INVITED FEATURE ARTICLE

Mangrove rehabilitation: a review focusing on ecological and institutional issues

P. E. R. Dale · J. M. Knight · P. G. Dwyer

Abstract Interest in mangrove rehabilitation has increased rapidly since 2003, as has awareness of the damaging effects of natural and anthropogenic pressures that contribute to mangrove loss, which is estimated at 1–2 % per annum. The major pressures are from urbanization and other development in all areas and forestry and fisheries especially where communities depend on mangroves for their livelihood. However rehabilitation success has been uncertain, reflecting gaps in integration between human and ecological components of the rehabilitation system. In particular there are government level issues of gaps and inconsistency in policy and failure in application. Some rehabilitation efforts have had limited success for several reasons including: having insufficient information, using inappropriate methods, not involving local communities, or not following all the steps in the processes that have been identified in the literature. A multi-disciplinary and integrated approach is needed to assist future planning and this needs capacity from a variety of areas in government, research and community. The review concludes with hope for a future where governments work with communities to develop policies and strategies for rehabilitating mangrove for resilience to changing environments.

Keywords Mangrove · Rehabilitation · Restoration · Environmental pressures · Government · Policy · Monitoring · Failure and success

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Introduction

Mangrove systems are threatened by both natural and anthropogenic processes that pose a risk for their long-term survival. This has received considerable attention in the literature with various estimates of mangrove loss world-wide in the order of 1–2 % annually (Duke et al. 2007). However, mitigation actions through restoration or rehabilitation can stem the losses and protect the services and values mangroves provide.

We reviewed the refereed literature to identify major issues in mangrove restoration and rehabilitation. There are three main components of the review. The first part sets the scene for rehabilitation, addressing definitions,

mangrove values, pressures and threats and the impetus for rehabilitation. The second part examines rehabilitation systems from the perspectives of both the human institutional and biophysical planning systems, including an overview of the rehabilitation process. The third part identifies and discusses major issues for rehabilitation: institutions and community, feasibility, failure and success and integrated approaches. Issues and gaps identified in the literature are summarised at the conclusion of each section or subsection.

Approach

The Web of Science and Scopus databases were searched for peer reviewed journal articles using the search terms '(mangrove OR mangal) AND restor*' and also '(mangrove OR mangal) AND rehab*'. A preliminary search for the terms in 'title keywords and abstract' (topic) yielded an Endnote library with 343 references for the combined restoration and rehabilitation searches after duplicates were removed. To narrow the search it was then restricted to the key terms in the title. This resulted in 65 references for 'restor*' and 21 for 'rehab*', a total of 86. This constituted the core information for the review. We limited the review as described because we considered that if the key terms were in the title then this was the primary focus of the research. However, additional references were subsequently obtained from the peer reviewed literature as considered relevant to the topic. References that were themselves reviews have been summarised in supplementary Table S1 as a reference source.

There has been a considerable increase in papers published on the topic after 2003 (see Fig S1). Overall 68 % of the total and 82 % of papers with an Asian context were published after 2003. Some explanatory factors may include the increasing public perception of the importance of environmental issues (e.g., Ren et al. 2008) or the recognition of the role mangroves can play in carbon sequestration to mitigate climate change (e.g., Alongi 2012).

Part 1: setting the scene

This section examines definitions, values (ecosystem services), pressures and threats and the impetus for rehabilitation.

What is meant by rehabilitation and restoration?

Terms used to describe an activity also establish expectations regarding desirability and achievability of the outcome. To clarify the concepts we will define what was, and now is, currently meant by the terms 'restore' and 'rehabilitate' and their derivatives. One of the earliest papers reviewed is that of Field (1998). Field contrasted rehabilitation with restoration, clearly differentiating between the two approaches and who used them. He argued that rehabilitation is the focus of land use managers and is concerned with replacing ecosystem structure or function that may be diminished or lost. In contrast, ecologists tend to focus on restoration as the act of returning an ecosystem back to, as much as possible, its 'original' condition; reflecting the definition of 'ecological restoration' from the Society for Ecological Restoration (Jackson et al. 1995). In Field's view restoration is a special case of rehabilitation, a view reflected by others such as Ellison (2000) and Chen et al. (2007) who regarded restoration as a goal of rehabilitation, and Gilman and Ellison (2007) who used rehabilitation as a generic term that included restoration. There are other views, some adopting relatively narrow definitions and others using the terms broadly and often interchangeably.

In the narrow view the term rehabilitation is not mentioned when reporting restoration (e.g., Hsu et al. 1998; Ruiz-Jaen and Aide 2005; Browder and Robblee 2009; Chen et al. 2009; Valentine-Rose and Layman 2011; Chen et al. 2012a; Rovai et al. 2013). Others are specific in defining restoration, describing the term as any process that is intended to return a system to a pre-existing state (Lewis 2005) or recovery (Lorenz and Serafy 2006).

Since around 2002 however, many papers use the terms broadly and do not clearly distinguish between them (e.g., Macintosh et al. 2002; Melville and Burchett 2002; Walton et al. 2007; Biswas et al. 2009; Matsui et al. 2010; Kamali and Hashim 2011; Ren et al. 2011; Rivera-Monroy et al. 2011; Rovai et al. 2012; Ye et al. 2013). Use of the terms interchangeably as in Turner and Lewis (Turner and Lewis 1997) has also been an increasing trend, although the terms *within* a text can often be distinguished in terms of process (rehabilitation) or goal (restoration) (Osuji et al. 2007; Moberg and Ronnback 2003; Hashim et al. 2010; Salmo et al. 2013). Combining the concepts, Vovides et al. (2011) used

the term 'functional restoration' and, although not clearly distinguishing this from rehabilitation, the concept could embrace both rehabilitation (function) and restoration (state).

Issues of definition

The early clarity of definition has been lost to some extent, as the terms rehabilitation and restoration have more recently been used less specifically. Nonetheless, the definition is important. High-level regulatory mechanisms (e.g., laws, policies) need clarity in order to minimize challenge over their application. Furthermore, consistent and agreed use of a definition is critical for managing expectations, in setting goals and monitoring outcomes for mangrove projects. In the light of these concerns, the use of the term 'rehabilitation' would reduce confusion as it encompasses the widest range of remedies for mangrove degradation. From here on we use the term 'rehabilitation', except where direct quotes use the term 'restoration'.

Mangrove ecosystem services in the rehabilitation literature

It is widely recognised that mangrove ecosystem services have a range of values for people, as noted in most of the rehabilitation papers reviewed (see details and references in supplementary Table S2). Barbier et al. (2011) provided a detailed review of estuarine ecosystem services and many papers provided a general review of the multiple roles of mangroves in supporting aquaculture and fisheries, in providing timber and fuel, in regulating atmospheric carbon and in protecting shorelines (e.g., Kairo et al. 2001; Bosire et al. 2003; Winterwerp et al. 2013) or listed specific services (e.g., Moberg and Ronnback 2003; Chen et al. 2012a).

Carbon sequestration is an important service that has recently been addressed by several authors (see Duke et al. 2007; Alongi 2012; Chen et al. 2012b; Donato et al. 2012; Matsui et al. 2012; Bashan et al. 2013; Rivera-Monroy et al. 2013; Winterwerp et al. 2013; Zhang et al. 2013). At a global level Giri et al. (2011) reported that mangroves had the capacity to sequester approximately 22.8 million metric tons of carbon each year. Losing mangroves will thus lead to reduced carbon capture and storage, with adverse climate change consequences (see Irving et al. 2011

for examples of losses of carbon capture and storage). Carbon sequestration is a compelling reason to rehabilitate mangrove forests.

References to socio-economic value tend to focus on developing countries where communities rely on mangroves for their livelihood (see Walters 1997). Valuing mangroves in economic terms is difficult. A useful overview of methods is in Boyer and Polasky (2004), for example, estimating the ratio of Benefits to Costs as a basic tool (referred to later in the context of feasibility). Socio-economic values also include aesthetics, (eco) tourism (Bosire et al. 2008; Mangora 2011) and education (Ren et al. 2011). That relatively few authors referred specifically to aesthetic and education values may reflect the difficulty of quantifying the benefits of aesthetics and education or of identifying all of the beneficiaries.

Issues and gaps

Competing land uses that threaten mangroves also limit rehabilitation opportunities. The economic approaches to assessing benefits and costs are for direct interventions to rehabilitate mangroves where damage or loss has already occurred. A question that is not usually addressed is: would the benefit-cost ratio of conserving or protecting existing mangroves (which may be relatively low cost) be higher than that of rehabilitation (which may be expensive and with success uncertain). This is discussed by Irving et al. (2011) and mentioned in Boyer and Polasky (2004). Also not addressed in the literature is the potential negative aspect of failed or ill-considered rehabilitation which has unintended consequences such as introducing ecosystem disservices (see Dale et al. 2014), for example, by providing habitats for water related health issues including mosquito-borne disease.

Having acknowledged the importance of mangroves we need to ask what are the pressures and threats that lead to mangrove degradation and loss? This is discussed next.

Pressures on and threats to mangrove systems

Mangrove rehabilitation is usually done to offset damage caused by stress arising from natural and anthropogenic changes in the environment that threaten the systems and result in degradation or loss.

Table 1 Stressors of mangrove systems as reported in the literature, by country (most recent first); + = included; ns = not stated or not specific; CC = Climate change

Major region/reference	Country	Carbon/CO2	Deforestation	Urbanization and development	Pollution	CC Temperature	Storm not only CC	CC Sea level	Modifying hydrology including freshwater	Agriculture and fertilizer	Fish and aquaculture
Asia											
Chen et al. (2013)	China			+							
Ye et al. (2013)	China						+				+
Zhang et al. (2012)	China		+	+	+	+					+
Chen et al. (2012a)	China			+							+
Ren et al. (2009)	China			+							+
Ren et al. (2008)	China		+	+					+		+
Chen et al. (2009)	China			+				+		+	+
Chen et al. (2007)	China		+	+						+	
Maliao and Polohan (2008)	Philippines			+							+
Primavera and Esteban (2008)	Philippines			+						+	+
Walton et al. (2007)	Philippines		+	+						+	+
Katon et al. (2000)	Philippines		+	+							+
Hashim et al. (2010)	Malaysia		+	+							
Aung et al. (2011)	Myanmar		+	+		+	+			+	+
Stone et al. (2008)	India			+							
Selvam et al. (2003)	India			+							
Wickramasinghe et al. (2009)	Thailand			+			+				+
Arquitt and Johnstone (2008)	Thailand		+	+					+		+
Winterwerp et al. (2005)	Thailand		+								+
Macintosh et al. (2002)	Thailand		+	+						+	+
Tri et al. (1998)	Vietnam					+	+			+	+
Winterwerp et al. (2013)	Asia		+	+		+		+		+	+

Table 1 continued

Major region/reference	Country	Carbon/CO2	Deforestation	Urbanization and development	Pollution	CC Temperature	Storm not only CC	CC Sea level	Modifying hydrology including freshwater	Agriculture and fertilizer	Fish and aquaculture
N and Central America											
Rivera-Monroy et al. (2013)	USA	+			+		+	+	+		
Bashan et al. (2013)	Mexico						+	+	+		
Taylor (2012)	USA			+							
Rivera-Monroy et al. (2011)	USA			+	+				+		
Vovides et al. (2011)	Mexico		+	+	+						+
Valentine-Rose and Layman (2011)	Bahamas			+					+		
Alleman and Hester (2011)	USA					+		+			
Matsui et al. (2010)	USA			+							+
Smith et al. (2009)	USA					+				+	
Krumholz and Jadot (2009)	Grand Cayman			+	+						
Lorenz and Serafy (2006)	USA			+					+		
Milano et al. (2007)	USA			+							
Toledo et al. (2001)	Mexico		+								
McKee and Faulkner (2000)	USA			+			+				+
Imbert et al. (2000)	Caribbean			+	+		+		+		
Llanso et al. (1998)	USA			+					+	+	+
South America											
Rovai et al. (2012)	Brazil			+	+	+	+	+			+
Duarte et al. (2009)	Brazil	+		+	+	+		+	+	+	+
Botero and Salzwedel (1999)	Colombia			+						+	
Twilley et al. (1998)	Colombia			+					+		
Oceania											
Donato et al. (2012)	Micronesia					+	+	+			

Table 1 continued

Major region/reference	Country	Carbon/CO2	Deforestation	Urbanization and development	Pollution	CC Temperature	Storm not only CC	CC Sea level	Modifying hydrology including freshwater	Agriculture and fertilizer	Fish and aquaculture
Gilman and Ellison (2007)	Samoa		+	+		+		+			+
Melville and Burchett (2002)	Australia		+	+					+		
Africa											
Mangora (2011)	Tanzania		+	+							
Osuji et al. (2007)	Nigeria			+							
Bosire et al. (2003)	Kenya		+	+							
Kairo et al. (2001)	East Africa		+	+	+		+		+		+
Rubin et al. (1998)	Ghana		+						+		
Not specified											
Irving et al. (2011)	ns	+			+	+					
Erwin (2009)	various					+			+		
Biswas et al. (2009)	ns			+			+			+	+
Gilman et al. (2008)	ns	+		+			+	+			
Duke et al. (2007)	ns	+	+	+	+	+		+			+
Olguin et al. (2007)	ns				+						
Lewis (2005)	ns			+							+
Holguin et al. (2001)	ns		+	+	+				+		+
Yap (2000)	ns		+	+						+	+
Field (1999)	ns		+	+				+	+		
Kaly and Jones (1998)	ns		+	+							
Field (1998)	ns		+	+						+	+
% of references in each column for each change		7.9	36.5	82.5	20.6	20.6	17.5	17.5	27.0	21.0	46.0

Most of the research reviewed referred to various stresses. At a global level, Duarte et al. (2009) listed changes in human activity (between 1970 and 2005) that impacted coastal ecosystems, referring to mangroves as the 'last port of call' for impacts from terrestrial systems, that is, mangroves receive the cumulative effects of human activity.

Because pressures, stresses and threats that cause mangrove degradation are the same ones that potentially inhibit rehabilitation, recognising them is a critical part of planning of rehabilitation. Table 1 lists 10 categories of stressors that were cited as responsible for mangrove degradation. Eighty-two percent of the reviewed references identified urbanization and development-related activities as threatening or stressing mangroves. In this context infrastructure related to highway construction was mentioned by several authors, including Rivera-Monroy et al. (2011) who attributed highway construction to altered hydrology that impacted a Columbian mangrove-lagoon ecosystem. Impacts from fishponds (fish and aquaculture) and deforestation were identified in 46 and 36.5 % of references respectively. Deforestation was especially important for Asia (45 % of references) and for Africa (80 % of references). Both activities reflect a livelihood aspect of coastal communities in the tropics (particularly in Asia) that are potential sources of conflict for rehabilitation projects unless local communities support and are involved in the process.

Climate change issues were generally absent in the reviewed literature until the twenty-first century. There appear to be three concerns related to climate change: temperature, extreme weather events and sea level rise. Sea level rise was considered to be the greatest threat by Gilman et al. (2008) in their review. Climate related changes were reported in around 20 % of the references in Table 1, with 34.3 % of these published in the last two years. Two key papers focussing on the effects of climate change and mangrove rehabilitation are Erwin (2009) and Gilman et al. (2008). Erwin (2009), in a policy paper focused on the Mekong Delta, reviewed the complex issue of climate and wetland change, indicating that the effect of stressors and their synergies could lead to a range of responses from mangrove expansion to functional extinction. Gilman et al. (2008) provided a useful analysis of how climate and related changes can affect mangrove systems, and how mangroves may resist

(their term) and keep pace with, for example, sea level change.

Issues and gaps

The key issues identified in this section are that urbanization and development are universally considered important stressors, although varying by degree and area. The nature and amount of development is generally not under the control of those who undertake rehabilitation and this highlights the need for high-level policy to guide development so that impacts on mangroves are avoided, mitigated or effectively offset.

The effects of climate change are uncertain and depend on specific situations, but are not issues that rehabilitation can directly control. There is some potential for carbon sequestration to mitigate climate change and this may further increase interest in mangrove rehabilitation.

Gaps in knowledge include a lack of full understanding of mangrove processes (e.g. Salmo et al. 2013) and of function (e.g., Ye et al. 2013) especially in an Asian context (e.g., Gilman and Ellison 2007; Biswas et al. 2009). Having established key stressors we now discuss, in the next section, the impetus for mangrove rehabilitation.

Impetus for mangrove rehabilitation

Mangrove rehabilitation has become an issue worldwide because of mangrove degradation and extensive losses (see Field 1998 and the review by Valiela et al. 2001; for additional detail of mangrove losses see supplementary Table S3). Positive reasons for rehabilitation noted in the reviewed literature include conservation, landscaping, multiple use for high yields, coastal protection (Field 1999), sediment stabilisation, habitats and water treatment (Winterwerp et al. 2005). Irving et al. (2011) in their review concluded that even small rehabilitation projects can provide benefits such as nutrient cycling and habitat for other plants and animals as well as providing carbon capture and storage (noted also by Gilman and Ellison (2007)).

Changing attitudes to the environment have added impetus for mangrove rehabilitation, with community concerns especially important in developing nations

(e.g., China: Ren et al. 2008). This was articulated by Bosire et al. (2008) who noted that, whereas industrialized coastal societies do not depend directly on mangroves, in developing countries local communities do rely on mangrove ecosystems both directly and indirectly for their livelihood. Thus there has to be a balance between conserving the environment, achieving economic efficiency and ensuring equity for local people (Field 1999). Furthermore, when communities understand the importance and value of mangrove services they are more likely to support rehabilitation (Imbert et al. 2000; Macintosh et al. 2002; Moberg and Ronnback 2003).

Issues and gaps

The impetus for rehabilitation stems from mangrove degradation and subsequent loss of services and so a key issue is urgency for action, as continued losses further damage the mangrove ecosystems and the organisms dependent on them. Gaps include a lack of information, for example from surveys results about human views on mangrove value, education about mangroves and how this can be integrated into rehabilitation projects.

Having identified the impetus for rehabilitation the process of rehabilitation is next considered.

Part 2: rehabilitation processes

There is a considerable literature on the processes for undertaking mangrove rehabilitation. Here we separate methodological issues into two parts. The first focuses on the human institutional system of policy, planning, setting aims, goals and objectives and developing strategies. The second considers the biophysical implementation system leading to implementing rehabilitation. This includes selecting methods, implementing projects and monitoring in an adaptive management framework. Figure 1 shows the key components and their interactions as identified in the literature. Details with references are provided in supplementary Table S4.

The human institutional system

The human institutional system is concerned with the role of government in policy and its implementation.

Government embodies a high-level of power by means of the rules and policies it puts in place. Also needed is an organizational structure that can facilitate projects and provide legislative support and legitimacy for rehabilitation, points noted by Katon et al. (2000) and addressed by Maliao and Polohan (2008) and Primavera (2000), both in the context of the Philippines. Others with a strong policy content include Walton et al. (2006) and Erwin (2009).

Policy development, its delivery and enforcement are critically important and vary by country and political systems. Although mangrove loss may be the result of pressures, stresses and threats another reason can be failures in policy, management and, in particular, in enforcement, reflecting a gap between policy and practice (see Mangora 2011, with examples). This is not a recent phenomenon: in 2000 Primavera reported, for the Philippines, problems with conflicting policies within the same agencies as well as enforcement failure. Primavera and Esteban (2008) no longer reported the policy problems identified in Primavera (2000) and that possibly reflected an improvement. This is a view supported by Boyer and Polasky (2004) who recognised that there had been a change in public policy towards protecting wetlands. Policy underpins the development of priorities, setting of aims, goals, objectives and strategies reviewed below.

Setting priorities

There is a need to prioritise rehabilitation strategies especially when resources are limited (Erwin 2009; Sheaves et al. 2014). This is not well covered in the rehabilitation literature. Several papers refer to priority but often with only one or two mentions in the abstract or text (e.g., Field 1998; Kaly and Jones 1998; Tri et al. 1998; Moberg and Ronnback 2003; Boyer and Polasky 2004; Gilman et al. 2008; Rovai et al. 2012; Chen et al. 2013; Rivera-Monroy et al. 2013). Most do not suggest a way forward in setting priorities though they may state priorities that apply in their research. For example, for Barbier et al. (2011) improving assessment of ecosystem services was an urgent and top priority, and, for Erwin (2009), maintaining biodiversity was seen as a high priority goal. Biswas et al. (2009) provided some practical guidance noting that priorities should be based on
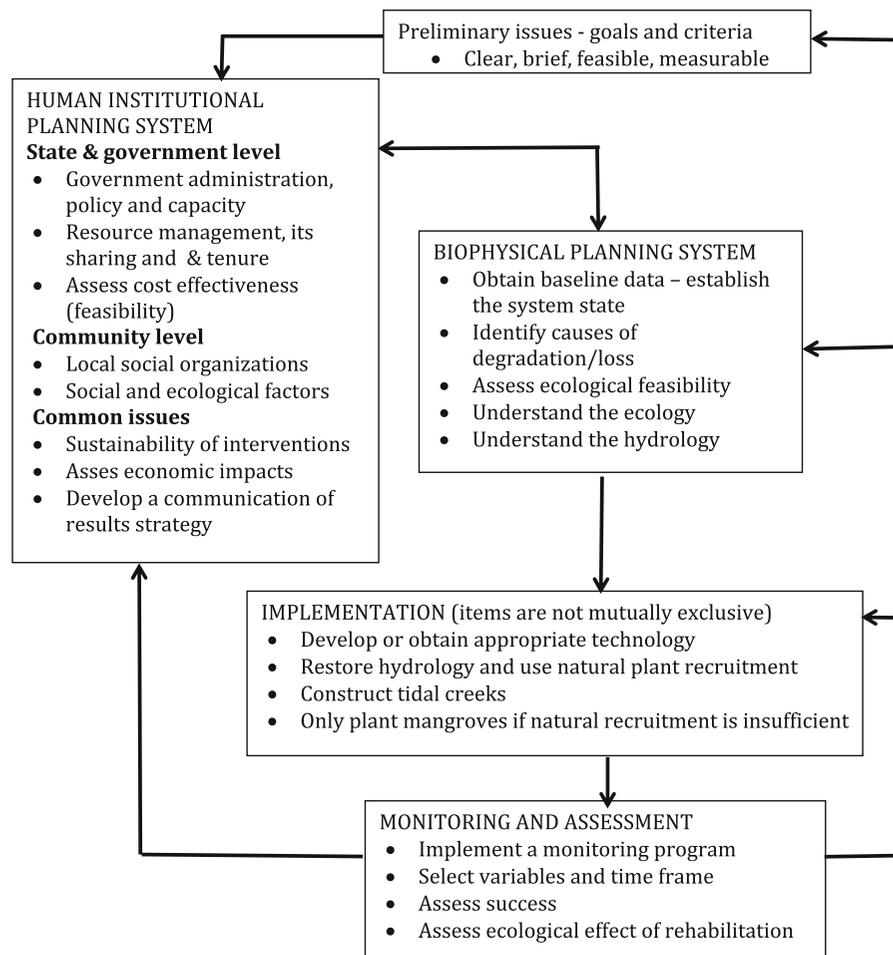
Fig. 1 A concept map for rehabilitation-key components. (References for the components in the figure are tabulated in the Supplementary materials: Table S4 and S1 List of references)

pragmatic and socially determined trade-offs between human and ecological issues.

How to select and prioritise rehabilitation sites is important, but possibly equally important is the need to identify sites that are not degraded and that can, at relatively low cost, be conserved (see Irving et al. (2011) who made a similar point).

Setting aims and goals

Aims and goals provide general guidance and should ideally be developed under policy and rules developed by government and its agencies. A high-level goal would be to achieve a self-sustainable mangrove ecosystem that is resilient to change (Ruiz-Jaen and Aide 2005). However assessing achievement of such a

goal may be limited by the requirement for "considerable scientific expertise" as noted by Field (1998:9) but which may not be available for specific projects.

Objectives and strategies

Objectives and strategies provide specific guidance for a project and must be clear (Chen et al. 2009; Chen et al. 2012a; Ren et al. 2011). Objectives broadly outline ways and the degree to which a project will manage or remove stressors to improve ecological function. Importantly, community must be taken into account. As Field (1999: 52) stated: "It is vital to stress the importance of identifying the objectives of carrying out a rehabilitation programme and to integrate such objectives with the culture and welfare of the

local communities dependent on the mangrove eco-system for sustenance." From a practical perspective Lewis and Gilmore (2007) suggested several strategies and checklists to improve outcomes. These are referred to later.

Issues and gaps

Rehabilitation needs to be underpinned by strong, clear, implementable and enforceable policy including setting priorities and balancing interests. None of these are well covered in the specific rehabilitation litera-ture, though some mention is made of issues of inconsistent policy within and between agencies, lack of enforceability, inadequacy (lack of capacity) and suggestions of impropriety (corruption- Primavera 2000). As well as lack of enforcement, problems arise from overlapping jurisdictions, inconsistencies between agencies, legacies of previous decisions and land ownership that rarely matches landscape hydro-logic units (see also Dale et al. (2010) for an Australian intertidal wetland example).

Biophysical implementation system

Rehabilitation strategies

Although there are checklists for rehabilitation (e.g., Lewis 2005; Lewis and Gilmore 2007), the main strategies are to plant mangroves and/or to restore hydrology. Planting appears to be the most common method either alone or in combination with other environmental modifications (Toledo et al. 2001; Krumholz and Jadot 2009; Aung et al. 2011; Bashan et al. 2013). Planting may not be the most effective rehabilitation method. As Lewis (2005: 404) argued "restoration has, unfortunately, emphasized planting mangroves as the primary tool in restoration, rather than first assessing the reasons for the loss of mangroves in an area and working with the natural recovery processes that all ecosystems have." Devel-oping this concept Lewis and Gilmore (2007) recom-mended that planting should only be considered if natural regeneration is not sufficient to meet objectives.

Restoring tidal hydrology and connections within mangrove systems and with the tidal source, thereby making use of natural processes, is a cost effective

way to rehabilitate mangroves (Vose and Bell 1994; Kaly and Jones 1998; Lugo 1998; Lewis 2005; Lewis and Gilmore 2007; Chen et al. 2012a; Winterwerp et al. 2013). The concept of connections was expanded by Moberg and Ronnback (2003: 41) as it included "ecological knowledge and understanding of the multi-functionality and interconnectedness of ecosys-tems." Often, restoring connections involves remov-ing or modifying obstructions to tidal connection such as artificial berms (Vose and Bell 1994; Llanso et al. 1998) or opening abandoned shrimp ponds (Matsui et al. 2010). Use of LiDAR data by Knight et al. (2009) highlights though, the importance of mapping the micro-topography within mangrove systems and the need to consider habitat within the mangrove forest rather than simply viewing mangroves as a single unit within the broader intertidal landscape.

Monitoring approach and timeframes

There are two main issues relating to monitoring of rehabilitation projects: the first concerns how moni-toring is carried out; the second relates to the monitoring time frame. First, the lack of both a consistent approach and of generally accepted criteria for monitoring limit the development of a general methodology and this has been recognized for decades (Field 1998; Ruiz-Jaen and Aide 2005; Bashan et al. 2013). As Gilman and Ellison (2007) noted this leads to a paucity of quantitative information critical for assessing success and for informing future projects and wider policy.

Referring to monitoring variables, several authors considered that diversity, structure, ecological pro-cesses (or functionality) were all important for mon-itoring (e.g., Ruiz-Jaen and Aide 2005; Bosire et al. 2008; Valentine-Rose and Layman 2011). Examples of the range of variables identified from the literature are listed in Table 2. Some studies refer to special purpose variables, such as for assessing the effects of rehabilitation on the macro-benthos (Chen et al. 2007) or for comparing the effect of different aged mangrove plantations on the associated intertidal macro-fauna (Macintosh et al. 2002). Others considered specific indicator species or communities. Most focus on fish (Llanso et al. 1998; Lorenz and Serafy 2006; Milano et al. 2007; Valentine-Rose and Layman 2011) and/or crustaceans (Macintosh et al. 2002 (who also

considered biodiversity); Walton et al. 2007; Smith et al. 2009; Browder and Robblee 2009).

Second, the timeframe for monitoring is an issue noted by Vovides et al. (2011) and has been mentioned by others. To monitor the success or otherwise of a rehabilitation project requires considerable time and depends on a number of factors. Kaly and Jones (1998) suggested that, for fast growing mangroves, 5–10 years may be sufficient for establishment; implying that in other cases it may need to be much longer to capture succession in mangrove communities. Examples of monitoring reported include a number that were of relatively short duration, for example: as little as 1 year (Hashim et al. 2010; Aung et al. 2011); 22 months (Vose and Bell 1994); 3 years (Bashan et al. 2013). There were some longer term monitoring programs including: Motamedi et al. (2014) 4–6 years; Matsui et al. (2010) up to 6 years; Zhang et al. (2012) 5–13 years; McKee and Faulkner (2000) comparing 6 and 14 year old rehabilitation sites with 50 year old forest; Twilley et al. (1998) 40 years based on modeling; Salmo et al. (2013) 8–50 years; and Walters (2000) 5–60 years. Even so, there is agreement that time frames are likely to be too short for full evaluation (e.g., Kaly and Jones 1998; Osuji et al. 2007).

One way to extend the monitoring timeframe is through the use of remote sensing, which can provide information both currently and retrospectively. For example, Ren et al. (2011) created an inventory of changes at a mangrove rehabilitation site through analysis of satellite imagery over a 21 year period. Although not captured in the literature search, the handbook by Lewis and Brown (2014) recommended using remote sensing in monitoring (and also at other stages of a project).

Issues and gaps

Issues in mangrove rehabilitation methods include lack of understanding of the system dynamics as noted by Salmo et al. (2013) and Ye et al. (2013). In part this results from inadequate monitoring which leads to a number of shortcomings including insufficient data. For example, a lack of information can, when selecting sites, can lead to sub optimal choices and waste of resources; for monitoring, an absence of clear criteria, can lead to relying on visual assessment in the short

term but this is likely to be inappropriate or inconsistent in the longer term as observers are replaced.

Incorporating appropriate hydrological conditions into projects, in suitable circumstances, would be likely to increase natural recruitment and subsequent success, as well as being cost effective. This has been referred to by several authors, but has not been widely adopted (e.g., Lewis 2005; Lewis and Gilmore 2007; Chen et al. 2012).

Part 3: issues affecting rehabilitation success

There are several important issues in implementing rehabilitation. Rehabilitation specific issues include a need for institutional strength and community support as a basis for rehabilitation, feasibility- the likelihood of economic or ecological success-and the importance of integrated approaches.

Institutional strength and community support

This section addresses institutional strength (or capacity) at a high-level and community involvement at the project planning and implementation level. Without institutional strength, mangrove rehabilitation can be inhibited (see Mangora (2011) for Tanzania). Institutions working with community have the potential capacity to promote effective implementation and guard against failure.

Institutional strength can be difficult to achieve. It is especially complicated with multi-agency programs. For projects with foreign aid support in developing nations, management can be problematical because of the potential for conflict around responsibility among multiple agencies. This was one of the issues discussed by Botero and Salzwedel (1999) for a project in Columbia, and Katon et al. (2000) for a project in the Philippines (Cogtong Bay). In the Cogtong Bay case a strategy of co-management was adopted where resource users and government shared responsibility with a community-based approach. However, problems originating outside the community area could not be resolved. For that, government is needed to provide legitimacy and, although the project had been a success, Katon et al. (2000:36) noted "Continuing support from the political power structure is required if laws are to be enforced and if resource management gains are to be preserved."

Community involvement is critical to success. This is because human impacts are one of the drivers of mangrove degradation and loss and so necessitate human inclusion in rehabilitation (Twilley et al. 1998). Supporting this Gilman and Ellison (2007) refer to a community mangrove conservation ethic and Aung et al. (2011) note practical involvement is crucial to rehabilitation success. Further, if communities are not included then resources can be wasted (Field 1998).

Community involvement is especially important where communities rely on and value mangroves for their livelihood, as in developing countries, (e.g., Walters 1997; Field 1999; Biswas et al. 2009; Ren et al. 2009). Walters (1997:1) argued that "socio-economic factors were more important, by and large, than ecological factors in determining the relative success of restoration efforts". The essential question was not whether human factors should be integrated with ecological rehabilitation but rather how to integrate them; arguing that rehabilitation and socio-economic development can be compatible, even in poor countries. This brings together fundamental ecological principles and policy constraints and illustrates the importance of connections between government agencies and local people (Ren et al. 2009). It is a view shared by Moberg and Ronnback (2003) who acknowledged a growing awareness of the ecological and socio-economic importance of mangrove systems. On the other hand external non-human stressors need also to be accounted for and Datta et al. (2012) stressed the importance of involving community in solving problems where local communities were increasingly vulnerable, such as from sea level rise.

Economic and ecological feasibility

Policy development and its enforcement are critically important but government agencies also have to consider the economic and ecologic feasibility of projects. Feasibility depends on the project resources and knowledge available as relevant to goals, objectives and scale. Feasibility assessment should inform policy on an ongoing basis. This was addressed by Tri et al. (1998). They estimated the costs and benefits (of both direct and indirect uses) from rehabilitation in Vietnam resulting in an overall Benefit to Cost ratio in the range of 4.65–5.69. Contingent valuation (or willingness to pay) is another method for assessing the value of mangrove services to local communities. Using this method Stone et al. (2008) reported a benefit to cost ratio

of 3.48 in an Indian study and Tuan et al. (2014) reported a figure of 3.4 for a Vietnamese study. These positive Benefit to Cost ratios indicate the economic feasibility of rehabilitation. However the tendency seems to be to assume that outcomes planned will be achieved, that is, that projects are ecologically feasible. The evidence so far indicates that ecological success is uncertain.

Asking if rehabilitation is ecologically feasible is crucial to success. The answer may not be clear because of lack of sufficient knowledge of mangrove ecosystems. As Kaly and Jones (1998: 656) noted: "Most workers in the field acknowledge that restoring an ecosystem to exactly original condition is unrealistic." See also Bashan et al. (2013) and Duarte et al. (2009:29) who referred to the fiction of a "Neverland": "where everything remained perpetually unchanged". Vovides et al. (2011) takes this further querying whether a system, which may appear to be similar to a natural one, can completely fulfill the primary functions of a natural mangrove system. These references should not be interpreted to imply that rehabilitation is not feasible. Feasibility depends to a large extent on having realistic goals and objectives and following established guidelines (e.g., Lewis 2005).

Failure and success

The literature frequently reports lack of success in mangrove rehabilitation (see Lewis 2005; Bosire et al. 2008; Primavera and Esteban 2008; Mangora 2011; Chen et al. 2012a; Rovai et al. 2013; Winterwerp et al. 2013). The lack of success relates to many factors which result from failure to follow the procedures broadly exemplified in Fig. 1 or the seven "Emerging restoration principles" of Lewis (2005:414).[1] Two

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[1] Summary of the seven Emerging restoration principles (CAPITALS inserted) (Lewis 2005)

1. First get the HYDROLOGY right.

2. Do not START by planting mangroves: first find out why mangroves are not there.

3. See if the REASON for mangrove absence can be corrected; if not choose another site.

4. Use a REFERENCE SITE: to identify the conditions suitable for mangroves in the project area. (Lewis continues with advice on observations to make).

5. For the reference site, be clear about its TOPOGRAPHY before considering another area.

6. Construct TIDAL CREEKS to enhance water movement in and out and facilitate fish access.

7. EVALUATE COSTS early in project planning– maximize cost-effectiveness.

Table 2 Examples of variables monitored in mangrove rehabilitation

General topic	Variable/data	References
Remote sensing data	Imagery (air photos or satellite)	Field (1998), Basham et al. (2013) and Lewis and Brown (2014)
Plant data (species and structure)	Mangrove species	Field (1998) and Rovai et al. (2012)
	Mangrove growth	Field (1998), Wickramasinghe et al. (2009), Hashim et al. (2010) and Aung et al. (2011)
	Mangrove survival	Field (1998) and Hashim et al. (2010)
	Forest structure (e.g., density, height, DBH)	Field (1998), McKee and Faulkner (2000), Bosire et al. (2003), Rovai et al. (2012) and Basham et al. (2013)
Other biota	Macrobenthos	Chen et al. (2007) and Chen and Ye (2011)
	Invertebrates and macrofauna	McKee and Faulkner (2000), Macintosh et al. (2002), Chen et al. (2007), Walton et al. (2007), Smith et al. (2009), Browder and Robblee (2009) and Wickramasinghe et al. (2009)
	Fish	Llanso et al. (1998), Lorenz and Serafy (2006), Milano et al. (2007) and Valentine-Rose and Layman 2011
	Litter decomposition	McKee and Faulkner (2000)
Substrate	Soil organic matter, total N, C, P, TOC, redox, soil particle size, trace metals	McKee and Faulkner (2000) (also sulphides), Bosire et al. (2003), Chen et al. (2007), Wickramasinghe et al. (2009), Zhang et al. (2012) (organic C), Salmo et al. (2013) and Rovai et al. (2013) (trace metals)
	Nitrogen fixation	Vovoides et al. (2011)
Water quality, duration	Salinity, Chlorophyll a, water residence time	Rivera-Monroy et al. (2011) and Rovai et al. (2013)
Topography/tidal data	Elevation	Rovai et al. (2013)
	Tide height, water speed, sediment transport in channel	Basham et al. (2013)
Impacts/outcomes	Pests, land use practices (grazing, cutting fish pond construction	Field (1998)
	Assess outcomes against objectives	Field (1998)
	Estimate cost of project	Field (1998)

reasons for lack of success include neglecting ecological function due to a lack of baseline information and/or poor (or missing) post project management. Lack of baseline information can lead to selecting sites with unsuitable hydrology, soil and/or topography or sites subject to erosion, or planting inappropriate species. Some of these reasons are exemplified by Chen et al. (2012a) who assessed rehabilitation projects in China and identified a range of weaknesses and barriers to success in addition to neglecting ecological function. They included poor understanding of socio-economic and political factors, lack of scientific process to assess the causes of degradation and insufficient communication of results.

Although failure is a major issue for rehabilitation, there are successes. Primavera and Esteban (2008) found failure was common but they also found exceptions where mangrove survival rates were around 90 %. They characterized the successes as projects with moderate budgets, community involvement and co-management with local government, considering the relevant issues and incorporating many of the activities in Fig. 1. At a minimum, adhering to the seven principles advocated by Lewis (2005) would increase the likelihood of success. This is consistent with later literature such as Winterwerp et al. (2013) who repeated the call to improve rehabilitation methods and technologies so as to

facilitate recovery of appropriate hydrological and morpho-dynamic conditions. Finally, a prerequisite for successful rehabilitation of mangrove systems is an interdisciplinary understanding of how the system works noted by some authors and addressed in the next section.

Integrated multi-disciplinary approaches

Social science and ecological issues cannot be viewed in isolation from other matters and so integrated and multi-disciplinary approaches are important. This has been explicitly recognized by several authors (e.g., Moberg and Ronnback 2003; Biswas et al. 2009). Biswas et al. (2009) proposed an integrated approach that took account of both ecological and socio-economic factors suitable for rehabilitation in south east Asia. Several disciplines are relevant and include, but are not limited to, ecology, hydrology, engineering and economics at various scales, depending on the specific project. This is a relatively neglected area especially for social science issues in rehabilitation, as earlier recognised by Walters (1997), and more recently by Datta et al. (2012).

General issues

The major issues for rehabilitation are in the area of environmental uncertainty, policy, gaps in basic knowledge, monitoring issues, assessing feasibility and the need for multi-disciplinary approaches. The issues appear to be most problematical in the developing world and this may relate to issues of economic and human capacity.

Intertidal ecosystems are dynamic and the future is uncertain. This raises issues of uncertainty. One way to deal with uncertainty is to take a precautionary approach (Tri et al. 1998; Biswas et al. 2009; Alongi 2012) but few other authors in the review referred to this. Although a precautionary approach may be embedded into legislation[2] especially in the developed

world, Biswas et al. (2009) noted it was generally lacking in south east Asia.

Policy and its enforcement appears to be a weakness, and institutional strengthening would be one way to improve the situation. At government level there is a policy-practice gap and this needs to be addressed with consistent approaches between and within agencies leading to better priority setting and balancing interests.

Basic ecological information is lacking in several areas including mangrove processes and functions. Monitoring lacks a clear set of applicable criteria and methods (including timelines and what might be reasonably realistic in terms of project objectives). In addition to transferring ecological theory across areas (the inter- or multi-disciplinary approach) as suggested by Field (1998), transferring research findings across different systems is fraught with difficulty. This is not only because of the inherent complexity of the systems, but also because of the interactions between biotic and abiotic constituents within systems (Chen and Ye 2011).

Assessing feasibility is important for agencies that have to prioritise, select and resource potential projects. There is a need to integrate economic and ecologic feasibility assessment. This is not generally done, in part due to the discipline boundaries that would need to be crossed (at least economics and ecology). Benefit-cost analysis is one potentially useful tool though it cannot adequately address all the costs and benefits or identify all who pay or benefit. As an example, although positive mangrove system services are well documented, the potential for poorly considered mangrove rehabilitation to lead to unexpected and negative outcomes (disservices or costs) for human health are not addressed in the literature reviewed.

Many problems stem from barriers to understanding resulting from discipline boundaries. This is a recurrent theme. To overcome the barriers a multi-disciplinary approach would yield benefits to projects particularly in assessing both economic and ecological feasibility.

Concluding comments

The future is uncertain and mangrove systems are dynamic, responding, *inter alia* to some significant stressors: urbanization and development, aquaculture and forestry. A precautionary approach especially with respect to climate change is being advocated by

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[2] Environmental Protection and Biodiversity Conservation Act 1999 (Commonwealth of Australia) Sect. 391 (2) "The *precautionary principle*" is the principle that lack of full scientific certainty should not be used as a reason for postponing a measure to prevent degradation of the environment if there are threats of serious or irreversible environmental damage.

some, but likely to be increasingly important as sea level rise issues become urgent.

A critical issue is the involvement and participation of both government and communities, especially in the developing world. While the ecological and physical environment is the focus of on ground rehabilitation activities, the role of government policy, its enforcement and involvement of communities and stakeholders is critically important for providing legitimacy, support and commitment.

The greatest practical weakness is in the area of monitoring. It often lacks standard procedures and is time and resource limited. The lack of many long-term research studies published in the refereed literature is unfortunate as some of the knowledge gaps might be filled if there were results available from longer term follow-up projects. Even so there remains the issue of whether and to what extent information and results can be transferred across systems.

The future direction of mangrove rehabilitation research needs to address the issues and fill the gaps identified in this review. It is urgent. "The urgent need for restoration set against a background of limited resources, clearly demands a more holistic approach…" Sheaves et al. (2014: 37). To do this requires resources, capacity and an inter-disciplinary approach, involving teams with skills appropriate to each project- at the least ecology, hydrology, economics and an understanding of the cultural context.

The review concludes on a positive note, anticipating a future where governments work with communities to develop policies and strategies based on good science to achieve best practice in rehabilitation. This would protect existing and rehabilitate damaged mangroves for resilience to changing environments.

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