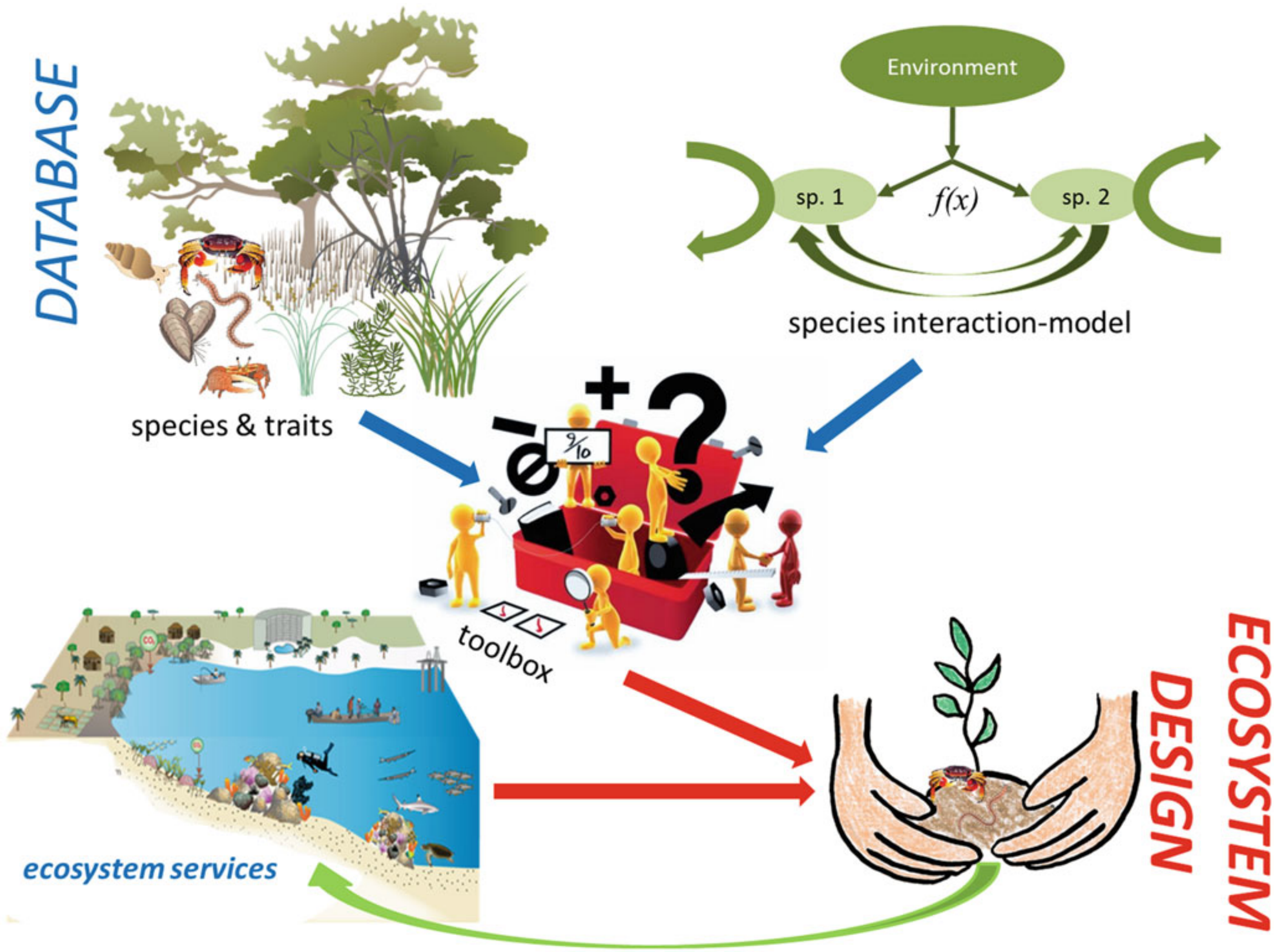

Fig. 16.2 The database of information on species and their traits and the species interaction-model jointly feed the toolbox that assists the design of an ecosystem to provide particular ecosystem services to society (Cartoons downloaded from www.clipartbest.com and ian.umces.edu)

1. Assess local and regional needs for ecosystem services to be provided.
   More specifically,
   Which ecosystem services should be provided?
   Which species and combinations of species drive those ecosystem processes that underlie these services?
   What are the specific characteristics of the target habitat?
   Which regionally occurring species are capable of thriving under these conditions?
   How will the habitat have to be modified (e.g., with respect to currents or hydrology) to support the establishment of target species and the provision of the desired services?
2. Define a set of these services as goals for the establishment of a functioning ecosystem in a degraded area.
3. A toolbox (Fig. 16.2) of information on species characteristics and requirements, as well as on the species-specific contributions to service-provisioning, including interspecific interactions under the given environmental conditions, recommends a set of suitable species from the regionally available species pool. Such a toolbox requires trait-based models to determine which species assemblages are most effective (Laughlin 2014) in providing the desired ecosystem services, and the choice of suitable and appropriate species would be facilitated by knowledge of previous community composition.
4. Install a set of initial species in the degraded area.
   Subsequent natural succession will shape and fine-tune this novel designed ecosystem (unless this semi-natural development deviates from the aim of providing particular ecosystem services, and counteraction to semi-natural succession will be required ("gardening intervention")).
5. Upon installation and subsequent development of the designed ecosystem, long-term monitoring will allow for evaluating the success of the design and intervention if needed, since clear aims and goals had been defined.

16.3.2 Toolbox for Ecosystem Design

As a toolbox for this process, we will need a database of species characteristics that will provide the information necessary to decide which species from a regional pool to implement into the to-be-designed ecosystem. A framework of response- and effect-traits (Hedberg et al. 2013; Laughlin 2014) will be essential for selecting appropriate sets of species with respect to being able to cope with the prevailing environmental conditions (response traits) and the provision of the desired ecosystem service(s) (effect traits). This requires a sound understanding of the species' environmental requirements, being reflected by their small-scale distribution along environmental gradients (Nobbs et al. 2015). On the other hand, if the geomorphological (Balke and Friess 2015) or hydrological (Lewis 2005) environmental settings of the degraded area do not meet the requirements needed as basis for restoration of mangroves, suitable environmental conditions have to be restored (Lewis 2005; Matsui et al. 2010). This, together with selecting species from the naturally occurring regional species pool is reflected in the conceptual approach of community-based ecological mangrove (mangroveactionproject.org/) and Ecological Mangrove Rehabilitation (www.mangroverestoration.com).

In many cases, of course, our understanding of species and their interactions with, and dependencies on, other species is still rudimentary and far from being deep enough to allow for such a toolbox (c.f. Ellison 2000). In some other cases of foundation or key species we might know enough to design simple functioning ecosystems and develop and implement those basal communities made up by minimum sets of species required to provide a particular ecosystem service. A simple, albeit relevant, example might be coastal protection through supporting sedimentation and preventing erosion. Mangrove species with extensive aerial root systems, such as *Rhizophora* spp., will be more effective in this regard, whereas species with dense sub-surface root systems, such as *Avicennia* spp., will better stabilize the existing sediment. A combination of both might be the best solution in terms of service-provisioning, but might not be realizable because of environmental requirements and conditions, or combining several species might conflict with the optimal provision of other services. Restoring mixed-species forests is recommended to maximize biodiversity, food web connectivity and net ecosystem production (Alongi 2011) but might counteract optimal ecosystem design, if a particular service was best provided by a monospecific stand.

The simultaneous re-establishment of edible crab species would additionally provide the basis for extracting food (and producing income) for local human populations. If, however, their burrowing activity counteracts sediment stabilization, we should refrain from co-establishing these crabs – they will, with a certain probability, establish themselves naturally with time upon assisted establishment of the basal ecosystem engineers. In some cases, co-establishment of unwanted species might even be actively prevented (see above: "gardening intervention"). Competing ecosystem services that would require different community compositions might then be handled by spatial mosaics of these different communities and compartmentalizing different sets of service-providing units, actually resulting in semi-natural situations, to simultaneously ensure the provisioning of contrasting services.

16.4 Outlook

It is still a long way to go, before we will be able to design ecosystems for more complex services, such as C- or N-sequestration, but our increasing knowledge about the ecophysiology of particular species and the dynamics of communities is paving the road – and in a time of ever-increasing ecosystem degradation and loss, it seems worthwhile taking this road, once ecosystems and their services are lost locally and their re-establishment is desired. Transferring findings derived from relatively species-poor, albeit highly productive, mangroves might prove beneficial for the restoration and design of other ecosystems (c.f. Ellison 2000) to sustain the provisioning of ecosystem services to local human populations and mankind worldwide.

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