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Ecological engineering for successful management and restoration of mangrove forests

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Abstract

Great potential exists to reverse the loss of mangrove forests worldwide through the application of basic principles of ecological restoration using ecological engineering approaches, including careful cost evaluations prior to design and construction. Previous documented attempts to restore mangroves, where successful, have largely concentrated on creation of plantations of mangroves consisting of just a few species, and targeted for harvesting as wood products, or temporarily used to collect eroded soil and raise intertidal areas to usable terrestrial agricultural uses. I document here the importance of assessing the existing hydrology of natural extant mangrove ecosystems, and applying this knowledge to first protect existing mangroves, and second to achieve successful and cost-effective ecological restoration, if needed. Previous research has documented the general principle that mangrove forests worldwide exist largely in a raised and sloped platform above mean sea level, and inundated at approximately 30%, or less of the time by tidal waters. More frequent flooding causes stress and death of these tree species. Prevention of such damage requires application of the same understanding of mangrove hydrology.

Keywords: Mangrove forests; Restoration of mangrove forests; Ecological restoration; Mangroves

1. Introduction

Mangrove forests are ecologically important coastal ecosystems (Lugo and Snedaker, 1974) composed of one or more of the 69 species of plants called mangroves (Duke, 1992). These ecosystems currently cover 146,530 km of the tropical shorelines of the world (FAO, 2003). This represents a decline from 198,000 km of mangroves in 1980, and 157,630 km in 1990 (FAO, 2003). These losses represent about 2% per year between 1980 and 1990, and 1% per year between 1990 and 2000.

Examples of documented losses include combined losses in the Philippines, Thailand, Vietnam and Malaysia of 7445 km^2 of mangroves (Spalding, 1997). In Florida, approximately 2000 km^2 remain from an estimated historical cover of 2600 km^2 (Lewis et al., 1985). Puerto Rico has just 64 km^2 of mangrove remaining from an original mangrove forest cover estimated to have been 243 km^2 (Martinez et al., 1979). These figures emphasize the magnitude of the loss,

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and the magnitude of the opportunities that exist to restore areas like mosquito control impoundments in Florida (Brockmeyer et al., 1997), and abandoned shrimp aquaculture ponds in Thailand and the Philippines (Stevenson et al., 1999), back to functional mangrove ecosystems.

Restoration of areas of damaged or destroyed mangrove forests has been previously discussed by Lewis (1982a,b, 1990a,b, 1994, 1999, 2000), Crewz and Lewis (1991), Cintron-Molero (1992), Field (1996, 1998), Turner and Lewis (1997), Brockmeyer et al. (1997), Milano (1999), Ellison (2000), Lewis and Streever (2000) and Saenger (2002). Saenger and Siddiqi (1993) describe the largest mangrove afforestation program in the world, with plantings of primarily one species (*Sonneratia apetala*) over 1600 km^2 on newly accreting mud flats in Bangladesh. This was a multipurpose planting with the prime objective of "... providing land sufficiently raised and stabilized to be used for agricultural purposes ..." through encouraged accretion of sediments by the plantings. It is estimated that 600 km^2 of raised lands have now been converted to such uses. Blasco et al. (2001) estimate survival of these plantings to presently cover about 800 km^2 after about a 50% loss due to cyclones and insect pest outbreaks.

In spite of the success in Bangladesh, most attempts to restore mangroves often fail completely, or fail to achieve the stated goals (Lewis, 1990a, 1999, 2000; Erftemeijer and Lewis, 2000). This paper is intended to review those factors that can be applied by ecological engineers and ecologists to insure successful management without damage, and successful restoration if damage has or does occur. In addition, following the suggestions in Weinstein et al. (2001), emerging restoration principles will be stated.

2. Key terms and principles

Restoration or rehabilitation may be recommended when an ecosystem has been altered to such an extent that it can no longer self-correct or self-renew. Under such conditions, ecosystem homeostasis has been permanently stopped and the normal processes of secondary succession (Clements, 1929) or natural recovery from damage are inhibited in some way. This concept has not been analyzed or discussed with any great detail as it pertains to mangrove forests (Detweiler et al., 1975; Ball, 1980; Lewis, 1982a,b, are the few exceptions), and thus 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.

The term "restoration" has been adopted here to specifically mean any process that aims to return a system to a pre-existing condition (whether or not this was pristine) (sensu Lewis, 1990c), and includes "natural restoration" or "recovery" following basic principles of secondary succession. Secondary succession depends upon mangrove propagule availability, and I suggest a new term, "propagule limitation" to describe situations in which mangrove propagules may be limited in natural availability due to removal of mangroves by development, or hydrologic restrictions or blockages (i.e. dikes) which prevent natural waterborne transport of mangrove propagules to a restoration site. Such situations have been described by Lewis (1979) for the U.S. Virgin Islands, Das et al. (1997) for a mangrove restoration site in the Mahanadi delta, Orissa, India, and by Hong (2000) for similar efforts at Can Gio, Vietnam.

"Ecological restoration" is another important term to include in this discussion and has been defined by the Society for Ecological Restoration (SER, 2002) as the "process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed". The goal of this process is to emulate the structure, functioning, diversity and dynamics of the specified ecosystem using reference ecosystems as models.

Ecological engineering, which involves creating and restoring sustainable ecosystems that have value to both humans and nature (Mitsch and Jørgensen, 2004) has been characterized as having two primary goals: (1) the restoration of ecosystems that have been substantially disturbed by human activities ... and (2) the development of new sustainable ecosystems that have both human and ecological value, to which I would add a third, which is to accomplish items (1) and (2) in a cost effective way. Engineers are routinely asked to generate engineer's estimates for construction projects, often oversee actual construction, and approve payments based upon successful completion of construction. Associated materials purchase and installation, such as plants in a wetland restoration project, are other items reviewed, approved and paid for. Projected costs are important to determine if a project is affordable, and final costs have to be controlled in the construction process.

As noted by Spurgeon (1999) "[I]f coastal habitat rehabilitation/creation is to be widely implemented, greater attempts should be made to: find ways of reducing the overall costs of such initiatives; devise means of increasing the rate at which environmental benefits accrue; and to identify mechanisms for appropriating the environmental benefits". It is the role of an ecological engineer, working in tandem with an ecologist, to see that such actions occur.

3. Ecology of mangrove forests

Mangroves are intertidal trees found along tropical shorelines around the world. They are frequently inundated by the tides, and thus have special physiological adaptations to deal with salt in their tissues. They also have adaptations within their root systems to support themselves in soft mud sediments and transport oxygen from the atmosphere to their roots, which are largely in anaerobic sediments. Most have floating seeds that are produced annually in large numbers and float to new sites for colonization.

Mangrove forests provide a number of ecological benefits including stabilizing shorelines, reducing wave and wind energy against shorelines, and thus protecting inland structures, supporting coastal fisheries for fish and shellfish through direct and indirect food support and provisions for habitat, and support of wildlife populations including a number of wading birds and sea birds.

Mangrove forests also support timber production for construction materials and supply some special chemicals for industry, and medicinal products for local use.

4. Ecological management of mangroves

As noted by Field (1998), "[T]he most common method of conserving mangrove ecosystems is by the creation of protected areas in undisturbed sites . . ." National parks, wildlife preserves and internationally protected sites are mentioned. However, as reported by Perdomo et al. (1998), 70% of the Cienaga Grande de Santa Marta, a 511 km^2 mangrove forest reserve in Colombia, have been killed by alterations of hydrology due to road and dike construction in the 1950s. Similar deaths of mangroves in a protected area due to modified hydrology are reported in Turner and Lewis (1997). Rubin et al. (1999) describe the destruction of the mangrove forests of the Volta River Estuary in Ghana due to two dams on the Volta River, and local timber harvesting. Ellison (2000) notes that "[D]espite repeated claims that mangrove forests can be managed sustainably . . . managed (and unmanaged) mangal continues to degrade and disappear at rates comparable to those seen in tropical wet forests (∼1.5% per year) . . ."

Clearly, mangrove forests have not been managed very well, even if left alone in terms of direct dredging and filling for coastal development (Lewis, 1977), or conversion to aquaculture ponds (Stevenson et al., 1999). In case, after case disruption of the existing hydrology of a forest is enough to kill it. One might assume that all of these cases involved the old misunderstanding that mangroves were worthless swamps, and today we know how to manage them better. The example of Clam Bay in Naples, FL, USA, however, (Turner and Lewis, 1997) shows that even modern day management ignores the realities of mangrove hydrology.

The issue appears to be that both ecologists and engineers (and ecological engineers) do not understand mangrove hydrology. Although a number of papers discuss the science of mangrove hydrology (Kjerfve, 1990; Wolanski et al., 1992; Furukawa et al., 1997), their focus has been on tidal and freshwater flows within the forests, and not the critical periods of inundation and dryness that govern the health of the forest. Kjerfve (1990) does discuss the importance of topography and argues that ". . . micro-topography controls the distribution of mangroves, and physical processes play a dominant role in formation and functional maintenance of mangrove ecosystems . . .". Hypersalinty due to year to year variations in rainfall can produce natural mangrove die-backs (Cintron et al., 1978), and disruption of normal freshwater flows that dilute seawater in more arid areas can kill mangroves (Perdomo et al., 1998; Medina et al., 2001). What is less understood is the role of tidal inundation frequency, and modifications to that factor, that can also stress and kill mangroves.

A series of papers beginning with Nickerson and Thibodeau (1985) and Thibodeau and Nickerson (1986), and continuing with McKee and Mendelssohn

(1988), McKee (1993, 1995a,b), and McKee and Faulkner (2000a,b) have clearly shown that differential survival and growth of mangrove species studied to date are related to the depth, duration and frequency of flooding and soil saturation. The processes involved are complicated and no single factor applies to all mangrove zones, but observations and data collection across transects through mangroves from low to higher elevations in Belize "... indicate that the higher-elevations sites were infrequently flooded over the soil surface, whereas the lower elevation sites near the shoreline were inundated twice daily. Tidal amplitude and water velocity decrease strongly with increasing distance from the shoreline and lead to restricted water movement and incomplete drainage of interior areas ...". In examining the correlations of measured environmental variables across transects with different dominant species of mangroves, three factors were examined for correlations with mangrove zonation. Within the three factors, flooding "had a high negative loading of relative elevation and a high positive loading of sulfide. Sulfide tends to accumulate in waterlogged soils, a process that is promoted in low elevation areas where water levels may not fall below the soil surface during a tidal cycle ...".

As noted by Koch et al. (1990) "sulfide toxicity has been implicated as a causative factor in the dieback of European and North American salt marshes ..." and Mendelssohn and Morris (2000) in reporting on the ecophysiological controls on the productivity of smooth cordgrass further define the toxic effects of sulfide as reducing ammonium uptake that "result in a plant nitrogen deficiency and lower rates of growth and primary production for poorly drained, inland *Spartina* marshes". A similar effect is likely in mangrove forests.

The point of all of this is that flooding depth, duration and frequency are critical factors in the survival of both mangrove seedlings and mature trees. Once established, mangroves can be further stressed if the tidal hydrology is changed, for example by diking (Brockmeyer et al., 1997). Both increased salinity due to reductions in freshwater availability, and flooding stress, increased anaerobic conditions and free sulfide availability can kill existing stands of mangroves.

For these reasons, any engineering works constructed near mangrove forests, or in the watershed that drains to mangrove forests, must be designed to allow for sufficient free exchange of seawater with the adjacent ocean or estuary, and not interrupt essential upland or riverine drainage into the mangrove forest. Failure to properly account for these essential inputs and exchange of water will result in stress and possible death of the forest.

5. Ecological restoration of mangroves

It has been reported that mangrove forests around the world can self-repair or successfully undergo secondary succession over periods of 15–30 years if: (1) the normal tidal hydrology has not been disrupted and (2) the availability of waterborne seeds or seedlings (propagules) of mangroves from adjacent stands is not limited or blocked (Lewis, 1982a; Cintron-Molero, 1992; Field, 1998).

Ecological restoration of mangrove forests has only received attention very recently (Lewis, 1999). The wide range of types of projects previously considered to be restoration, as outlined in Field (1996, 1998), reflect the many aims of classic mangrove rehabilitation or management for direct natural resource production. These include planting monospecific stands of mangroves for future harvest as wood products. This is not ecological restoration as defined above.

It is important to understand that mangrove forests occur in a wide variety of hydrologic and climatic conditions that result in a broad array of mangrove community types. In Florida, Lewis et al. (1985) have identified at least four variations on the original classic mangrove zonation pattern described by Davis (1940), all of which include a tidal marsh component dominated by such species as smooth cordgrass (*Spartina alterniflora*) or saltwort (*Batis maritima*). Lewis (1982a,b) describes the role that smooth cordgrass plays as a "nurse species", where it initially establishes on bare soil and facilitates primary or secondary succession to a climax community of predominantly mangroves, but with some remnant of the original tidal marsh species remaining. This has been further generalized by Crewz and Lewis (1991) (Fig. 1) as the typical mangrove forest for Florida, where tidal marsh components are nearly always present.

Finn (1996, 1999) describes the construction and operation of a mixed estuarine mesocosm as part of the Biosphere 2 experiment. Several of the subunits within the mesocosm contained mangroves transplanted from

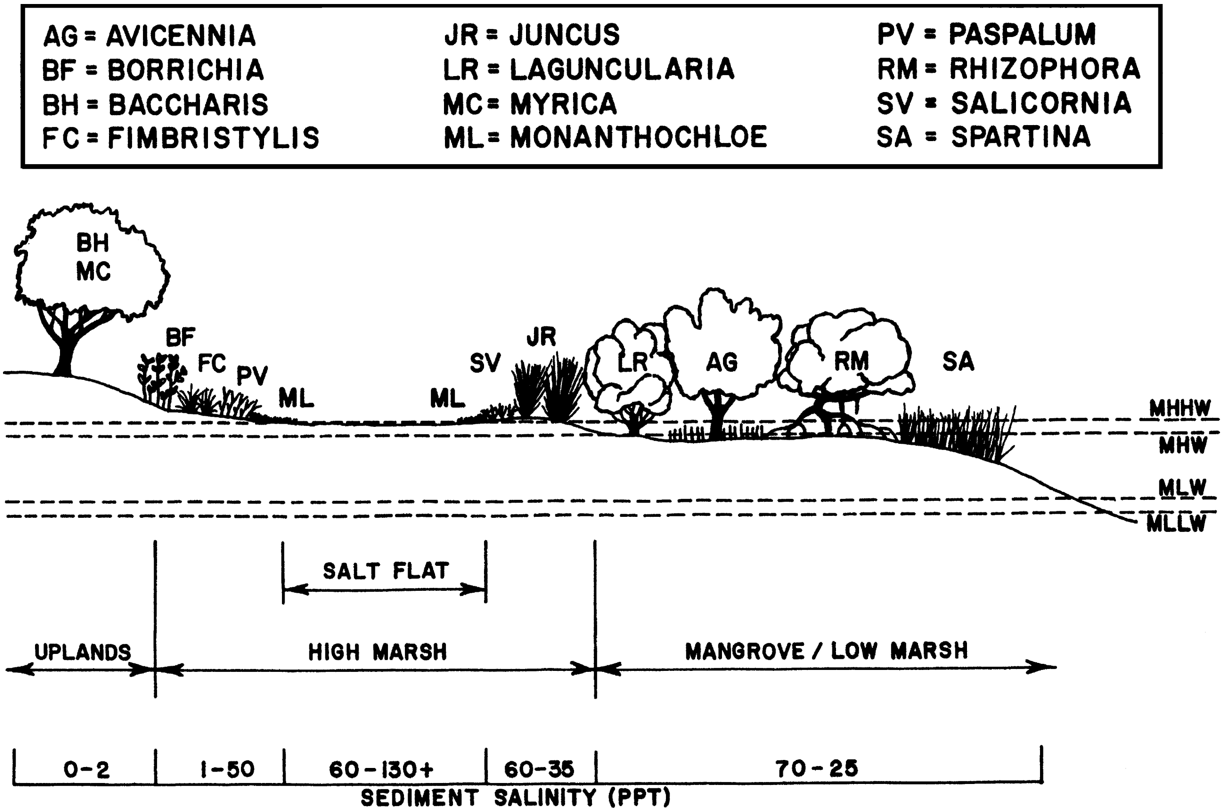

Fig. 1. Schematic diagram of the six components of the tropical coastal shelf ecosystem (modified from Crewz and Lewis, 1991).

Florida. No specific measurements of tidal inundation depth, duration and frequency at the source site of the mangroves were made, and the initial management of tidal effects in the mesocosm are not described in detail. The mesocosm and adjacent mesocosms exchanged water to simulate tides, but this was discontinued, and Finn (1996) indicates that the mangrove mesocosm had operated for 3 years without tides. The amount of inundation is not described in the non-tidal mesocosm, but Finn (1996) states that the experiment may be a useful tool for characterizing the effect of impounding mangroves. Finn (1999) describes the lack of understory vegetation in the mesocosm and notes that this compares favorably with natural systems. The transplanted mangroves have grown well in the mesocosm but most of the animals in the system, including fiddler crabs, periwinkles and coffee snails disappeared from the system between 1991 and 1993. There were restocked in 1994 but their fate is not reported in Finn (1999).

It is possible to restore some of the functions of a mangrove forest, salt flat or other systems even though parameters such as soil type and condition may have altered and the flora and fauna may have changed (Lewis, 1992). If the goal is to return an area to a pristine predevelopment condition, then the likelihood of failure is increased. However, the restoration of certain ecosystem traits and the replication of natural functions stand more chance of success (Lewis et al., 1995).

Because mangrove forests may recover without active restoration efforts, it has been recommended that restoration planning should first look at the potential existence of stresses such as blocked tidal inundation that might prevent secondary succession from occurring, and plan on removing that stress before attempting restoration (Hamilton and Snedaker, 1984; Cintron-Molero, 1992). The next step is to determine by observation if natural seedling recruitment is occurring once the stress has been removed. Only if natural recovery is not occurring should the final step of considering assisting natural recovery through planting be considered.

Unfortunately, many mangrove restoration projects move immediately into planting of mangroves without determining why natural recovery has not occurred. There may even be a large capital investment in growing mangrove seedlings in a nursery before stress factors are assessed. This often results in major failures of planting efforts. For example, Sanyal (1998) has recently reported that between 1989 and 1995, 9050 ha of mangroves were planted in West Bengal, India, with only a 1.52% success rate. In the Philippines, the Central Visayas Regional Project I, Nearshore Fisheries Component, a US$ 35 million World Bank Project targeted 1000 ha of mangrove planting between 1984 and 1992. An evaluation of the success of the planting in 1995–1996 by Silliman University (Silliman University, 1996; de Leon and White, 1999) indicated that only 18.4% of the 2,927,400 mangroves planted over 492 ha had survived. Another planned 30,000 ha planting effort funded by a US$ 150 million loan from the Asian Development Bank and Overseas Economic Cooperation Fund of Japan (Fisheries Sector Program, 1990–1995) was cut short after only 4792 ha were planted do to similar problems (Ablaza-Baluyut, 1995).

Platong (1998) in reporting on efforts at mangrove restoration in Thailand states that the Royal Forest Department of Thailand (RFD) reported 11,009 ha planted in Southern Thailand. Platong (1998) notes that RFD "is unable to justify the success of the plan because the replanted mangrove areas are just in seedling stage. There is no report that replanting mangroves are survived [sic] or destroyed by natural factors and human. The data being recorded are only the planted area and the amount of areas planned to be replanted" (p. 59). In addition "the Agriculture Department joined with the private sector in a mangrove replanting project for the King's 50th anniversary jubilee . . .. The target was 31,724 rai [5076 ha] in 57 areas. The Petrolium [sic] Authority of Thailand (PTT) replanted mangrove forest in Southern Thailand . . . between 1995 and 1997 about 11,062 rai [1770 ha] . . .. It is not easy to compare the success of mangrove replanting . . . because they are not the same scale, e.g. species, number of areas, location, timing and budget for maintenance after replanting". Platong (1998) also refers to planting of mangrove seeds or seedlings in areas that have not previously been forested.

Many of these failures result from afforestation attempts, which are an attempt to plant mangroves in areas that previously did not support mangroves. Often mudflats in front of existing or historical stands of mangroves are proposed restoration sites. Aside from the problem of frequent flooding greater than the tolerance of mangroves, it is questionable whether the widespread attempts to convert existing natural mudflats to mangrove forests, even if they succeeded, represent ecological restoration. In their review article on this matter, Erftemeijer and Lewis (2000) have commented that planting mangroves on mudflats would represent habitat conversion rather than habitat restoration, and strongly caution against the ecological wisdom of doing this.

Similar efforts in the Philippines, as reported by Custodio (1996), under "Threats to Shorebirds and their Habitats", state that "{H}abitat alteration in the wake of unabated increase in human population is still the most important threat to shorebirds in the Philippines. Some of the alteration, however, has been due to activities, which were of good intention. An example of this is the mangrove 'reforestation' programme which covered the feeding grounds of shorebirds in Puerto Rivas (Bataan) and parts of Olango Island" (p. 166). With these words in mind, it is worthwhile to note that Tunhikorn and Round (1996) state that ". . . Thailand is a major wintering and passage area for Palaeartic waterbirds. Large numbers of shorebirds are found both along its coastline, in mudflat and mangrove habitat . . ." and describe the intertidal mudflats, onshore prawn ponds, salt-pans and some remaining areas of mangroves along the Gulf of Thailand as "(P)robably the single most important site for shorebirds in the country" (p. 123). Finally, they describe the major threat to wintering shorebirds at Khao Sam Roi Yot National Park in Prachuap Khiri Khan province as modifications to "the hydrology and topography of coastal areas . . . by intensive prawn farming during 1988–1993" (p. 124).

Natural recruitment of mangrove seedlings, reflected in the careful data collection of Duke (1996) at an oil spill site in Panama showed that ". . . densities of *natural recruits* far exceeded both expected and observed densities of planted seedlings in both sheltered and exposed sites" (emphasis added) in restoration attempts at a previously oiled mangrove forest. Soemodihardjo et al. (1996) report that only 10% of a logged area in Tembilahan, Indonesia (715 ha) needed replanting because "The rest of the logged over area . . . had more than 2500 *natural seedlings* per ha" (emphasis added).

Lewis and Marshall (1997) have suggested five critical steps are necessary to achieve successful mangrove restoration:

1. Understand the autecology (individual species ecology) of the mangrove species at the site, in particular the patterns of reproduction, propagule distribution and successful seedling establishment.
2. Understand the normal hydrologic patterns that control the distribution and successful establishment and growth of targeted mangrove species.
3. Assess the modifications of the previous mangrove environment that occurred that currently prevents natural secondary succession.
4. Design the restoration program to initially restore the appropriate hydrology and utilize natural volunteer mangrove propagule recruitment for plant establishment.
5. Only utilize actual planting of propagules, collected seedlings or cultivated seedlings after determining through Steps 1–4 that natural recruitment will not provide the quantity of successfully established seedlings, rate of stabilization or rate of growth of saplings established as goals for the restoration project.

Callaway (2001) lists seven similar steps in order to design the best hydrology and geomorphological development of tidal marshes in California.

These critical steps are often ignored and failure in most restoration projects can be traced to proceeding in the early stages directly to Step 5, without considering Steps 1–4. Stevenson et al. (1999) refer to this approach as "gardening", where simply planting mangroves is seen as all that is needed. The successful plantings of large areas with one or two species, as described by Saenger and Siddiqi (1993), in Bangladesh, may seem a success story, but one must question whether large monotypic stands of mangroves are a worthwhile goal. Remembering the principles of ecological restoration, one should ask whether the results produce a mangrove forest similar in species composition and faunal use to the native mangrove forests of the area. Another issue is competition from large-scale plantings may prevent natural colonization by volunteer mangroves, and reduce the final biodiversity of the planted area. Another common problem is the failure to understand the natural processes of secondary succession, and the value of utilizing nurse species like smooth cordgrass in situations where wave energy may be a problem.

As an example of the problem, Kairo et al. (2001) in a recent paper with a title similar to this paper begin their section on "[H]istory of mangrove restoration and management" with this statement: "[M]angrove *planting* and management has a long history . . ." (emphasis added). Spurgeon (1999) does the same thing. Under his section on "Costs", for mangrove rehabilitation/creation it begins "[C]osts for mangrove *planting* can range . . ." (emphasis added). Although Kairo et al. (2001) later have a section on "natural regeneration" the emphasis throughout their paper is on planting. Thus, for the majority of papers written on mangrove restoration, there is an immediate assumption that mangrove restoration means mangrove planting. This leads then to ignoring hydrology and natural regeneration via volunteer mangrove propagules, and many failures in attempts to restore mangroves (Erftemeijer and Lewis, 2000).

The single most important factor in designing a successful mangrove restoration project is determining the normal hydrology (depth, duration and frequency, and of tidal flooding) of existing natural mangrove plant communities (a reference site) in the area in which you wish to do restoration. Both Vivian-Smith (2001) and Sullivan (2001), similarly recommend the use of a reference tidal marsh for restoration planning and design. The normal surrogate for costly tidal data gathering or modeling is the use of a tidal benchmark and survey of existing healthy mangroves. When this is done, a diagram similar to that in Fig. 1 will result. This then becomes the construction model for your project.

Fig. 1 is a typical cross section through a reference mangrove forest site. Actual survey data is generated to locate the existing topographic elevations within the forest. This figure is a synthesis of all the topographic information generated by Crewz and Lewis (1991). Table 1 modified from Detweiler et al. (1975) is actual data from a single mangrove forest on Tampa Bay, Florida. Both Fig. 1 and Table 1 show that the mangrove forests in Florida typically exist on a sloped platform above mean sea level, with typical surveyed elevations for mangrove species in the range of +30 to +60 cm above mean sea level. Likewise, Twilley and Chen (1998) report the topography of a basin mangrove

Table 1
Elevation ranges and mean elevation (NGVD datum) of 10 plant species found in the control transect of an undisturbed mangrove forest community near Wolf Branch Creek, Tampa Bay, FL, USA (modified from Detweiler et al., 1975)

Species	Number of quadrats	Range (ft)	Range (m)	Mean elevation (ft)	Mean elevation (m)
Rhizophora mangle	35	+0.2 to +1.6	+0.06 to +0.49	+1.0	+0.30
Avicennia germinans	49	+0.4 to +2.5	+0.12 to +0.76	+1.5	+0.46
Laguncularia racemosa	47	+0.7 to +2.5	+0.21 to +0.76	+1.5	+0.46
Spartina alterniflora	4	+1.6 to +1.7	+0.49 to +0.52	+1.7	+0.52
Salicornia virginica	10	+1.6 to +1.9	+0.49 to +0.58	+1.7	+0.52
Sesuvium portulcastrum	2	+1.7	+0.52	+1.7	+0.52
Limonium carolinianum	6	+1.6 to +1.7	+0.49 to +0.52	+1.7	+0.52
Batis maritima	14	+1.6 to +2.2	+0.49 to +0.67	+1.8	+0.55
Borrichia frutescens	2	+1.9	+0.58	+1.9	+0.58
Philoxerus vermicularis	5	+1.6 to +2.2	+0.49 to +0.67	+1.9	+0.58

forest at Rookery Bay had a “. . . bowl shape with a centre low of 45 cm > msl”. A similar profile section from Whitten et al. (1987) for a different group of mangrove species in Sumatra shows a similar pattern (Fig. 2). Finally, in Fig. 3, four sites in Australia are illustrated from Kenneally (1982). All show a similar location, at the upper third of the tidal range. Kjerfve (1990) reports that within the Klong Ngao creek-mangrove system in Thailand “. . . the mangrove wetland area above bankfull stage is only inundated 9% of the time. Specific locations within the wetland at higher elevations are flooded less frequently, and the system as a whole is only inundated 1% of the time”.

In an early review of percent tidal submergence and emergence for tidal marshes, Hinde (1954) reported that the tidal marsh in Palo Alto, California, had zones of tidal marsh vegetation that varied in their percent of time submerged from 20% for the highest *Salicornia*

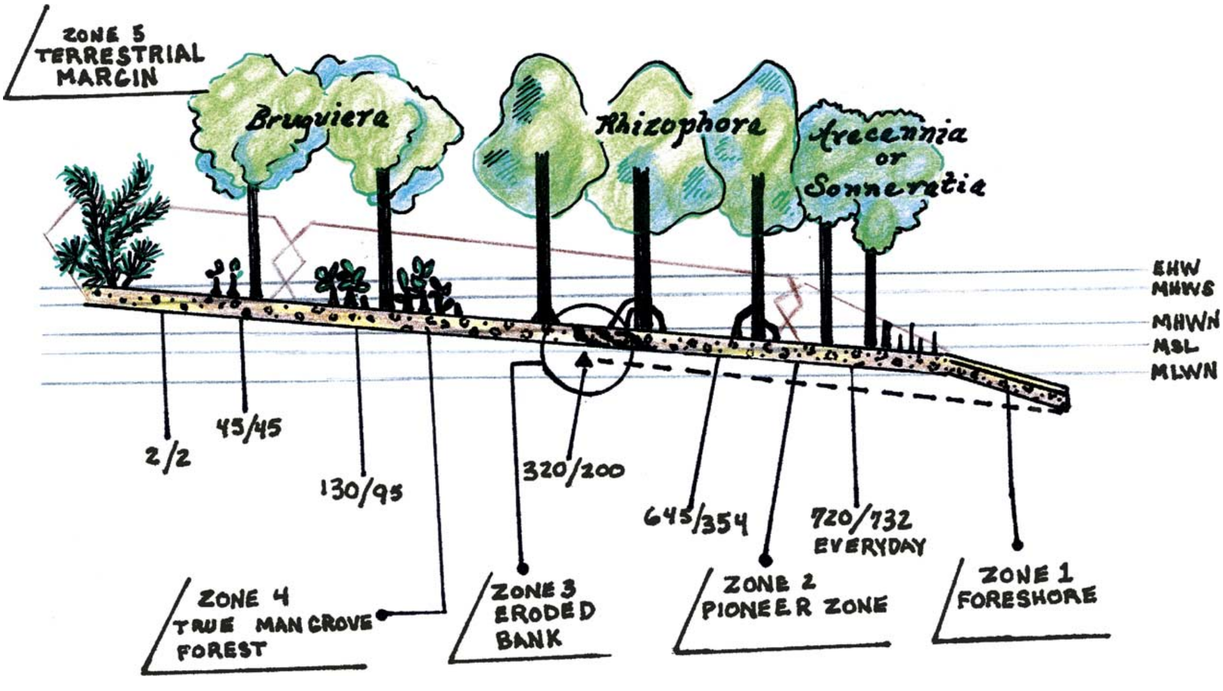

Fig. 2. Mangrove zonation related to tidal datums in Sumatra, Indonesia (modified from Whitten et al., 1987).

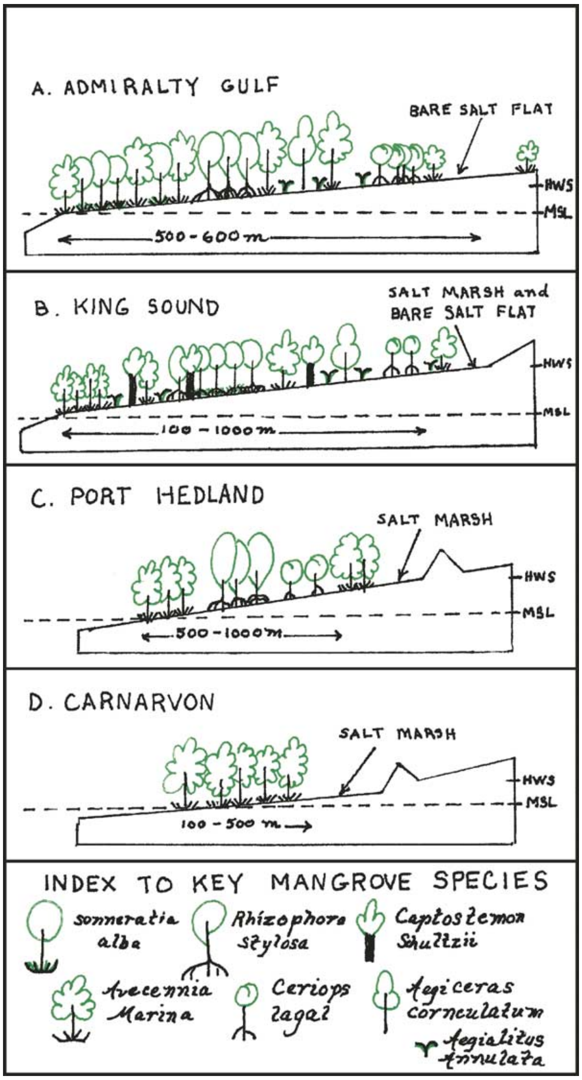

Fig. 3. Zonation of mangroves in western Australia (modified from Kenneally, 1982). Line added to emphasize mean sea level datum.

to 80% for the lowest *Spartina*. Thus, tidal marshes appear to have a range of tolerance for submergence greater than that of mangrove forests.

The implications of these data are significant, and often overlooked. First, it appears, based on the data generated to date that mangrove forests around the world have a similar pattern of occurrence, regardless of species composition, on a tidal plane above mean high water and extending to high water spring elevations. Second, this means that the time during which

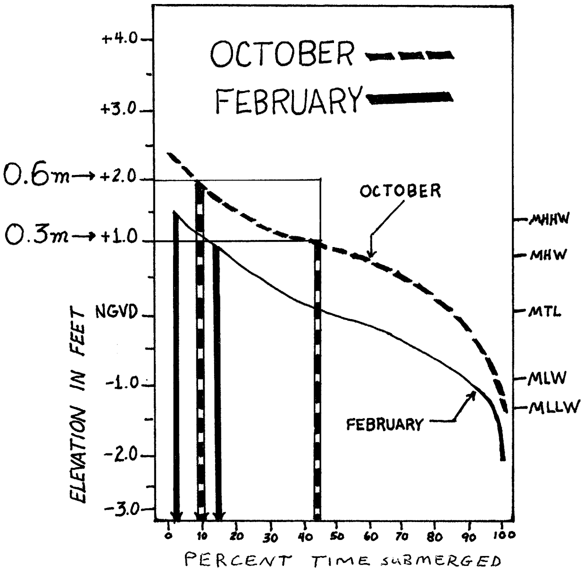

Fig. 4. The topographic position of mangroves on Tampa Bay, FL, USA (i.e. +0.3 to +0.6 m) in relationship to the percent time of submergence (modified from Lewis and Estevez, 1988).

mangroves are typically inundated by high tides is very restricted. Figs. 4 and 5 show two illustrations of the actual period of time that mangrove forests on Tampa Bay, FL, USA (Fig. 4 from Lewis and Estevez, 1988) and Gladstone, Queensland (Fig. 5 from Hutchings and Saenger, 1987) are inundated with tidal waters. Both sets of inundation curves relative to topography show that total time of inundation throughout a typical year is 30% or less. Fig. 4 shows the topographic zone within which mangroves occur on Tampa Bay (+0.3 to +0.6 m) and how frequently that zone is likely to be flooded based upon tide curves. Detailed studies of the Rookery Bay mangroves (Twilley and Chen, 1998) show similar data, with 152–158 tides per year recorded in two basin mangrove forests out of a potential of 700+ high tides per year in a system with mixed diurnal tides. Cahoon and Lynch (1997) report data for continuous water level monitoring in three red mangrove (*Rhizophora mangle*) forests, and one basin forest in southwest Florida. The mean total hours of flooding over a 2-year-period for the red mangrove forest was 6055 or 35.3% of the potential total for the three sites. The mean number of flooding events was 1184 or 1.65 tides per day. In contrast, the single basin forest site was flooded just 88 times in 2 years, yet total hours of flooding were 10,182

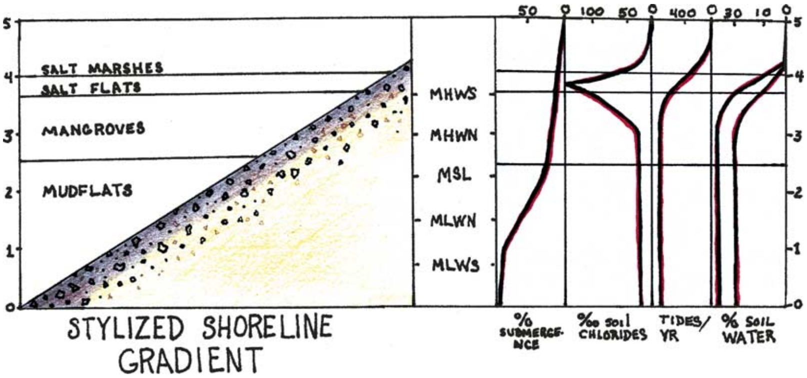

Fig. 5. Integration of vegetational boundaries with gradient-related and tidally induced boundary conditions based on data collected from study areas in Gladstone, Queensland, 1975–1983 (modified from Hutchings and Saenger, 1987).

or 59.4% of the potential time reflecting the trapping of both tidal waters and rainfall. This is not the prevailing understanding of mangrove tidal hydrology.

For example, Watson (1928) created five inundation classes ranging from Class 1, “inundated by all high tides”, to Class 5, occasionally inundated by exceptional or equinoctial tides”, and placed all the mangroves at his location in Malaysia in Classes 2–5 with distinct zonation based upon the nature of the tide that inundates an area rather than the number of times or total period of inundation. Field (1998) makes reference to topographical and hydrological changes to mangrove sites as a key to understanding rehabilitation needs, but provides no specific information. Perdomo et al. (1998) states that “[M]angroves may grow at sites which are permanently covered by shallow water . . .” without providing data to support this statement.

Although many authors note that mangroves appear to be limited to certain ground elevations relative to flooding frequency (Watson, 1928; Field, 1996; Ellison, 2000), few have ever quantified it, as noted above, and fewer still recognize the importance of this issue relative to mangrove management and restoration.

Options for restoration, as discussed before, include simply restoring hydrologic connections to impounded mangroves (Brockmeyer et al., 1997). Another is the construction, by excavation of fill or backfilling of an excavated area, to create a target restoration site with the same general slope, and the exact tidal elevations relative to a benchmark as the reference site, thus insuring that the hydrology is correct. The final graded topography of a site needs to be designed to match that found in an adjacent reference forest and checked carefully by survey during and at the completion of construction. Crewz and Lewis (1991) in examining the critical issues in success and failure in tidal marsh and mangrove restoration in Florida found that the hydrology, as created or restored by excavation to the correct tidal elevation, was the single most important element in project success. This is similar to the recommendations of Rozas and Zimmerman (1994) (as cited in Streever, 2000) for smooth cordgrass marsh creation on dredged material. Similar focused attention to the topographic grade relative to adjacent natural mangroves in constructed mangrove wetlands was shown to be the key to success in a project at Brisbane International Airport in Australia (Saenger, 1996).

McKee and Faulkner (2000a) report that two mangrove restoration sites were constructed respectively to grades of +45 cm (Site WS) and +43 cm (Site HC) relative to National Vertical Geodetic Datum (NGVD). No mention is made of how these elevations were determined. One of the referenced sites (WS) is described by Stephen (1984) as actually having variable final topographic elevations ranging from +24 cm to +190 cm at the time of completion of construction, with the +45 cm elevation being the original target elevation based upon surveys of the surrounding mature mangroves. Stephen (1984) noted that the best observed growth of mangroves was at +39 cm. Both Stephen (1984) and McKee and Faulkner (2000a) suggested the value of creating tidal creeks as part of these mangrove restoration projects in order to improve flushing. This is a predominant theme also in Zedler (2001) related to

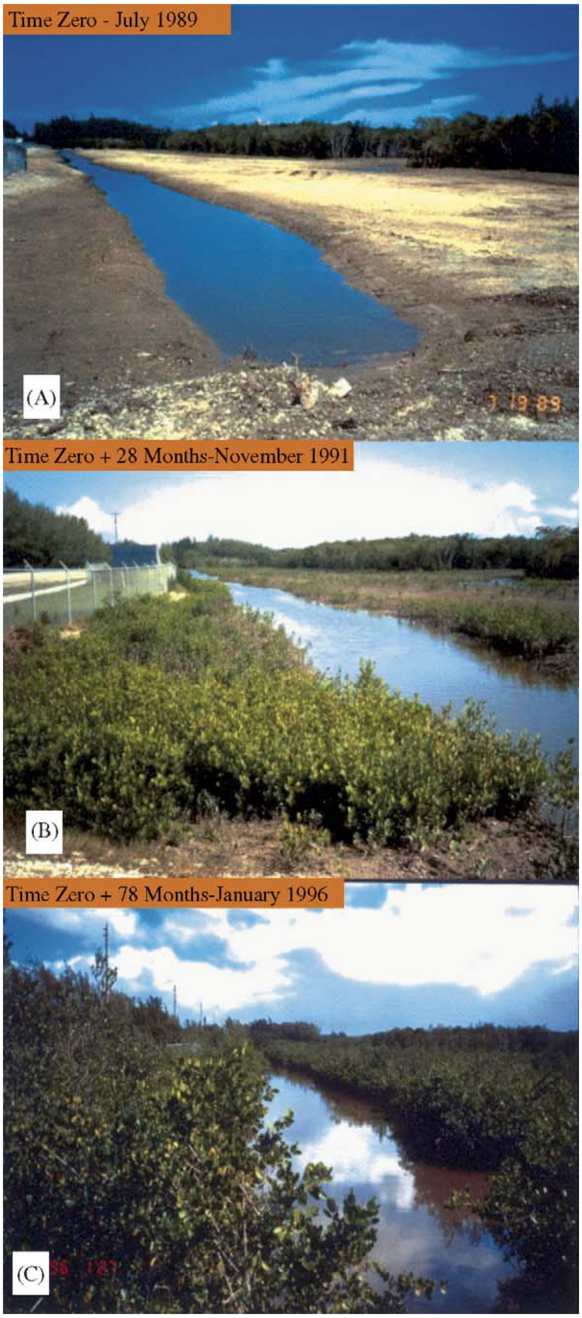

Fig. 6. Time series photographs of a hydrologic mangrove restoration project at West Lake Park, Hollywood, FL, USA (A) Time Zero, July 1989, (B) Time Zero + 28 months, November 1991 and (C) Time Zero + 78 months, January 1996. No planting of mangroves occurred. All vegetation derived from volunteer mangrove propagules.

tidal marsh restoration. Stephen (1984) also notes that consideration should be given to intentional variation of grade and creation of permanent ponded areas to provide habitat for small fish, wading birds, algae and oysters.

Fig. 6A–C show a time sequence over a period of 78 months from the completion of a portion of a hydrologic restoration at a 500 ha mangrove restoration site at West Lake near Fort Lauderdale, Florida. Lewis (1990a) describes the details of the work, but again success resulted from using a reference site, and targeting final constructed grades as the same as the adjacent undisturbed forest. This resulted in a final sloped grade from +27 cm to + 42 cm MSL. Extensive constructed tidal creeks were also added to the original plans, which had been designed without them. No planting of mangroves took place or was necessary. All three of the Florida species of mangroves (red mangrove (*Rhizophora mangle*), black mangrove (*Avicennia germinans*) and white mangrove (*Laguncularia racemosa*). volunteered on their own. Another form of this hydrologic restoration is to reconnect impounded mangroves to normal tidal influence (Turner and Lewis, 1997; Brockmeyer et al., 1997).

Both of these typical options require detailed review and discussion between an ecological engineer and a mangrove restoration ecologist. Further inputs may be needed from a surveyor, hydrologist, a geologist and finally the client paying the bills.

6. Controlling the costs of restoration

Lewis (submitted for publication) reports that the range of reported costs for mangrove restoration was US\$ 225–216,000 ha^{-1} without the cost of the land. Brockmeyer et al. (1997) was able to keep restoration costs to US\$ 250 ha^{-1} with careful placement of culverted openings to impounded mangrove wetlands along the Indian River Lagoon, USA. Similar types of this hydrologic restoration are reported in Turner and Lewis (1997). Milano (1999) described in some detail the planning and construction process for ten wetland restoration projects in Biscayne Bay, FL, USA (Miami), of which eight were mangrove restoration projects. Careful planning to achieve success was emphasized, as were methods of insuring cost control. The eight projects ranged in cost from US$ 4286–214,285 ha^{-1}, with a mean of US$ 100,308 ha^{-1}. King (1998) has updated his 1993 cost estimates (King and Bohlen, 1994) to 1997 cost estimates for various wetland restoration costs and lists mangrove restoration at US$ 62,500 ha^{-1} excluding any land costs. Lewis Environmental and Coastal Environmental (1996) give cost estimates of US$ 62,500 ha^{-1} for government tidal wetland restoration attempts and US$ 125,000 ha^{-1} for private efforts, again without factoring in land costs. It is obvious that at these rates, mangrove restoration can be expensive, and therefore should be designed to be successful to avoid wasting large amounts of hard-to-get restoration dollars.

7. Emerging restoration principles

1. Get the hydrology right first.
2. Do not build a nursery, grow mangroves and just plant some area currently devoid of mangroves (like a convenient mudflat). There is a reason why mangroves are not already there or were not there in the recent past or have disappeared recently. Find out why.
3. Once you find out why, see if you can correct the conditions that currently prevent natural colonization of the selected mangrove restoration site. If you cannot correct those conditions, pick another site.
4. Use a reference mangrove site for examining normal hydrology for mangroves in your particular area. Either install tide gauges and measure the tidal hydrology of a reference mangrove forest or use the surveyed elevation of a reference mangrove forest floor as a surrogate for hydrology, and establish those same range of elevations at your restoration site or restore the same hydrology to an impounded mangrove by breaching the dikes in the right places. The “right places” are usually the mouths of historic tidal creeks. These are often visible in vertical (preferred) or oblique aerial photographs.
5. Remember that mangrove forests do not have flat floors. There are subtle topographic changes that control tidal flooding depth, duration and frequency. Understand the normal topography of your reference forest before attempting to restore another area.
6. Construction of tidal creeks within restored mangroves forests facilitates flooding and drainage, and allows for entree and exit of fish with the tides.
7. Evaluate costs of restoration early in project design to make your project as cost-effective as possible.

8. Conclusions

Ellison (2000) asks the question “mangrove restoration: do we know enough?” His answer is that “[R]estoration of mangal does not appear to be especially difficult . . .” and comments that in contrast to the difficulties in restoring inland wetlands, “. . . it is more straightforward to restore tidal fluctuations and flushing to impounded coastal systems where mangroves could subsequently flourish . . .”. Thus, ecological restoration of mangrove forests is feasible, has been done on a large-scale in various parts of the world and can be done cost effectively. Lewis (2000) however, has pointed out that the failure to adequately train, and retrain coastal managers (including ecological engineers) in the basics of successful coastal habitat restoration all too often leads to projects “destined to fail, or only partially achieve their stated goals”. The National Academy of Science of the United States in their report entitled “Restoring and Protecting Marine Habitat—The Role of Engineering and Technology” (National Research Council, 1994) stated that “the principle obstacles to wider use of coastal engineering capabilities in habitat protection, enhancement, restoration and creation are the cost and the institutional, regulatory and management barriers to using the best available technologies and practices” (emphasis added).

It is unfortunate that much of the research into mangrove restoration that has been carried out to date has been conducted without adequate site assessment, and without documentation of the methodologies or approaches used, and that it often lacks subsequent follow-up or evaluation. Unsuccessful (or only partially successful) projects are rarely documented. Field (1998) reports that after contacting numerous international organizations to get an overview of mangrove restoration work worldwide, “(T)he response was almost complete silence”. He attributed this to bureaucratic sloth, proprietary reluctance to reveal important findings, inadequate dissemination mechanisms and a myopic view of the general importance of rehabilitation programmes. I would add that few scientists or organizations wish to report or document failures.

In summary, a common ecological engineering approach should be applied to habitat restoration projects. The simple application of the five steps to successful mangrove restoration outlined by Lewis and Marshall (1997) would at least insure an analytical thought process and less use of "gardening" of mangroves as the solution to all mangrove restoration problems. Those involved could then begin to learn from successes or failures, act more effectively and spend limited mangrove restoration monies in a more cost-effective manner.

References

Ablaza-Baluyut, E., 1995. The Philippines fisheries sector program. In: Coastal and Marine Environmental Management. Proceedings of a workshop, 27–28 March 1995, Bangkok, Thailand, Asian Development Bank, Bangkok, Thailand, pp. 156–177.

Ball, M.C., 1980. Patterns of secondary succession in a mangrove forest in south Florida. Oecologia (Berl.) 4, 226–235.

Blasco, F., Aizpuru, M., Gers, C., 2001. Depletion of the mangroves of continental Asia. Wetland Ecol. Manag. 9 (3), 245–256.

Brockmeyer Jr., R.E., Rey, J.R., Virnstein, R.W., Gilmore, R.G., Ernest, L., 1997. Rehabilitation of impounded estuarine wetlands by hydrologic reconnection to the Indian River Lagoon, Florida (USA). Wetland Ecol. Manag. 4 (2), 93–109.

Cahoon, D.R., Lynch, J.C., 1997. Vertical accretion and shallow subsidence in a mangrove forest of southwestern Florida, USA. Mangroves Salt Marshes 1 (3), 173–186.

Callaway, J.C., 2001. Hydrology and substrate. In: Zedler, J.B. (Ed.), Handbook for Restoring Tidal Wetlands. CRC Press, Boca Raton, Florida, pp. 89–117 (Chapter 3).

Cintron-Molero, G., 1992. Restoring mangrove systems. In: Thayer, G.W. (Ed.), Restoring the Nation's Marine Environment. Maryland Seagrant Program, College Park, Maryland, pp. 223–277.

Cintron, G., Lugo, A.E., Pool, D.J., Morris, G., 1978. Mangroves and arid environments in Puerto Rico and adjacent islands. Biotropica 10, 110–121.

Clements, F.E., 1929. Plant Competition. Carnegie Institute of Washington Publications, p. 398.

Crewz, D.W., Lewis, R.R., 1991. An Evaluation of Historical Attempts to Establish Emergent Vegetation in Marine Wetlands in Florida. Florida Sea Grant Technical Publication No. 60. Florida Sea Grant College, Gainesville, Florida.

Custodio, C.C., 1996. Conservation of migratory waterbirds and their wetland habitats in the Philippines. In: Wells, D.R., Mundikur, T. (Eds.), Conservation of migratory waterbirds and their wetland habitats in the East Asian-Australasian flyway. Proceedings of an International Workshop, Kushiro, Japan. 28 November–3 December, 1994. Wetlands International Asia Pacific, Kuala Lumpur, Publication No. 116, 163–173.

Davis, J.H., 1940. The ecology and geologic role of mangroves in Florida. Carnegie Inst. Wash. Pap. Tortugas Lab. No. 32. Publ. 517, 305–412.

Das, P., Basak, U.C., Das, A.B., 1997. Restoration of the mangrove vegetation in the Mahanadi Delta, Orissa, India. Mangroves Salt Marshes 1 (3), 155–161.

de Leon, T.O.D., White, A.T., 1999. Mangrove rehabilitation in the Philippines. In: Streever, W. (Ed.), An International Perspective on Wetland Rehabilitation. Kluwer Academic Publishers, The Netherlands, pp. 37–42.

Detweiler, T.E., Dunstan, F.M., Lewis, R.R., Fehring, W.K., 1975. Patterns of secondary succession in a mangrove community. In: Lewis, R.R. (Ed.), Proceedings of the Second Annual Conference on Restoration of Coastal Plant Communities in Florida. Hillsborough Community College, Tampa, Florida, pp. 52–81.

Duke, N., 1992. Mangrove floristics and biogeography. In: Robertson, A.I., Alongi, D.M. (Eds.), Tropical Mangrove Ecosystems. American Geophysical Union, Washington, DC, pp. 63–100.

Duke, N., 1996. Mangrove reforestation in Panama. In: Field, C. (Ed.), Restoration of Mangrove Ecosystems. International Society for Mangrove Ecosystems, Okinawa, Japan, pp. 209–232.

Ellison, A.M., 2000. Mangrove restoration: do we know enough? Rest. Ecol. 8 (3), 219–229.

Erftemeijer, P.L.A., Lewis, R.R., 2000. Planting mangroves on intertidal mudflats: habitat restoration or habitat conversion? In: Proceedings of the ECOTONE VIII Seminar Enhancing Coastal Ecosystems Restoration for the 21st Century, Ranong, Thailand, 23–28 May 1999. Royal Forest Department of Thailand, Bangkok, Thailand, pp. 156–165.

Food and Agricultural Organization (FAO), 2003. New global mangrove estimate. http://www.fao.org/forestry/foris/webview/forestry2/index.jsp%3Fgeold=0%26langid.

Field, C.D. (Ed.), 1996. Restoration of Mangrove Ecosystems. International Society for Mangrove Ecosystems, Okinawa, Japan.

Field, C.D., 1998. Rehabilitation of mangrove ecosystems: an overview. Mar. Pollut. Bull. 37 (8–12), 383–392.

Finn, M., 1996. The mangrove mesocosm of Biosphere 2: design, establishment and preliminary results. Ecol. Eng. 6, 21–56.

Finn, M., 1999. Mangrove ecosystem development in Biosphere 2. Ecol. Eng. 13, 173–178.

Furukawa, K.E., Wolanski, E., Mueller, H., 1997. Currents and sediment transport in mangrove forests. Estuar. Coast. Shelf Sci. 44, 301–310.

Hamilton, L.S., Snedaker, S.C. (Eds.), 1984. Handbook of Mangrove Area Management. East West Centre, Honolulu, Hawaii.

Hinde, H.P., 1954. The vertical distribution of salt marsh phanerograms in relation to tide levels. Ecol. Monogr. 24 (2), 210–225.

Hong, P.N., 2000. Effects of mangrove restoration and conservation on the biodiversity and environment in Can Gio district, Ho Chi Minh City. In: Asia-Pacific Cooperation on Research for Conservation of Mangroves, Proceedings of an International Workshop. The United Nations University, Tokyo, Japan, pp. 97–116.

Hutchings, P., Saenger, P., 1987. Ecology of Mangroves. University of Queensland Press, New York.

Kairo, J.G., Dahdouh-Guebas, F., Bosire, J., Koedam, N., 2001. Restoration and management of mangrove systems—a lesson from East African region. S. Afr. J. Bot. 67, 383–389.

Kenneally, K.F., 1982. Mangroves of Western Australia. In: Clough, B.F. (Ed.), Mangrove Ecosystems in Australia—Structure, Function and Management. Australian National University Press, Canberra, Australia, pp. 95–110.

King, D., 1998. The dollar value of wetlands: trap set, bait taken, don't swallow. Nat. Wetlands Newslett. 20 (4), 7–11.

King, D., Bohlen, C., 1994. Estimating the costs of restoration. Nat. Wetlands Newslett. 16 (3), 3-5+8.

Kjerfve, B., 1990. Manual for investigation of hydrological processes in mangrove ecosystems. UNESCO/UNDP Regional Project, Research and Its Application to the Management of the Mangroves of Asia and the Pacific (RAS/86/120).

Koch, M.S., Mendelssohn, I.A., McKee, K.L., 1990. Mechanism for the hydrogen sulfide-induced growth limitation in wetland macrophytes. Limnol. Ocean 35 (2), 399–408.

Lewis, R.R., 1977. Impacts of dredging in the Tampa Bay estuary 1876–1976. In: Pruitt, E.L. (Ed.), Proceedings of the Second Annual Conference of the Coastal Society—Time-stressed Environments: Assessment and Future Actions. The Coastal Society, Arlington, Virginia, pp. 31–55.

Lewis, R.R., 1979. Large scale mangrove restoration in St. Croix, U. S. Virgin Islands. In: Cole, D.P. (Ed.), Proceedings of the Sixth Annual Conference on Restoration and Creation of Wetlands. Hillsborough Community College, Tampa, Florida, pp. 231–242.

Lewis, R.R., 1982a. Mangrove forests. In: Lewis, R.R. (Ed.), Creation and Restoration of Coastal Plant Communities. CRC Press, Boca Raton, Florida, pp. 153–172.

Lewis, R.R., 1982b. Low marshes, peninsular Florida. In: Lewis, R.R. (Ed.), Creation and Restoration of Coastal Plant Communities. CRC Press, Boca Raton, Florida, pp. 147–152.

Lewis, R.R., 1990a. Creation and restoration of coastal plain wetlands in Florida. In: Kusler, J.A., Kentula, M.E. (Eds.), Wetland Creation and Restoration: The Status of the Science. Island Press, Washington, DC, pp. 73–101.

Lewis, R.R., 1990b. Creation and restoration of coastal wetlands in Puerto Rico and the US Virgin Islands. In: Kusler, J.A., Kentula, M.E. (Eds.), Wetland Creation and Restoration: The Status of the Science. Island Press, Washington, DC, pp. 103–123.

Lewis, R.R., 1990c. Wetlands restoration/creation/enhancement terminology: suggestions for standardization. In: Kusler, J.A., Kentula, M.E. (Eds.), Wetland Creation and Restoration: The Status of the Science. Island Press, Washington, D.C, pp. 417–422.

Lewis, R.R., 1992. Coastal habitat restoration as a fishery management tool. In: Stroud, R.H. (Ed.), Stemming the Tide of Coastal Fish Habitat Loss, Proceedings of a Symposium on Conservation of Coastal Fish Habitat, Baltimore, Md., 7–9 March 1991. National Coalition for Marine Conservation, Inc., Savannah, Georgia, pp. 169–173.

Lewis, R.R., 1994. Enhancement, restoration and creation of coastal wetlands. In: Kent, D.M. (Ed.), Applied Wetlands Science and Technology. Lewis Publishers, Inc., Boca Raton, Florida, pp. 167–191.

Lewis, R.R., 1999. Key concepts in successful ecological restoration of mangrove forests. In: Proceedings of the TCE-Workshop No. II, Coastal Environmental Improvement in Mangrove/Wetland Ecosystems, 18–23 August 1998, Danish-SE Asian Collaboration on Tropical Coastal Ecosystems (TCE) Research and Training, Network of Aquaculture Centres in Asia-Pacific, Bangkok, Thailand, pp. 19–32.

Lewis, R.R., 2000. Ecologically based goal setting in mangrove forest and tidal marsh restoration in Florida. Ecol. Eng. 15 (3–4), 191–198.

Lewis, R.R., submitted for publication. Mangrove restoration—costs and benefits of successful ecological restoration. Proceedings of the Mangrove Valuation Workshop, Universiti Sans Malaysia, Penang, April 4–8, 2001. Beijer International Institute of Ecological Economics, Stockholm, Sweden.

Lewis, R.R., Gilmore Jr., R.G., Crewz, D.W., Odum, W.E., 1985. Mangrove habitat and fishery resources of Florida. In: Seaman, W. (Ed.), Florida Aquatic Habitat and Fishery Resources, Florida Chapter. American Fisheries Society, Eustis, Florida, pp. 281–336.

Lewis, R.R., Kusler, J.A., Erwin, K.L., 1995. Lessons learned from five decades of wetland restoration and creation in North America. In: Montes, C., Oliver, G., Molina, F., Cobos, J. (Eds.), In: Ecological Basis of Restoration of Wetlands in the Mediterranean Basin, University of La Rabida(Huelva) Spain, 7–11 June 1993 Junta de Andalucia, Spain, pp. 107–122.

Lewis, R. R., Marshall, M. J., 1997. Principles of successful restoration of shrimp Aquaculture ponds back to mangrove forests. Programa/resumes de Marcuba '97, September 15/20, Palacio de Convenciones de La Habana, Cuba, p. 126.

Lewis, R. R., Estevez, E. D., 1988. The Ecology of Tampa Bay, Florida: An Estuarine Profile. National Wetlands Research Center, US Fish and Wildlife Service, Biological Report No. 85 (7.18), Washington, DC.

Lewis, R. R., Streever, W., 2000. Restoration of Mangrove Habitat. Tech Note ERDC TN-WRP-VN-RS-3. US Army, Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi.

Lewis Environmental Services, Inc., Coastal Environmental, Inc., 1996. Setting Priorities for Tampa Bay Habitat Protection and Restoration: Restoring the Balance. Tampa Bay National Estuary Program, Technical Publication #09-95, St. Petersburg, Florida.

Lugo, A.E., Snedaker, S.C., 1974. The ecology of mangroves. In: Johnson, R.F., Frank, P.W., Michener, C.D. (Eds.), Annual Review of Ecology and Systematics, 5, pp. 39–64.

Martinez, R., Cintron, G., Encarnacion, L.A., 1979. Mangroves in Puerto Rico: A Structural Inventory. Department of Natural Resources, Government of Puerto Rico, San Juan, Puerto Rico.

McKee, K.L., 1993. Soil physiochemical patterns and mangrove species distribution-reciprocal effects? J. Ecol. 81, 477–487.

McKee, K.L., 1995a. Seedling recruitment patterns in a Belizean mangrove forest: effects of establishment ability and physiochemical factors. Oecologia 101, 448–460.

McKee, K.L., 1995b. Interspecific variation in growth, biomass partitioning, and defensive characteristics of neotropical mangrove seedlings: response to availability of light and nutrients. Am. J. Bot. 82 (3), 299–307.

McKee, K.L., Mendelssohn, I.A., Hester, M.W., 1988. Reexamination of porewater sulfide concentrations and redox potentials near the aerial roots of *Rhizophora mangle* and *Avicennia germinans*. Am. J. Bot. 75 (9), 1352–1359.

McKee, K.L., Faulkner, P.L., 2000a. Restoration of biogeochemical function in mangrove forests. Rest. Ecol. 8 (3), 247–259.

McKee, K.L., Faulkner, P.L., 2000b. Mangrove peat analysis and reconstruction of vegetation history at the Pelican Cays, Belize. Atoll Res. Bull. No. 46, 45-58.

Medina, E., Fonseca, H., Barboza, F., Francisco, M., 2001. Natural and man-induced changes in a tidal channel mangroves system under tropical semiarid climate at the entrance to the Maracaibo lake (Western Venezuela). Wetland Ecol. Manag. 9 (3), 233–243.

Mendelssohn, I.A., Morris, J.T., 2000. Ecophysiological controls on the productivity of *Spartina alterniflora* Loisel. In: Weinstein, M.P., Kreeger, D.A. (Eds.), Concepts and Controversies in Tidal Marsh Ecology. Kluwer Academic Publishers, Boston, pp. 59–80.

Milano, G.R., 1999. Restoration of coastal wetlands in southeastern Florida. Wetland J. 11 (2), 15–24, 29.

Mitsch, W.J., Jørgensen, S.E., 2004. Ecological Engineering and Ecosystem Restoration. John Wiley and Sons, Inc., Hoboken, NJ.

Nickerson, N.H., Thibodeau, F.R., 1985. Associations between pore water sulfide concentrations and the distribution of mangroves. Biogeochemistry 1, 183–192.

National Research Council, 1994. Restoring and Protecting Marine Habitat-The Role of Engineering and Technology. National Academy Press, Washington, DC.

Perdomo, L., Ensminger, I., Espinosa, L.F., Elster, C., Wallner-Kersanach, M., Schnetter, M.-L., 1998. The mangrove ecosystem of Cienaga Grande de Santa Marta (Colombia): observations on regeneration and trace metals in sediment. Mar. Pollut. Bull. 37 (8–12), 393–403.

Platong, J., 1998. Status of Mangrove Forests in Southern Thailand. Wetlands International—Thailand Programme. Hat Yai, Thailand, Publication No. 5.

Rozas, L.P., Zimmerman, R.J., 1994. Developing design parameters for constructing ecologically functional marshes using dredged material in Galveston Bay, Texas. In: Dredging'94, Proceedings of the second International Conference on Dredging and Dredged Material Placement, vol. 1. American Society of Civil Engineers, New York, NY, pp. 810–822.

Rubin, J.A., Gordon, C., Amatekpor, J.K., 1999. Causes and consequences of mangrove deforestation in the Volta Estuary, Ghana. Some recommendations for ecosystem restoration. Mar. Pollut. Bull. 37 (8–12), 441–449.

Saenger, P., 1996. Mangrove restoration in Australia: a case study of Brisbane International Airport. In: Field, C.D. (Ed.), Restoration of Mangrove Ecosystems. International Society for Mangrove Ecosystems, Okinawa, Japan, pp. 36–51.

Saenger, P., 2002. Mangrove Ecology. In: Silviculture and Conservation. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Saenger, P., Siddiqi, N.A., 1993. Land from the seas: the mangrove afforestation program of Bangladesh. Ocean Coastal Manag. 20, 23–39.

Sanyal, P., 1998. Rehabilitation of degraded mangrove forests of the Sunderbans of India. In: Program of the International Workshop on Rehabilitation of Degraded Coastal Systems, Phuket Marine Biological Center, 19–24 January 1998, Phuket, Thailand, p. 25.

Silliman University, 1996. Assessment of the Central Visayas Regional Project-I: Nearshore Fisheries Component. Final Draft, vol. 1, Dumaguete City, Philippines.

Society for Ecological Restoration (SER), 2002. SER International Science and Policy Working Group. The SER Primer on Ecological Restoration. (www.ser.org/content/ecological_restoration_primer.asp).

Soemodihardjo, S., Wiroatmodjo, P., Mulia, F., Harahap, M.K., 1996. Mangroves in Indonesia—a case study of Tembilahan, Sumatra. In: Fields, C. (Ed.), Restoration of Mangrove Ecosystems. International Society for Mangrove Ecosystems, Okinawa, Japan, pp. 97–110.

Spalding, M.D., 1997. The global distribution and status of mangrove ecosystems. Intercoast Network Newslett. 1, 20–21, Special Edition #1.

Spurgeon, J., 1999. The socio-economic costs and benefits of coastal habitat rehabilitation and creation. Mar. Pollut. Bull. 37 (8–12), 373–382.

Stephen, M.F., 1984. Mangrove restoration in Naples, Florida. In: Webb Jr., F.J. (Ed.), Proceedings of the 10th Annual Conference on Wetlands Restoration and Creation. Hillsborough Community College, Tampa, Florida, pp. 201–216.

Stevenson, N.J., Lewis, R.R., Burbridge, P.R., 1999. Disused shrimp ponds and mangrove rehabilitation. In: Streever, W.J. (Ed.), An International Perspective on Wetland Rehabilitation. Kluwer Academic Publishers, The Netherlands, pp. 277–297.

Streever, W.J., 2000. *Spartina alterniflora* marshes on dredged material: a critical review of the ongoing debate over success. Wetland Ecol. Manag. 8 (5), 295–316.

Sullivan, G., 2001. Chapter four. Establishing vegetation in restored and created coastal wetlands. In: Zedler, J.B. (Ed.), Handbook for Restoring Tidal Wetlands. CRC Press, Boca Raton, Florida, pp. 119–155.

Thibodeau, F.R., Nickerson, N.H., 1986. Differential oxidation of mangrove substrate by *Avicennia germinans* and *Rhizophora mangle*. Am. J. Bot. 73, 512–516.

Tunhikorn, S., Round, P.D., 1996. The status and conservation needs of migratory shorebirds in Thailand. In: Wells, D.R., Mundikur, T. (Eds.), Conservation of Migratory Waterbirds and Their Wetland Habitats in the East Asian-Australasian Flyway, Proceedings of an International Workshop, Kushiro, Japan, 28 November–3 December 1994. Wetlands International-Asia Pacific, Kuala Lumpur, Malaysia, Publication No. 116, pp. 119–132.

Turner, R.E., Lewis, R.R., 1997. Hydrologic restoration of coastal wetlands. Wetland Ecol. Manag. 4 (2), 65–72.

Twilley, R.R., Chen, R., 1998. A water budget and hydrology model of a basin mangrove forest in Rookery Bay, Florida. Mar. Freshwater Res. 49, 309–323.

Vivian-smith, G., 2001. Box 2.1. Reference data for use in restoring Tijuana Estuary. In: Zedler, J.B. (Ed.), Handbook for Restoring Tidal Wetlands. CRC Press, Boca Raton, Florida, pp. 59–63.

Watson, J.G., 1928. Mangrove Forests of the Malay Peninsula. Malayan Forest Records No. 6. Fraser and Neave Ltd., Singapore.

Weinstein, M.P., Teal, J.M., Balletto, J.H., Strait, K.A., 2001. Restoration principles emerging from one of the world's largest tidal marsh restoration projects. Wetland Ecol. Manag 9 (3), 387–407.

Whitten, A.J., Damanik, S.J., Anwar, J., Hisyam, N., 1987. The Ecology of Sumatra. Gadjah Mada University Press, Indonesia.

Wolanski, E., Mazda, Y., Ridd, P., 1992. Mangrove hydrodynamics. In: Robertson, A.I., Alongi, D.M. (Eds.), Tropical Mangrove Ecosystems. American Geophysical Union, Washington, DC, pp. 436–462.

Zedler, J.B. (Ed.), 2001. Handbook for Restoring Tidal Wetlands. CRC Press, Boca Raton, Florida.