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ORIGINAL PAPER

Long-term development of tidal mitigation wetlands in Florida

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Abstract Monitoring periods for compensatory wetland mitigation projects are relatively short, typically 3 to 5 years. Although forested wetlands may require decades to develop structural characteristics similar to those of natural systems, studies that describe long-term trends in site development are rare. Eighteen mitigation sites in Florida that had originally been sampled in 1988 were re-visited in 2005. Changes in mangrove community composition and stand structure occurring over this timeframe at ten of these sites are described and compared with other mangrove wetlands in Florida. Factors limiting development of the remaining sites are discussed. The continued persistence and development of the majority of these mitigation sites indicates that the mitigation process can be successful, at least in terms of compliance with the typical permit requirements. Basal area and height had increased at most sites, and some were difficult to visually distinguish from adjacent natural stands of mangroves. However, even after 13–25 years, stand structure in mangrove mitigation wetlands in Florida still differed from that of natural sites. Although the number of mangrove species was similar, mitigation sites had lower basal area and height than natural sites, and were more dense and complex than natural sites.

Keywords Mangrove stand structure · Mitigation · Excavated wetlands

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Introduction

Many areas in Florida have experienced losses of mangrove swamps over the last few decades. Lewis et al. (1985) estimated that, by the 1980's, approximately 600 km^2 (23%) of the mangrove forests in Florida had already been lost, relative to historic levels. In some areas, the losses have been particularly dramatic. For example, in Biscayne Bay, a loss of more than 52,200 ha (82%) of mangroves was documented by Lewis (1982a). In Tampa Bay, 4,423 ha (44%) have been lost (Lewis 1982a). Recent reports suggest that the rate of mangrove loss is decreasing. In 2004, the total mangrove acreage was estimated at 275,750 ha, a loss of 325 ha since 1998 (Dahl 2006). Due to the interconnectivity of mangroves and other coastal ecosystems such as seagrasses and coral reefs, and their importance in maintaining fisheries productivity, continued loss of mangrove forests could have widespread deleterious consequences for tropical nearshore ecosystems (Mumby et al. 2004).

The U.S. Army Corps of Engineers and Florida Department of Environmental Regulation require permits for excavation or fill of certain wetland types, but originally there was no requirement for mitigation (Lewis 1990). In the mid- to late 1980s, mitigation for adverse wetland impacts began to receive increased attention due to the passage of a new wetlands protection act by the Florida legislature (Lewis 1990). As a result, mitigation to offset wetland degradation and loss became a major focus of wetland restoration and creation efforts (Lewis 1990). Success of mitigation sites is typically evaluated based on relatively simple criteria, such as survival of planted stock or measurements of percent cover, over some period of time, usually 3–5 years or less (Mitsch and Wilson 1996). Although the use of performance curves based on data from known age sites has been suggested by a number of authors as a way to understand the development of restoration and mitigation sites, the development of such tools has been impeded by a lack of appropriate long-term datasets (Simenstad and Thom 1996; Kentula 2000). Crewz and Lewis (1991) suggested that monitoring periods of 10–25 years may be required to evaluate mangrove mitigation success based on vegetative structural characteristics, but studies that describe long-term trends in site development are rare. The present study describes changes in plant community composition and mangrove stand structure occurring over a timeframe of nearly two decades at wetland mitigation sites in southern and central Florida. Structural characteristics of mitigation wetlands dominated by mangroves are compared with natural mangrove sites.

Methods

Twenty-three mitigation wetland sites in central and southern Florida were first sampled in 1988 as part of an earlier project to assess mitigation success (T. Roberts 1988, Tennessee Technological University, Cookeville, TN, unpublished data). In 2005, 18 of these sites were re-visited. The locations, planting dates, and ages of these sites are shown in Table 1. Of these 18 sites, all except one had originally been planted with mangroves or a combination of red mangrove (*Rhizophora mangle*) and emergent marsh

Table 1 Locations, planting dates, and ages of 18 mitigation wetlands sampled in 1988 that were revisited in 2005 for this study

Site	Latitude	Longitude	County	Year planted	Age (in 2005)
Admiral's Cove	26° 54.346	80° 05.132	Palm Beach	1980	24
Don Acres	25° 58.096	80° 08.021	Dade	1985	20
Ft. Myers Wharf[a]	27° 38.729	82° 52.383	Lee	1987	17
Gandy Bridge[a]	27° 53.527	82° 32.074	Hillsborough	1982	23
Hammer Point	25° 01.404	80° 30.788	Monroe	1984	21
Island Shoppes[a]	27° 15.389	80° 11.931	St. Lucie	1984	20
Kritzer[a]	25° 04.951	80° 26.605	Monroe	1983	21
Linda Road	25° 10.127	80° 22.920	Monroe	?	?
Lookout Point	27° 52.756	82° 31.767	Hillsborough	1985	20
MacDill AFB[a]	27° 49.664	82° 28.431	Hillsborough	1986	18
Miramar	27° 16.995	80° 12.662	St. Lucie	1984	21
Peace River	27° 56.965	82° 01.216	Sarasota	1983	22
Punta Gorda[a]	26° 55.332	82° 03.126	Charlotte	1983	22
Sailfish Point	27° 10.392	80° 09.925	St. Lucie	1980	25
Thunder Bay[a]	27° 52.990	82° 38.367	Pinellas	1986	19
Troutman[a]	26° 29.135	82° 00.268	Lee	1987	17
Whiskey Creek	26° 34.542	81° 53.916	Lee	1975	30
Windstar[a]	26° 06.660	81° 46.939	Collier	1983	21

[a] Indicates sites sampled in 2005 because they were accessible and dominated by mangroves

grasses (primarily *Spartina alterniflora)*. One site had originally been planted only with *S. alterniflora*, but had subsequently developed into mangrove forest.

In 2005, mangrove community composition and structure data were collected from 10 of the 18 sites that were both dominated by mangroves and accessible for sampling (Table 1). For the remaining 8 sites, site conditions were described, including the presence or absence of mangroves. All but the Island Shoppes site were wetland creation projects at which uplands had been graded to lower elevations. The Island Shoppes project involved planting mangrove seedlings in a portion of an existing wetland from which the trees had been removed.

To avoid introducing any potential bias in the data due to differences in sample size and methods, data were collected using the same protocols as in the original 1988 study. Three 2 m × 2 m plots were sampled at each site, near those sampled in 1988, based on landmarks identified in the author's field notes. This plot size was selected based on growth form and typical stem densities at the sites. Larger plot sizes used in studies of mature forests (e.g. 0.04 ha) would have necessitated the counting of extremely high numbers of stems. All mangroves were identified by species, and the number of stems in each of 5 size classes (Table 2) was recorded. Mean basal area (m^2 ha^{-1}) of trees greater than 2.5 cm diameter at breast height (DBH) was calculated for each site using a modification of the method described in Cintron and Novelli (1984), in which the midpoints of size classes III–V (Table 2) were used in place of individual DBH measurements. Mean basal area was not calculated for 1988 data since all of the sites except one contained only trees less than 2.5 cm DBH. The average canopy height was measured for each plot using a graduated survey rod.

Table 2 Mangrove size classes used in this study

Size class	DBH range (cm)
I	0–1.3
II	1.3–2.5
III	2.5–5.1
IV	5.1–10.2
V	>10.2

Paired *t*-tests (JMP 5.1) were used to evaluate changes in average canopy height between 1988 and 2005. The 95% confidence intervals constructed from the paired *t*-test analyses were then used to estimate rate of height increase during the first two decades of site development. Using 2005 data, a mangrove structural complexity index (I_c) was calculated according to the formula I_c = number of species × mean stem density (stems > 2.5 cm DBH ha^{-1}) × mean total basal area (m^2 ha^{-1}) × mean stand height (m) × 10^{-6} (McKee and Faulkner 2000). The data obtained in the present study were used to compare structural characteristics (e.g. number of mangrove species, mean height, mean basal area, and mean stem density) of the sampled mitigation sites with other mangrove wetlands in Florida using data from Pool et al. (1977) and McKee and Faulkner (2000). The sites described in Pool et al. (1977) and McKee and Faulkner (2000) were located on the Atlantic coast of Florida south of Miami, and along the Gulf coast of Florida, from Naples southward to Everglades City, near some of the same sites sampled in the present study. Data reported by Pool et al. (1977) and McKee and Faulkner (2000) were converted to the same units of measure and the I_c re-calculated. The combined dataset was analyzed by multi-dimensional scaling (MDS) using standardized data and Euclidean distance as the similarity measure (PRIMER 5.1). Standardization is recommended when different parameters are measured by different methods and units (Pielou 1984). Prior to analysis, density data were transformed by multiplying by 10^{-3} to minimize the influence of large numbers on the outcome of the analysis (Clarke and Warwick 2001).

Results

Vegetative characteristics

Species composition

In Florida, three mangrove species occur: the red mangrove (*R. mangle*), black mangrove (*Avicennia germinans*), and the white mangrove (*Laguncularia racemosa*) (Odum et al. 1982). In their early development stages, most sites were dominated by a single mangrove species (Fig. 1). In 1988, three sites were

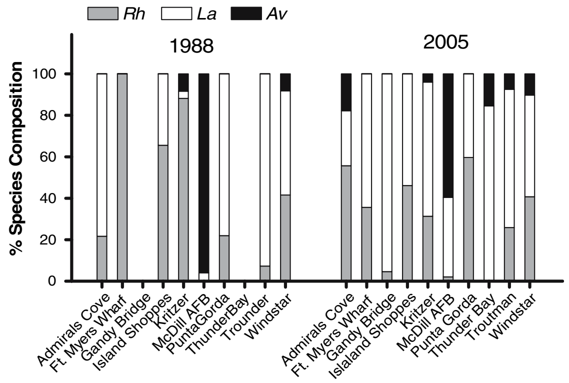

Fig. 1 Percent species composition of mangrove mitigation sites in 1988 and 2005

dominated by *Rhizophora*, Fort Myers Wharf (100%), Island Shoppes (66%), and Kritzer (88%) (Fig. 1). The MacDill AFB site was predominantly (>95%) *Avicennia*; *Avicennia* was present at only two other sites in 1988, where it represented a very small proportion (<10%) of the mangrove community (Fig. 1). The Admiral's Cove, Punta Gorda, and Troutman sites were predominately (>75%) *Laguncularia* (Fig. 1). Two sites, Gandy Bridge and Thunder Bay, lacked mangroves in 1988. Only two sites, Kritzer and Windstar, contained all three mangrove species at the time of sampling in 1988 (Fig. 1). Since *Rhizophora* had been the only species planted, the presence of *Avicennia* and *Laguncularia* at these sites was due to volunteer recruitment by mangrove seeds or seedlings.

By 2005, *Laguncularia* had become the dominant species at a majority of the sites, including two sites that had lacked mangroves in 1988, and one site that was formerly 100% *Rhizophora* (Fig. 1). *Avicennia* was present at only six sites, where it generally represented less than 20% of the mangrove community (Fig. 1). Mangrove species richness increased in four of the eight sites that had contained mangroves in 1988. By 2005, all three mangrove species were present at five sites (Fig. 1). Two sites that had originally been planted with both red mangrove and emergent marsh vegetation, Don Acres, and Gandy Bridge (Crewz and Lewis 1991), had developed into mangrove swamps by 2005. Thunder Bay had initially been planted with the marsh grass *S. alterniflora* (and contained no mangroves in 1988), but had subsequently been colonized by volunteer *Laguncularia* seedlings.

Size class distribution

With the exception of the Windstar site, all sites contained only small trees in size classes I and II (<2.5 cm DBH) when first sampled in 1988 (Fig. 2). Only 1 site, Island Shoppes, contained large trees in size class V (>10.2 cm DBH) in 2005. Individuals in size class I were present at all sites in 2005 due to volunteer recruitment. *Rhizophora* recruitment was observed at all sites except Lookout Point and MacDill AFB (Fig. 2a). Forty to fifty percent of the sites contained *Rhizophora* and *Laguncularia* in size classes I through IV (Fig. 2a, b), indicating continuous and ongoing recruitment of these species. Colonization by *Avicennia* was less frequent; of the seven sites not containing *Avicennia* in 1988, only 3 sites subsequently became colonized by that species (Fig. 2c). Only one site contained *Avicennia* in size classes I through IV, indicating less frequent and more episodic volunteer recruitment patterns by this species. *Avicennia* seedlings also were observed less frequently than other species in 2005 (Fig. 2c).

Canopy height

Results of the paired *t*-test analysis indicated that there were significant differences in average mangrove canopy height between 1988 and 2005 ($P < 0.0008$). Average mangrove canopy height increased during the interval between sampling periods at all except one site (Admiral's Cove). This site was one in which the mangroves are routinely pruned to maintain a scenic view of the waterfront. Excluding this site, the rate of increase in canopy height from 1988 to 2005 ranged between 5.4 and 25 cm year^{-1}, with an average of 16.8 cm year^{-1} (Table 3). The highest rate of increase in canopy height (25.0 cm year^{-1}) was observed at the Island Shoppes site. This site differed from all others sampled since it had been planted in an existing wetland that had been cleared rather than in an excavated site. The slowest rate of height increase occurred at the Kritzer site (5.4 cm year^{-1}). This site, located in an area of scrub mangroves on Key Largo, differed from the others in that the substrate was

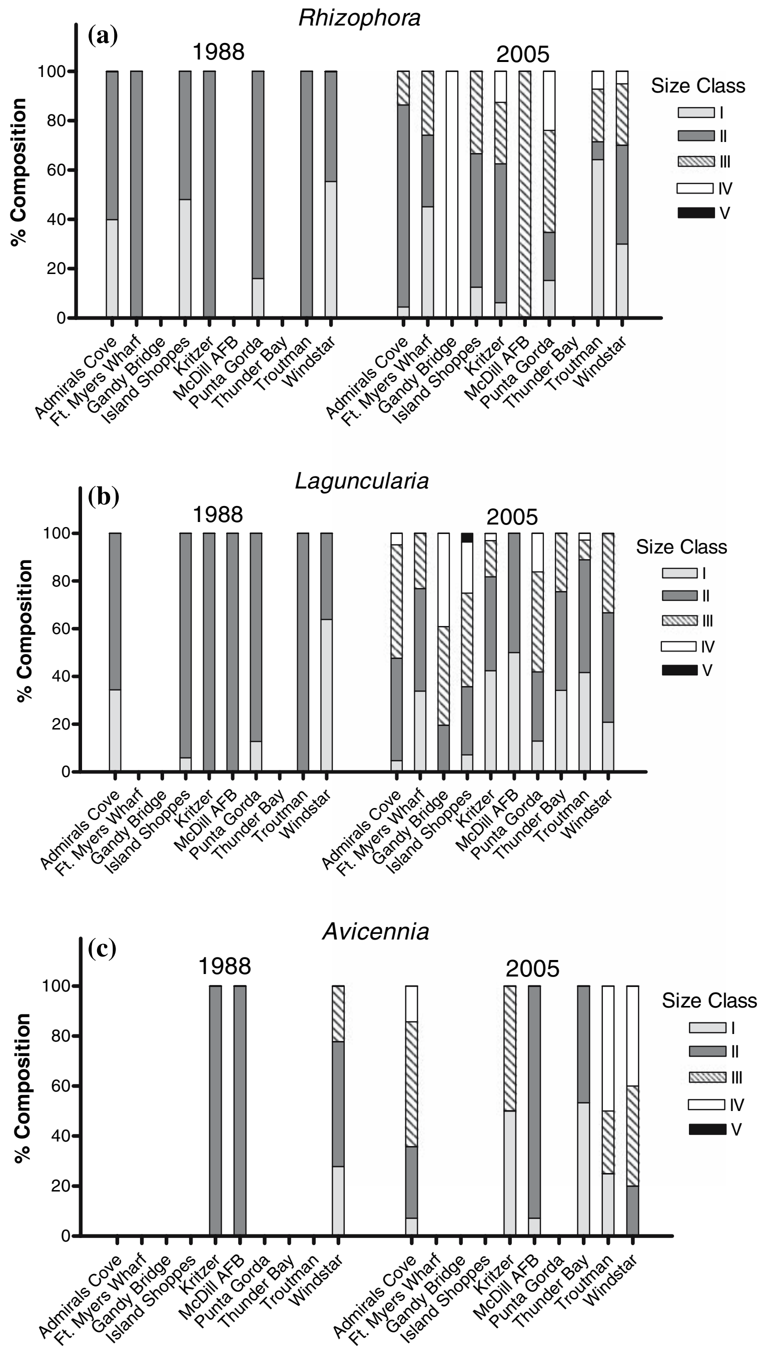

Fig. 2 Percent composition by size class in 1988 and 2005 for each mangrove species

composed largely of calcareous marl. Based on the 95% confidence intervals for canopy height constructed from the paired *t*-test analysis (excluding both the trimmed and scrub sites), estimated rates of increase in average canopy height for mangrove mitigation wetlands in Florida during the first two decades of site development are predicted to range from 13 cm year^{-1} to 23 cm year^{-1}.

Table 3 Estimated rates of increase in mangrove canopy height from 1988 to 2005

Site	Average canopy height (m)		Rate of increase (cm $year^{-1}$)
	1988	2005	
MacDill AFB	0.7	2.4	10.8
Punta Gorda Isles	1.2	5.0	23.8
Ft. Myers Wharf	0.6	3.0	14.9
Troutman	1.0	4.1	19.5
Windstar	2.6	5.5	18.1
Kritzer	0.7	1.6	5.4
Admiral's Cove	1.8	1.7	NA[a]
Island Shoppes	2.2	6.2	25.0

[a] Height is artificially maintained by pruning

Comparison with other Florida mangrove wetlands

Structural complexity indices (I_c) of mangrove mitigation wetlands were more variable than those of natural mangrove wetlands, ranging from less than 0.01 to 27.8, with an average of 7.0 (Table 4). I_c values for natural mangrove wetlands ranged from 0.2 to 5.0, with an average of 2.1 (Table 4). The MDS plot (stress = 0.01) indicated that despite some obvious similarities, structural characteristics (e.g. number of mangrove species, mean basal area, mean stem density, and mean canopy height) of 13 to 25 year-old mitigation sites differed from natural mangrove wetlands (Fig. 3). Although the number of mangrove species in mitigation wetlands was similar

Table 4 Vegetative characteristics of 19 mitigation and natural mangrove wetlands in Florida

Site	Type[a]	# Species	Canopy height (m)	Basal area (m^2/ha)	Density (stems $\geq$ 2.5 cm DBH ha^{-1})	I_c	Source
Admiral's Cove	M (24)	3	1.7	26.4	21,666	2.9	This study
Ft. Myers	M (17)	2	3.0	15.7	17,500	1.6	This study
Gandy Bridge	M (23)	2	6.4	67.6	29,167	25.0	This study
Island Shoppes	M (20)	2	6.2	47.3	21,666	12.7	This study
Kritzer	M (21)	3	1.6	19.7	10,833	1.0	This study
MacDill AFB	M (18)	3	2.4	1.2	833	0.01	This study
Punta Gorda	M (21)	2	5.0	69.4	40,000	27.8	This study
Thunder Bay	M (19)	1	3.7	15.1	16,667	0.93	This study
Troutman	M (17)	3	4.1	13.8	9,166	1.6	This study
Windstar	M (21)	3	5.5	20.1	15,000	5.0	This study
Windstar	M (13)	3	3.6	3.2	6,830	0.2	McKee and Faulkner (2000)
Henderson Creek	M (6)	2	4.8	18.4	27,700	4.9	McKee and Faulkner (2000)
Ten Thousand Islands A	N	2	6.3	26.0	2,400	0.8	Pool et al. (1977)
Ten Thousand Islands B	N	2	7.3	35.9	3,600	1.9	Pool et al. (1977)
Ten Thousand Islands C	N	2	9.0	60.2	4,600	5.0	Pool et al. (1977)
Rookery Bay	N	3	6.5	34.7	6,560	4.4	Pool et al. (1977)
Turkey Point	N	1	1.0	6.0	25,030	0.2	Pool et al. (1977)
Henderson Creek	N	3	7.5	26.3	1,840	1.1	McKee and Faulkner (2000)
Windstar	N	2	7.4	28.2	2,131	1.3	McKee and Faulkner (2000)
Mean values							
Mitigation	$N = 12$	2.4	4.0	26.5	18,086	7.0	All
Natural	$N = 7$	2.2	6.4	31.0	6,594	2.1	All

[a] N = Natural, M = Mitigation; Age of mitigation sites at time of sampling shown in ( )

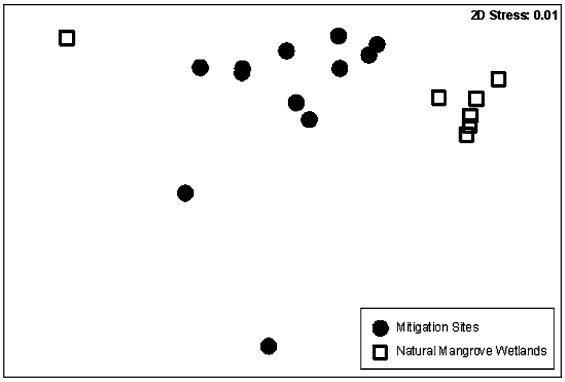

Fig. 3 Multidimensional scaling plot of mangrove structural characteristics in mitigation and natural mangrove wetlands in Florida

to natural sites, mitigation sites had lower basal area and height than natural sites, and were more dense and complex than natural sites (Table 4).

Discussion

Mitigation compliance success

Of the eighteen sites which were re-visited in 2005, 13 (72%) were dominated by mangroves, and would likely be considered ''successful'' mitigation projects based on typical performance criteria in Section 404 permits (Streever 1999). Only two sites, Linda Road and Hammer Point, both on Key Largo, were total failures (no mangroves present). The Linda Road site may never have been planted, or planted seedlings did not survive, as no seedlings were present during the first survey in 1988. The Hammer Point site had been planted but probably failed because the planting elevation was too low (Crewz and Lewis 1991) and the site remained inundated even at low tide. Two other sites, Miramar and Lookout Point, contained a few isolated mangrove plants, but site elevations may have been too high to support a mangrove community, as indicated by a paucity of obligate wetland plant species. Miramar seemed to be a successful project during the initial survey in 1988, but in 2005 there was evidence that subsequent sediment deposition during tropical storms or hurricanes had altered the flooding regime sufficiently to result in a shift to a non-wetland plant community. Both sites had been extensively colonized by *Schinus terebinthifolius* (Brazilian pepper). This species, an invasive exotic, was present at many (65%) of the sites investigated; it typically occurred in a narrow fringe adjacent to the upland edge. The growth of the mangroves at Admiral's Cove had been limited by pruning. The Peace River site appeared to be successful in 1988, but mangroves had subsequently been removed, as only seedling mangroves were present in 2005. It is not known whether these management practices had been approved in the original permit.

To evaluate mitigation compliance success, it is necessary to compare existing site conditions with permit requirements. Unfortunately, we were able to obtain permit information for only one of the projects. The difficulty in obtaining permit records for older (>10 years) wetland mitigation sites was also noted by Crewz and Lewis (1991) and Cole and Shafer (2002). For the one mangrove mitigation project in this study for which we were able to obtain copies of the original permit, the permit conditions stated only that ''an area of fill ... shall be scraped to 0.8 ft NGVD (±0.5 ft.) and re-vegetated with natural wetland species.'' Since this site was dominated by mangroves when visited in 2005, the permit criteria were met. The continued persistence and development of the majority of mangrove mitigation wetlands sites re-visited 17 years after they were initially sampled indicated that the mitigation process can be successful, at least in terms of compliance with the typical permit requirements (Streever 1999).

Factors limiting mitigation site development

Factors limiting mitigation site development included incorrect site elevation and hydrology, invasion by exotic species, conflicting land uses, and human activity. Three sites were apparently unsuccessful due to inappropriate planting elevation (either too low or too high). If site elevations are too high, this can lead to invasion and dominance by exotic species such as *S. terebinthifolius*, rather than mangroves, as seen at Lookout Point. Although intolerant of intertidal conditions, *S. terebinthifolius* can become established at higher elevations and eventually compete with mangroves (Crewz and Lewis 1991). Re-grading the site to the correct intertidal elevation is usually required in order to eliminate exotics and facilitate mangrove colonization and development (R. R. Lewis 2006, Lewis Environmental Services, Inc., Salt Springs, FL, personal communication). The importance of correct site elevation has been noted by numerous authors (Lewis 2005 and references cited therein). Since all except one of the sites in this study involved excavation of uplands to achieve the final planting elevation, careful surveys of site topography in comparison to nearby natural mangrove stands would have increased overall mitigation success of these sites.

Two sites at which wetland presence conflicted with intended property uses resulted in the wetlands either being dramatically altered or destroyed by human activity. This highlights the importance of site location in the ultimate success of mitigation projects Roberts (1991). The Peace River site adjacent to Interstate Highway 75 may have been mowed or sprayed with herbicide, whereas the Admiral's Cove site mentioned previously had been pruned to maintain a scenic water view. Mangrove pruning is regulated by the 1996 Mangrove Trimming and Preservation Act in sections 403.9321–403.9334 of the Florida Statutes (State of Florida 1996). In general, mangroves may not be pruned to a height less than 2 m; however, there are exemptions, including maintenance trimming of a previously authorized configuration. Activities such as these obviously prevent mitigation sites from obtaining the structural complexity they otherwise would. Reducing vertical complexity likely has adverse effects on birds that might use the mangroves for roosting as well as reducing the amount of organic material exported to the adjacent water-body. The likelihood that such degradation might occur should be considered by regulatory agencies prior to issuance of permits.

Changes in canopy height

Previous studies have suggested that mangroves are capable of reaching maturity within 20–30 years (Lugo and Snedaker 1974; Lugo 1980). In this study, mangrove mitigation wetlands ranging in age from 13 years to 23 years had not yet reached a canopy height similar to that of natural mangrove forests. This study provides generalized estimates of expected increases in canopy height of planted mangrove wetlands during the first two decades of site development, but it is important to recognize the limitations of estimating growth from data collected at only two points in time. As such, the linear growth estimates presented in this study may not be valid for very young sites, or sites older than those in this study. However, since the estimates of growth reported here were obtained from a number of sites that varied widely in soil type, hydrology, and species composition, the data should be adequate to provide general estimates of potential growth which could be used in the development of realistic performance standards for mangrove mitigation and restoration sites.

The slowest rates of increase in height in this study were at the Kritzer site on Key Largo. The substrate at this site was largely calcareous marl and planted mangroves at this site had attained a height of only 1.6 m after 21 years. This site was similar to the descriptions of natural stands of scrub mangroves in the Florida Keys provided by Lugo and Snedaker (1974) and Pool et al. (1977). As Lugo (1980) noted, growth and productivity rates of scrub mangroves are extremely slow. Due to their dwarf stature, these sites will never develop the structural complexity typical of other mangrove forest types. This should be taken into consideration when establishing performance standards for planted mangrove wetlands in these areas.

Plant community succession and recruitment

Use of the marsh grass *S. alterniflora* as a ''nurse'' plant for natural mangrove colonization was first promoted by Lewis and Dunstan (1976), because of its ability to stabilize bare sediments much more rapidly than mangrove plantings, at significant cost savings (Lewis 1982b). Once established, it was thought that stands of *Spartina* would effectively trap and hold mangrove propagules, facilitating mangrove establishment (Lewis 1982b). However, this is the first study to confirm the efficiency of this approach and document the timeframes over which the transition from emergent marsh to mangrove forest can occur in mitigation wetlands.

Understanding natural patterns of succession and recruitment in a given area could lead to significant improvements and cost savings in design and implementation of restoration and mitigation projects. This study confirms that if site elevations are suitable, mangrove planting is probably unnecessary in areas with an abundance of mangrove propagules. Recent work by Lewis et al. (2005) provides support for this conclusion. They document a successful 500 ha mangrove restoration project near Ft. Lauderdale, Florida, at which all three mangrove species became established without planting. In the present study, it was noteworthy that the mangrove species composition at many of the sites visited in this study changed during the period between 1988 and 2005. The most common pattern was an increase in volunteer *Laguncularia* at sites at which *Rhizophora* had been planted. Volunteer recruitment and colonization by *Avicennia* was observed less frequently. Future restoration and mitigation efforts could consider placing greater emphasis on the planting of this species, or facilitation of its natural colonization by broadcasting collected seeds, depending on local variations in natural mangrove forest succession patterns.

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