Journal of Coastal Research	17	4	936–948	West Palm Beach, Florida	Fall 2001

Evaluation of Sand Fence and Vegetation for Dune Building Following Overwash by Hurricane Opal on Santa Rosa Island, Florida†

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ABSTRACT

MILLER, D.L.; THETFORD, M., and YAGER, L., 2001. Evaluation of sand fence and vegetation for dune building following overwash by Hurricane Opal on Santa Rosa Island, Florida. *Journal of Coastal Research,* 17(4), 936–948. West Palm Beach (Florida), ISSN 0749-0208.

Santa Rosa Island, a barrier island located in the panhandle of Florida, was severely impacted by hurricane Opal's 3–4 m tidal surge in October 1995. Rapid reestablishment of the fragmented dune system through sand accumulation and stabilization is essential for many wildlife and plant species and protection of coastal structures against storm surge. Comparisons of sand accumulation rates for two biodegradable materials, three-fence orientations and non-fenced controls were assessed in a secondary dune position. Effect of winter and spring planting without supplemental water on survival and growth of nursery-grown sea oats and bitter panicum was also evaluated. Wood and Geojute material sand fences in three orientations were installed at six sites. Sand accumulation associated with these fence material/orientation combinations and non-fenced controls was measured twice a year (1996–99). There were no significant differences in sand accumulation between Geojute and wood fences at most positions for the first eight months. Following this, Geojute degraded and its accumulated sand was no more than that of the controls 18 months after installation. Sand accumulation did not differ significantly among wood fence configurations at most distances from the fence. Through time the straight–conventional wood and perpendicular-wood fence treatments had consistently higher sand accumulation values compared to unfenced controls. While survival of transplanted sea oats and bitter panicum was not effected by season of planting, growth varied with planting season.

ADDITIONAL INDEX WORDS: *Sea oats, Bitter panicum, restoration.*

INTRODUCTION

Sand dunes protect gulf coastal barrier islands and adjacent mainland from seasonal high tides, storm surges and hurricane-generated waves and provide critical habitat for endemic beach mice (DAHL and WOODARD, 1977; SWILLING *et al.,* 1997). In October 1995, Hurricane Opal's 3–4 m storm surge leveled extensive sections of sand dunes along the Florida panhandle. Highways and coastal buildings were left vulnerable to subsequent storms (WEBB *et al.,* 1997). Fragmentation of the dune system on Santa Rosa Island, the barrier island most impacted by the storm, may also pose a threat to beach mice populations. Re-establishment and stabilization of hurricane-created gaps must be accomplished as rapidly as possible.

Recommendations for dune building from other coastal areas have not been adequately tested in the Florida panhandle and may not apply to barrier islands on this coast. Sand fence is frequently used to enhance sand accumulation (HOTTA *et al.,* 1991; MENDELSSOHN *et al.,* 1991) but recommendations for the most effective sand fence configurations vary among sites. Long-term sand accumulation was not improved by the addition of side spurs to straight fencing in Louisiana. However, a straight fence configuration may be less effective where strong winds occasionally blow parallel to the fence.

While synthetic fabrics of appropriate porosity (around 50%) are as good as wooden slat fence in accumulating sand, biodegradable materials are preferred for sand fence construction as nonbiodegradable material may present a hazard for burrowing animals. Geojute fabric, a product frequently used in erosion control, is biodegradable, less expensive than wood fence and has porosity appropriate for sand accumulation. Evaluation of Geojute as an alternative to the commonly used wooden sand fence would establish if this product could be used as an efficient fence material for dune restoration.

00113 received 25 July 2000; accepted in revision 25 April 2001.
† *Published as Florida Agricultural Experiment Station Journal Series No. R-0771.*

Vegetation assists in trapping sand and is essential for anchoring accumulated sand (DAHL and WOODARD, 1977). Because plant recolonization may be slow, recommendations for dune restoration usually include planting of native grasses (MENDELSSOHN *et al.,* 1992, GIBSON and LOONEY, 1992, MORTON *et al.,* 1994). Sea oats (*Uniola paniculata*) and bitter panicum (*Panicum amarum*) are frequently planted for dune restoration as they have deep fibrous roots that efficiently trap and stabilize sand. In addition, these plants are adapted to harsh beach conditions (salt spray, low soil nutrient content, low soil moisture, sand abrasion, *etc.*). However, recommendations for the most appropriate time to plant sea oats and bitter panicum vary. Although BARNETT and CREWZ (1997) suggest a planting window of March through November, for Florida sites north of Tampa, summer planting requires supplemental watering due to high evapotranspiration rates (DAHL and WOODARD, 1977; BARNETT and CREWZ, 1997). Others have recommended planting in cooler seasons (between late fall to early spring) as supplemental watering may be eliminated when evapotranspiration is lower, thereby reducing the effort and resources required for dune restoration.

To date sand fence studies have been generally poorly replicated in space and therefore do not lend themselves to rigid statistical verification. Because approximately 75% of Santa Rosa Island remains undeveloped and hurricane Opal fragmented the dune system in more than 10 locations, an opportunity to replicate restoration techniques in space was available. Objectives of this study were: 1) to evaluate the effects of sand fence orientation (straight-conventional, straight-perpendicular and oblique) and material (Geojute or wood) on sand accumulation in the secondary dune position and 2) to determine the effects of late fall and spring planting seasons on sea oat and bitter panicum survival and growth.

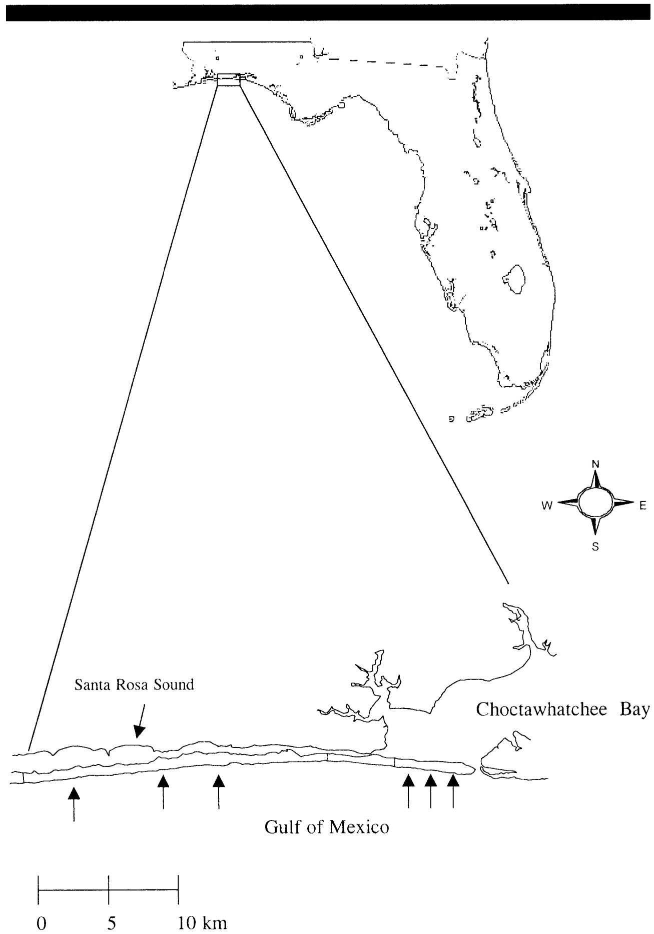

Figure 1. Map of Florida with insert showing the location of Santa Rosa Island. ↑ indicate the location of the six replicate sites and Santa Rosa Sound.

STUDY SITE

This study was conducted on Eglin Air Force Base, Santa Rosa Island, Florida (30° 18′ N, 87° 16′ W) (Figure 1). The island is separated from the mainland by Santa Rosa Sound (width approximately 0.50 km) along the western portion of the property and by Choctawhatchee Bay (width approximately 5 km) along the eastern section. Santa Rosa Island is a Holocene barrier island supplied by sediment west of Shell Island, Florida (STONE and STAPOR, 1996). Historically, the island maintained one of the most stable shorelines along the entire Northeastern Gulf Coast (OTVOS, 1982). Soils of the island are almost 100% quartz sand with a median diameter of approximately 0.25 mm. The island has a mild, subtropical climate, with mean annual precipitation of 152 cm, and rainfall peaks in summer and late winter/early spring (Figure 2). From September–February northerly winds prevail while southerly winds occur for the remainder of the year. Mean monthly wind strength is higher in the fall, winter and spring than during summer months.

Study sites were positioned on level overwashed areas which supported beach dunes prior to Hurricanes Opal and Erin. The mosaic of coastal dunes and swales on the island support four major plant communities: coastal interdunal swale, mesic flatwoods, scrub, and beach dunes. Typical vegetation of dunes includes *Ceratiola ericiodes, Hypericum reductum, Uniola paniculata, Spartina patens, Balduina angustifolia, Paronychia erecta, Cakile constricta, Chrysoma pauciflosculosa, Chrysopsis godfreyi, Conradina canescens, Ipomea pes-caprae, Iva imbricata, Oenothera humifusa, Panicum amarum, Physalis angustifolia, Schizachyrium maritimum,* and *Smilax auriculata.* Nomenclature follows CLEWELL (1985).

METHODS

Fence Treatments

Sand fence of three configurations (straight-conventional, straight-perpendicular and oblique) and two materials (wood and Geojute) were installed at six replicate overwash sites (dunes leveled with little remaining vegetation). Each site was at least 2.5 km long (Figure 1 & 3). Three sites were located on the eastern portion of Santa Rosa Island and the others were located on the western portion of the island. While all sites had similar damage from hurricane Opal, because of greater fetch across Choctawhatchee bay, wind

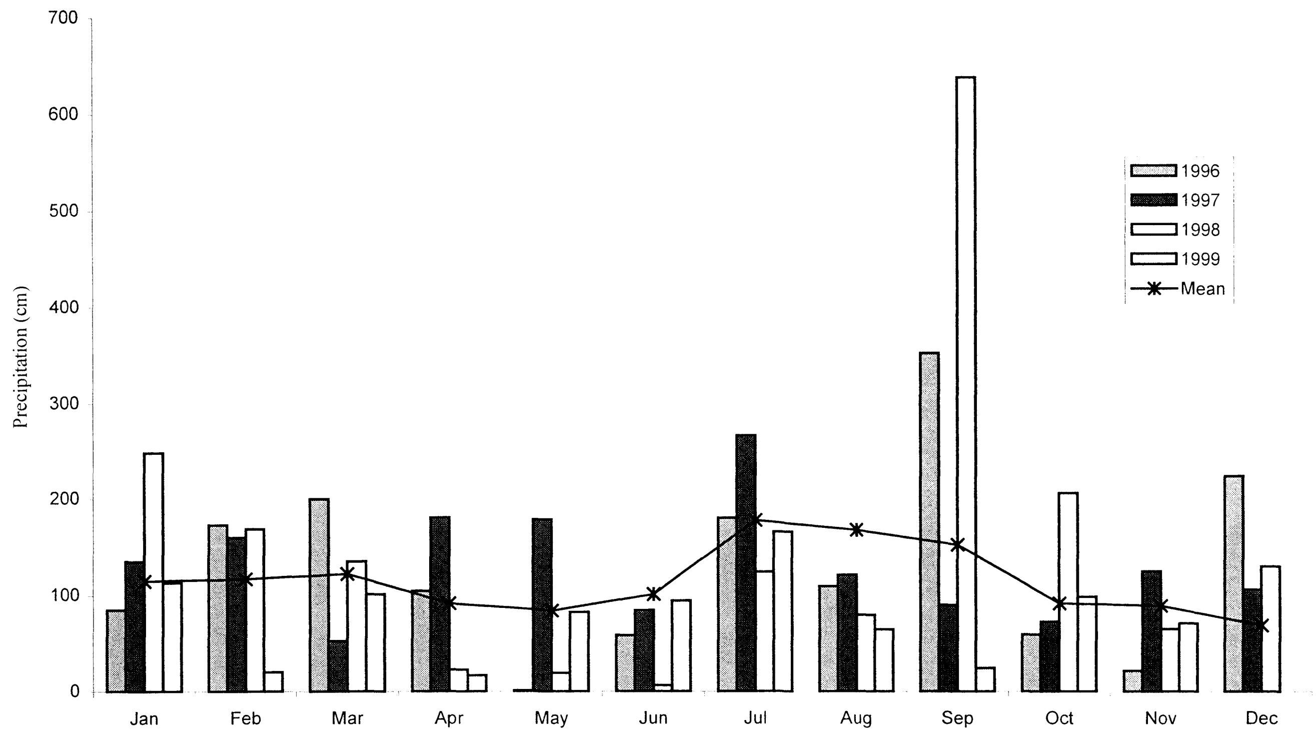

Figure 2. Total monthly precipitation (cm) at Hurlburt Field, Eglin Air Force Base, located approximately 0.5 km north of Santa Rosa Island study site. Precipitation average represents a 13 year period.

speeds in association with frontal passage (North/Northwest winds) are greater on the eastern end of the island.

The wood fence consisted of 3.8 cm-wide by 1.2 m high wooden slats bound together with steel wire. The Geojute fabric was 1.2 m high. Both materials had a porosity of 50%. The following three configurations were used: 1) straight-conventional—sand fence placed parallel to the shore, 2) straight-perpendicular—sand fence placed parallel to the shore with a 3 m perpendicular spur spaced at a 5 m interval along the northern side of the fence, 3) oblique—sand fence placed in alternating diagonal pattern to the shore (Figure 3).

Each fence material/orientation combination (treatment) within each site was 45 m long for a total of 270 m of fence per site with an additional 45 m of non-fenced beach to serve as a control. Treatments were randomly placed in line with the remaining secondary dunes system, avoiding any remaining vegetation and approximately 100–120 m from the mean high tide line.

Monitoring Sand Accumulation

For each material/orientation at each site, eight transects spaced every 5 m perpendicular to the beach for a total of 54 transects per site were surveyed using a level and stadia rod. Transects extended 16 m north and south of the fence. Beginning 1 m west of the eastern end of each fence treatment, positions were marked with flags at 1, 6, 11 and 16 m north and south of the fence (Bay/Sound and Gulf sides). Elevation was measured at all flagged locations and midway between all flags of the first row (1 m) and midway between the flags on the first and second row (6 m) from the fence. Dune height change was determined by change in elevation relative to the benchmark for each treatment. Sand accumulation (volume) was based on change in relative evaluation of each survey point multiplied by the area represented by that point. For better comparison with other studies volume estimates were determined for an area which encompassed the planting (to 6 m on Gulf side) and 9 m on the bay/sound side within each treatment. A baseline elevation was determined August–September 1996 and elevation profiles were measured November 1996, February–March 1997, November 1997, March–April 1998 and November–December 1998 and March–April 1999.

Planting Season

Experiment 1

Fence treatments and non-fenced controls were divided into three sections and seasonal plantings of sea oats and bitter panicum (10 cm liners) were randomly assigned to each of two sections. The remaining section (control) was not planted. Planting took place on December 4–6 1996 and March 18–19, 1997. Alternating species wee transplanted at a depth of approximately 18 cm on the Gulf side in 6 rows starting 1½ m from the fence, spaced 1 m apart. No supplemental water or amendments were provided. For each season, thirty-eight plants of each species were planted for each treatment (including non-fenced controls) at each replicate site for a total of 1596 plants/species/season.

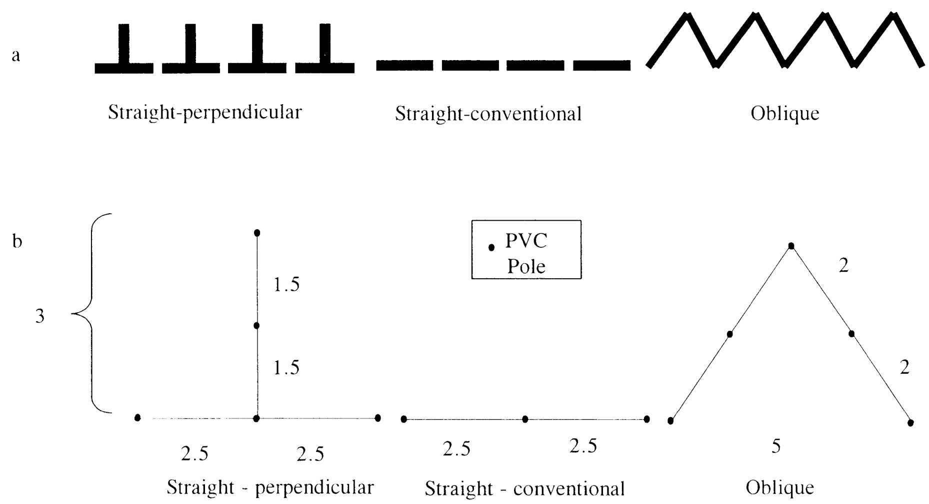

Figure 3 a. Sand fence configuration and alignment. Figure 3 b. Dimensions for construction of single 5 m section for each sand fence configuration.

The planting experiment was designed as a randomized block, split plot design with sites as blocks, fence type/orientation as main treatments, and season of planting as a split plot. However, sand accumulation near fences was different for fall and spring plantings. Initial analysis indicated percent survival for both species was correlated with the initial elevation at the time of planting. Consequently, for data collected in 1997, to isolate the effects of season of planting and remove the confounding effects of the fence treatments, analysis of variance was performed using only survival values for 228 plants of each species (38 each site) transplanted into the control treatment (non-fenced sections). Elevation in control sites did not differ between seasons (significant sand accumulation did not occur). Similar analyses were performed for the growth variables measured. Length of the longest leaf, basal width, tiller number and inflorescence number were measured for surviving plants per season of planting. Plant survival and growth were evaluated October 1997, October 1998 and June 1999.

In 1998, only two of the western sites were evaluated for survival before the arrival of Hurricane Georges. Georges heavily impacted transplants. Thus, survival 1–1.5 years after planting is reported for two sites evaluated before Georges. Prior to Hurricane Georges, eastern sites were inspected but data was not taken. At these sites, mortality of both sea oats and bitter panicum in association with winter sand movement was high. Survival at all sites was determined immediately following Georges.

Only one of the six sites was relatively non-impacted by the tidal surge associated with Georges. Thus, to determine effects of season of planting on survival and growth 2–2.5 yrs after transplant, analysis was restricted to mean survival of the 266 sea oats and bitter panicum planted at the non-impacted site. Sand accumulation at this western site did not correlate with survival and growth. Thus, survival and growth was assessed separately for plants associated with each fence treatment (block) and planting season combination.

Experiment 2

To further test effect of planting season on sea oat survival, an additional experiment was established in the fall and spring of 1989/1999. At three of the original fence sites, 100 seedlings per fence treatment were transplanted on November 9–13, 1998, and April 14–16, 1999 for a total of 2400 plants/season. Planting procedures followed those utilized in the first experiment. However, to avoid confounding effects of elevation, plants were placed more than 16 m in front of fence treatments. Plant survival was evaluated in September 1999. Length of the longest leaf, basal width, tiller number and inflorescence number were measured for surviving plants per season of planting per fence treatment.

Sand Accumulation Statistical Analysis

The sand accumulation experiment was a randomized block, split plot design with sites as blocks, fence material/orientation as main treatments and planting season as splits. Because adjacent fences noticeably affected sand accumulation for treatments, elevation measurements taken from within 6 m west of the easternmost end and 4 m east of the westernmost end of the treatments were removed from the analyses. All other sand accumulation data were treated as subsamples for each planting season. Sea oats recovered from previously undetected rhizomes remaining after hurricane Opal altered accumulation in one control section and one fence treatment each at different sites. Elevation and volume data from these treatments were excluded from the analysis. For each date, separate analyses of elevation were performed for each distance from the fence for the Bay/Sound and the Gulf side. Planting season did not significantly affect sand accumulation and was removed from the analyses. Final re-

Table 1. *Mean sand accumulation with sand fence on Santa Rosa Island, Florida.*

Dates	Time	Total Accumulation[a] (m^3)	Accumulation/Linear Meter of Beach (m^3/m)
Sept 96–Nov 96	3 months	492	1.82
Sept 96–Feb 97	6 months	893	3.31
Sept 96–Nov 97	15 months	1430	5.29
Sept 96–Mar 98	19 months	1521	5.63
Sept 96–Oct 98	26 months	1685	6.24
Sept 96–Mar 99	31 months	1656	6.13

[a] Site dimension = 270 × 17m.xc

ported analyses used a randomized block design with sites as blocks and fence types as treatments. Mean separations for each fence treatment were performed using the Bonferroni multiple comparison procedure.

RESULTS

Sand Accumulation

Accumulation rate and amounts varied across the island but in general accumulation patterns for the western three sites (separated from the mainland by Santa Rosa Sound) and eastern three sites (separated from the mainland by Choctawhatchee Bay) were similar (Figure 1). Maximum sand accumulation of 1685 m^3 (270 × 17 m), averaged for all sites and fence treatments, was recorded 26 months (September 1996 to October 1998) after fence installation (Table 1). However, eastern sites had more rapid and greater maximum accumulation of 1831 m^3 after 15 months compared to 1635 m^3 after 28 months for western sites. With the exception of one sample date, accumulation rates in control sections were greater at eastern sites (Table 2).

Tropical storm Josephine impacted fenced sites within one month of baseline readings. Although landfall on October 8, 1996 was approximately 100 miles east of Santa Rosa Island, 25–35 mph winds associated with the storm influenced fenced sites two days before landfall. Also, because of the eastward track of the storm, the high wind was not accompanied by rainfall on Santa Rosa Island. As a result, 29% of the maximum sand accumulation associated with fenced sites occurred between September and November 1996 (Table4 1) with the majority of the accumulation taking place during the two days of storm influence. Accumulation rates were between 0.95–2.86 m^3/meter/month and 0.27–0.80 m^3/m/month (Sept.–Nov.) in association with the various fence treatments for eastern sites and western sites, respectively (Table 2). In contrast, non-fenced sites lost sand as a result of Josephine with accumulation of −0.70 m^3/m. Dune height, measured 3 m either side of the fence, increased a range of 0.20–0.95 m as a result of the storm.

After tropical storm Josephine, highest mean rate of accumulation for fenced sites, 0.83 and 0.28 m^3/m/month, eastern and western sites, respectively, was recorded the first three winter months following fence installation. Thus, for fenced sites, 53% of maximum sand accumulation, 2.63 m^3/m–4.01 m^3/m, was deposited within the first 6 months after installation (Sep. 96–Feb. 97) (Table 1 and 2). Accumulation for non-fenced sites demonstrated a net sand loss in the same period with an accumulation of −0.46 m^3/m. The remaining 47% of maximum sand accumulation for fenced sites (22 months; Feb. 97–Oct. 98) was deposited at a slower rate of 0.13 m^3/m/month.

Frequent hurricane and tropical storm activity along the Florida panhandle impacted beaches throughout our study (1995–1999). In addition to increased sand accumulation in association with tropical storm Josephine, high tides associated with several storms including Hurricanes Danny (1997, 1–2 m tidal surge) and Georges (1998, 2–3 m tidal surge), both deposited and removed sand at experimental sites. Net sand accumulation for the six sites associated with fences was 1685 m^3 in November 98 and 1656 m^3 in March 1999 (Table 1). Because eastern sites were more impacted by Hurricane Georges, accretion for eastern sites was 1959 m^3 in March 1998 and 1862 m^3 in March 1999.

Fence Material

Regardless of configuration or material, sand fence was essential for rapid sand accumulation in overwash sites on Santa Rosa Island. Sand accumulation in association with non-fenced controls on eastern sites was not recorded until 6 months after baseline readings while non-fenced controls on western sites never consistently accumulated sand (Table 2). After nearly three years (September 96–March 99), mean accumulation for the non-fenced sites was 1.19 m^3/m compared to 6.14 m^3/m for fenced treatments (Table 3).

Table 2. *Relationship of fence designs and mean sand accumulation (m^3/m) for eastern and western sites on Santa Rosa Island, Florida.*

Material	Orientation	Sep 96–Nov 96 3 Months		Sep 96–Feb 97 6 Months		Sep 96–Nov 97 15 Months		Sep 96–Mar 98 19 Months		Sep 96–Oct 98 26 Months		Sep 96–Mar 99 31 Months	
		East	West	East	West	East	West	East	West	East	West	East	West
Wood	Oblique	4.09	0.70	4.50	2.02	6.72	5.53	7.72	6.23	4.05	5.92	7.25	7.99
Wood	Perpendicular	3.47	1.06	6.19	1.83	9.32	4.30	9.10	5.09	7.83	9.08	6.73	8.52
Wood	Straight	3.82	0.68	5.35	1.53	7.27	6.02	7.37	7.75	8.16	8.40	7.94	7.91
Geojute	Oblique	1.49	1.18	4.88	1.88	4.21	3.34	4.95	3.53	4.37	3.69	4.16	3.59
Geojute	Perpendicular	1.85	−0.18	4.53	0.73	6.61	3.29	6.46	0.46	6.13	5.00	6.11	4.44
Geojute	Straight	2.42	1.36	4.72	2.13	3.90	3.22	5.09	4.12	6.38	3.92	5.21	3.87
Non-fenced		−0.20	−1.21	0.73	−2.23	1.12	−3.84	2.18	−2.08	4.41	0.15	3.99	−0.68
Average without control		2.86	0.80	5.03	1.69	6.34	4.28	6.78	4.53	6.15	6.00	6.23	6.05

Table 3. *Relationship of fence design and mean sand accumulation on Santa Rosa Island, Florida.*

Material	Orientation	n	Sep 96–Nov 96 3 Months	Sep 96–Feb 97 6 Months	Sep 96–Nov 97 15 Months	Sep 96–Mar 98 19 Months	Sep 96–Oct 98 26 Months	Sep 96–Mar 99 31 Months
Wood	Oblique	6	2.39 b[a]	3.26 ab	6.12 b	6.97 b	6.03 ab	7.62 a
Wood	Perpendicular	6	2.27 ab	4.01 b	6.81 b	7.10 b	8.45 a	7.62 a
Wood	Straight	6	2.25 ab	3.44 b	6.81 b	7.56 b	8.28 a	7.93 a
Geojute	Oblique	5	1.30 ab	3.08 ab	3.69 b	4.10 ab	3.96 ab	3.82 ab
Geojute	Perpendicular	6	0.84 ab	2.63 ab	4.95 b	3.46 ab	5.57 ab	5.28 a
Geojute	Straight	6	1.89 ab	3.43 b	3.56 b	4.60 ab	5.15 ab	4.54 ab
Non-fenced		5	−0.70 a	−0.46 a	−0.86 a	0.04 a	1.84 b	1.19 b

[a] Mean sand accumulation (m^3/m). Letters within a column followed by the same letter do not differ ($p \leq 0.05$).

Geojute performed similarly to wood for 6–15 months but the material degraded rapidly and dune height near Geojute fences diminished thereafter (Figure 4, 5 & 6). Initially, the crest of Geojute built dunes was within 1 m of fences. After Geojute degradation the dune profile was flattened on the bay/side with the crest more often found either 3.5 m gulfward or bayward of the fence line. Also, within 1 m of the fence, Geojute influenced areas had lower dune height compared to at least 1 of the wood fence configurations after Nov. 1997 (Figure 7, 8 & 9). Mean maximum accumulation for Geojute (4.89 m^3/m) was 60% of that for wood (8.12 m^3/m). The accumulation rate for Geojute and wood was similar for the first 6 months at 0.50 and 0.60 m^3/m/month, respectively. Nevertheless, accumulation rate for Geojute decreased to 0.20 m^3/m/month (Nov. 97 to Mar. 98; 5 months) and 0.04 m^3/m/month (last 12 months) while accumulation rate for wood remained high at 0.59 m^3/m/month (Nov. 97 to March 98; 5 months) before decreasing to 0.04 m^3/m/month (last 12 months). Volume of sand accumulated did not differ significantly between wood and Geojute fences throughout the study (Table 2). But, sand accumulation with Geojute was significantly greater than that of non-fenced controls only after 15 months while accumulation with wood fence was significantly greater than non-fenced controls throughout the study except after hurricane Josephine. Elevation profile data agreed with sand accumulation data except that decreased dune height near Geojute fences was more pronounced and evident sooner (15 months vs. 24 months) than loss of accumulated volume (Figure 4–9, Table 4 and 5).

On most dates, dune height in association with all configurations of wood fence were greater compared to non-fenced controls to a distance of 3.5 m on the bay side and 1 m, bay/sound and gulf side of fences (Tables 4 and 5). Although not significantly different from non-fenced controls, increased dune height in association with wood fences was recorded to a distance of 6 m on the Gulf side of fences (November 1996–March 1998) and to 11 m (the max. distance measured from the fence) 2 years following installation (October 1998). On the bay side, accumulation significantly greater than that of non-fenced controls reached 6 and 11 m approximately one year following installation. Increased elevation on the Gulf side at 11 m was associated with impacts of hurricane Georg-

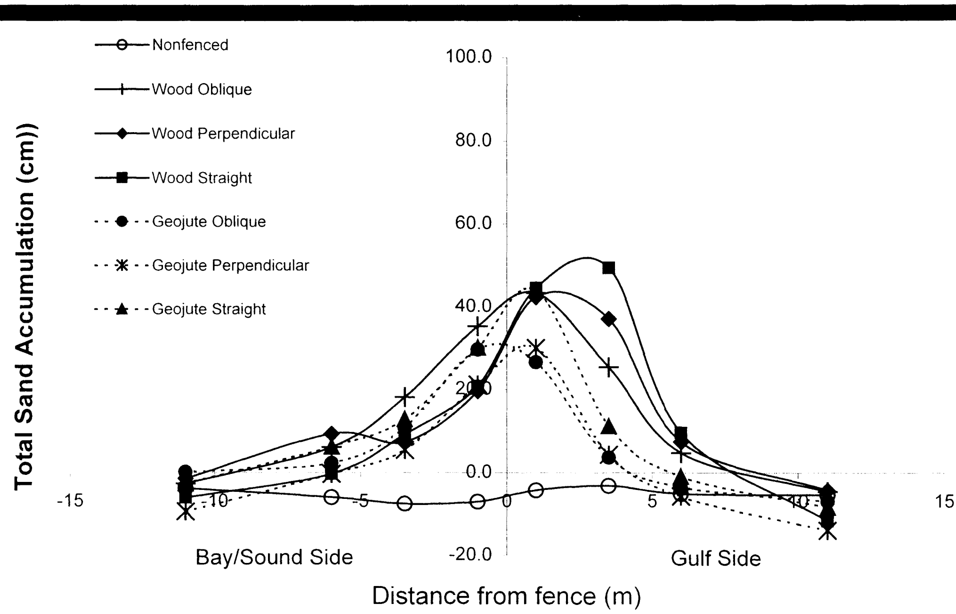

Figure 4. Total sand accumulation at varying distances on bay/sound and gulf side of sand fence and control (nonfenced treatment aligned with fence) for each fence treatment from August 1996 to November 1996.

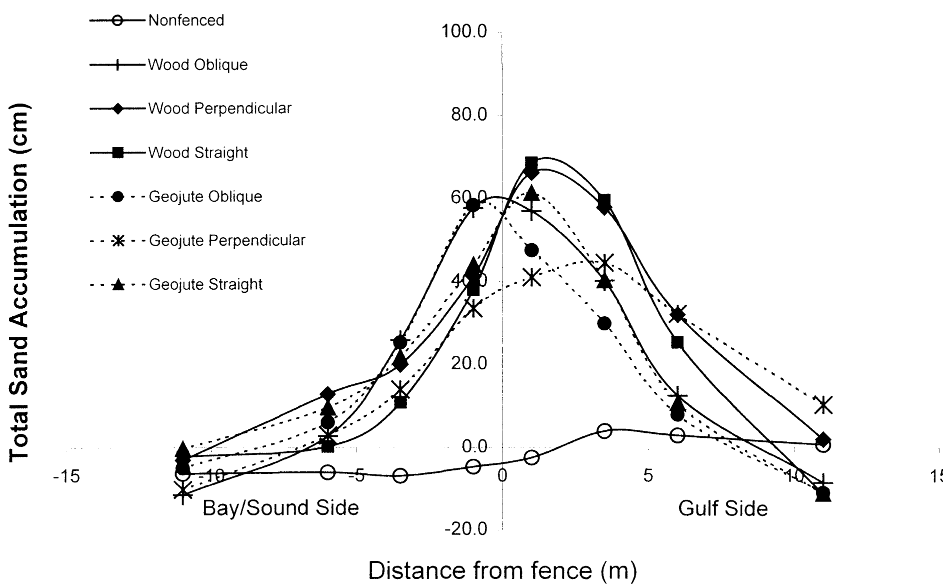

Figure 5. Total sand accumulation at varying distances on bay/sound and gulf side of sand fence and control (nonfenced treatment aligned with fence) for each fence treatment from August 1996 to February 1997.

es (Fall 1998). After 31 months crest height of wood fence was five times greater than crest height of non-fenced controls (Figure 9).

The crest of sand accumulation was initially found on the Gulf side of wood fences (November 1996 to February 1997) (Figures 4 & 5). Yet, from November 1997 to March 1999, the crest of sand accumulation was found on the bay side. After 31 months, the crest was found 1 m from the wood fence on the bay/sound side with a maximum elevation of 1.29 m and minimum of 0.40 m. Dune crest for the non-fenced control was found on the Gulf side and increased to a maximum of 0.18 m during hurricane Georges.

Fence Configuration

Sand fence configurations made little difference in sand accumulation. After tropical storm Josephine (September 96–November 1996), only the oblique wood fence resulted in sand accumulation greater than that of non-fenced controls (Table 2). Yet, both perpendicular and oblique wood fence performed almost equally well. Throughout the remainder of the study, there were no significant differences in sand accumulation among wood fence configurations. However, the straight and perpendicular wood fence had consistently more significantly greater accumulation compared to non-fenced controls than did the oblique wood fence. Dune height did not differ significantly among wood fence configurations at most distances from the fence (Figure 4–9; Tables 4 and 5).

Regardless of fence material or configuration, planting sea oats and bitter panicum did not significantly effect sand accumulation the first year. However, after two years of plant growth at the only site not impacted by Hurricane Georges, dune height and accumulation were significantly greater with planted sea oats and bitter panicum compared to non-planted fenced and non-fenced treatments.

Hurricane Opal did not totally uproot sea oats and bitter panicum but did remove or bury all aboveground growth. Growth from remaining underground rhizomes increased foliar cover from 0–4% after two years and unlike transplants, extant plants began contributing to sand accumulation one year following fence installation.

Experiment 1. Planting of Sea Oats and Bitter Panicum

Fence Effects

Wind excavation of transplants was the greatest cause of plant mortality. Because plants placed at higher elevation were more susceptible to wind excavation, transplant survival was negatively correlated with sand accumulation at time of planting ($p=0.0001$). As a result, percent plant survival ($p=0.0001$) one year following transplant was less, 17–47% and 6–40% for bitter panicum and sea oats, respectively on eastern sites, which had greater dune height at the time of planting (mean dune height ranged from 0.4–0.72 m up to 6 m from fence on the Gulf side), compared to western sites (mean dune height=0.24 m) with survival rates of 62–92% and 30–91% for sea oats and bitter panicum, respectively. Even with loses due to excavation, mean percent survival of sea oats and bitter panicum 11 and 7 months after transplant was 54% and 62%, respectively, across sites and treatments.

Eastern sites continued to lose sea oat and bitter panicum plants and by the fall of 1998 less than 20% remained for any treatment. In contrast, minimal plant loss continued on western sites until Hurricane Georges impacted two of the three sites, burying all surviving plants. On the remaining relatively non-impacted site, survival two years after transplant

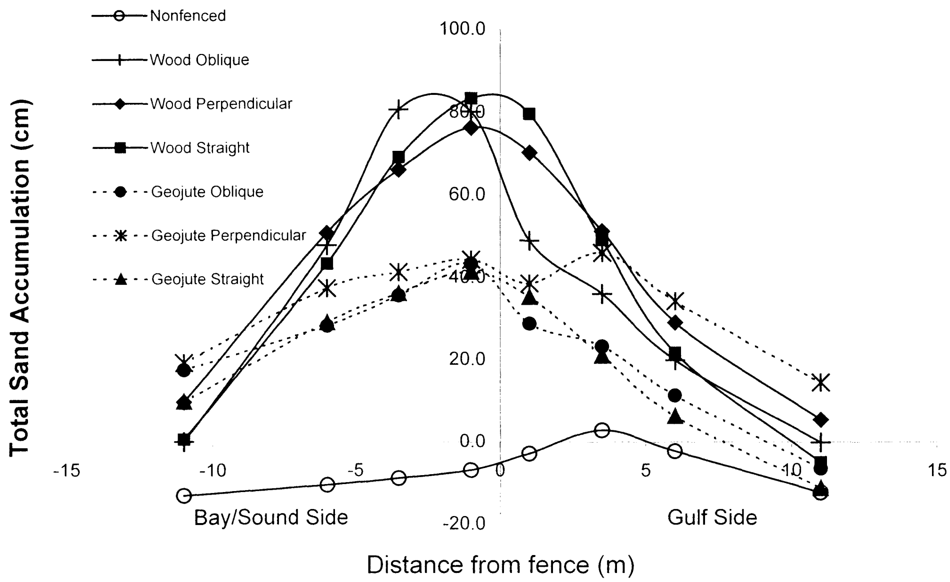

Figure 6. Total sand accumulation at varying distances on bay/sound and gulf side of sand fence and control (nonfenced treatment aligned with fence) for each fence treatment from August 1996 to November 1997.

was high, 72–82% and 63–83% for sea oats and bitter panicum, respectively.

Planting Season

7–11 Months Following Planting. For non-fenced plots, mean percent survival of sea oats and bitter panicum ranged from 66–84% and did not differ significantly between planting dates (Table 6). Because elevation in fenced areas was positively correlated with planting date (p=0.0001), differences in growth and survival between planting dates were assessed for non-fenced plots only (no significant elevation difference existed between planting dates). March planted bitter panicum were taller with greater basal width and number of inflorescence than those planted in December. Also,

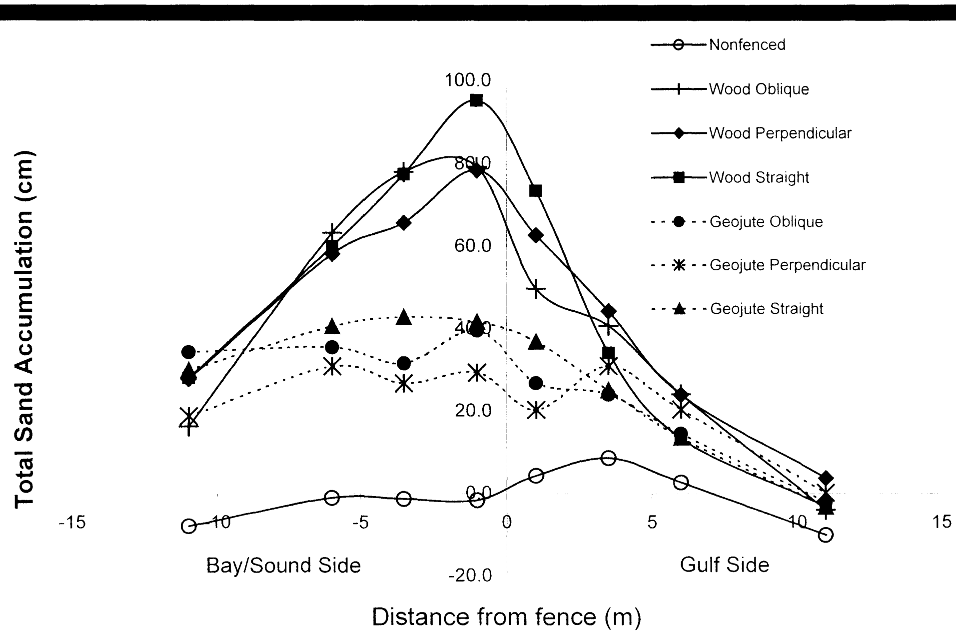

Figure 7. Total sand accumulation at varying distances on bay/sound and gulf side of sand fence and control (nonfenced treatment aligned with fence) for each fence treatment from August 1996 to March 1998.

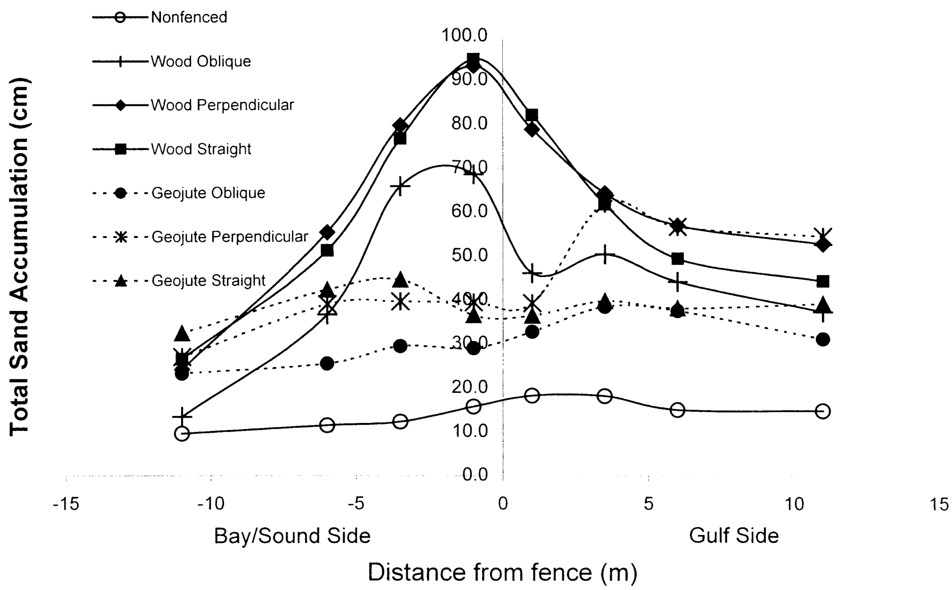

Figure 8. Total sand accumulation at varying distances on bay/sound and gulf side of sand fence and control (nonfenced treatment aligned with fence) for each fence treatment from August 1996 to October 1998.

March planted sea oats were taller with greater basal width than December planted sea oats. Regardless of time of planting, sea oats did not produce inflorescence until the second growing season following planting.

1.5–2 Yrs Following Planting. Mean survival of sea oats for two western sites evaluated before Hurricane Georges declined after the first 7–11 months to 79 and 74% for fall and spring plantings, respectively. Also, mean survival for bitter panicum was 66 and 62% for fall and spring plantings, respectively. Less than 20% survival on eastern sites was recorded but assessment of differences between seasons of planting was not made. One month following Hurricane

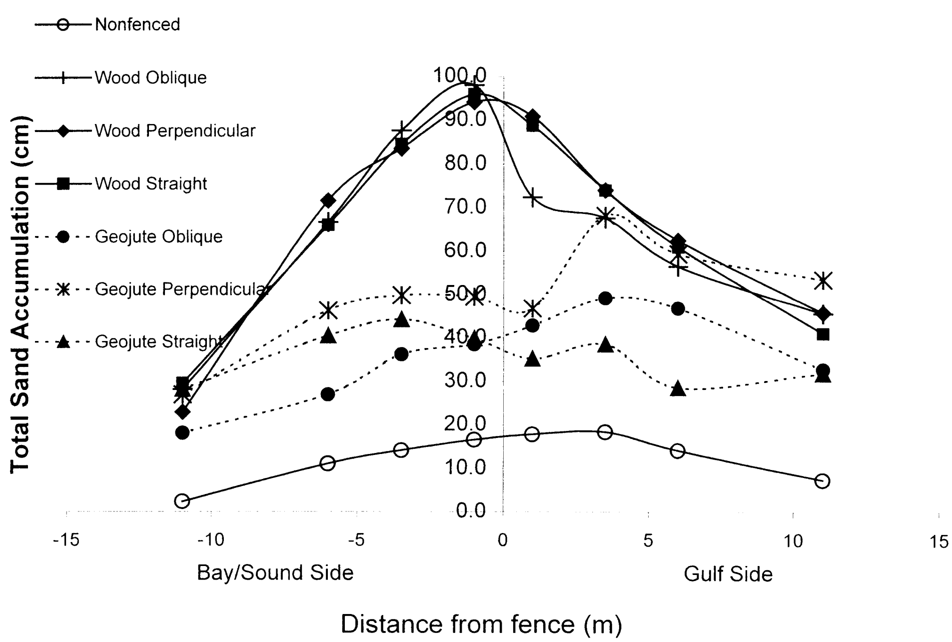

Figure 9. Total sand accumulation at varying distances on bay/sound and gulf side of sand fence and control (nonfenced treatment aligned with fence) for each fence treatment from August 1996 to March 1999.

Table 4. *Sand accumulation p-values for fence treatment effects at varying distances on the Bay / Sound and Gulf sides of the fence treatments for November 1996, February 1997, November 1997, March 1998, October 1998 and March 1999.*

	Distance From Fence (m)									
	Gulf Side					Bay/Sound Side				
Date	1	3.5	6	11	16	1	3.5	6	11	16
November 1996	**0.0005**[a]	**0.0002**	0.4063	0.8044	0.6451	**0.0008**	**0.0170**	0.4158	0.8839	0.9818
February 1997	**0.0001**	**0.0254**	0.3818	0.7870	0.8754	**0.0001**	**0.0062**	0.3556	0.8792	0.7970
November 1997	**0.0001**	**0.0261**	0.1693	0.5399	0.5091	**0.0001**	**0.0001**	**0.0001**	**0.0338**	0.6674
March 1998	**0.0001**	0.4761	0.8954	0.9935	0.9918	**0.0001**	**0.0001**	**0.0011**	**0.0165**	0.2192
October 1998	**0.0001**	0.2557	0.5934	0.7061	0.6472	**0.0001**	**0.0002**	0.1806	0.8123	0.8373
March 1999	**0.0001**	**0.0217**	0.1307	0.3916	0.5370	**0.0001**	**0.0001**	**0.0009**	0.6260	0.5634

[a] Bolded values are significant ($p \leq 0.05$).

Georges, sea oats and bitter panicum survival on eastern sites ranged from <1% to 11%. For the site not impacted by Georges, mean survival remained the same for March and December plantings and ranged from 63–81% (Table 7). By 1998, March-planted sea oats were taller, had greater basal width and a greater number of tillers and ramets than December-planted sea oats. Regardless of time of planting, inflorescence production remained low for sea oats.

2–2.5 Yrs Following Planting; 1 Site Only. Of the 299 individuals of each species planted on the only site not impacted by Hurricane Georges, mean survival after 2–2.5 years did not vary significantly by planting date (Table 8). Also, because accumulation at the time of planting was less at this site than eastern sites, fence treatments did not appear to influence transplant survival. Survival for sea oats was 73 and 80%, for fall and spring, respectively and 63 and 82% for bitter panicum planted in fall and spring planting, respectively. No significant differences in any growth variable measured remained for either sea oats or bitter panicum by 1999.

Experiment 2. Sea Oat Plantings

Planting Season

Similar to the first experiment, planting date did not impact percent survival for sea oats; 83% for both spring and fall plantings (Table 9). Because the second planting was placed more than 16 m gulfward of fences, fence treatments did not significantly impact survival or growth of sea oats. In

Table 5. *Mean separation of sand accumulation at varying distances on the Bay / Sound and Gulf sides of the fence for November 1996, February 1997, November 1997, March 1998, October 1998 and March 1999 using the Bonferonni mean separation procedure.*

		Control	Wood			Geojute		
Date	Direction and Distance From Fence	(Non-fenced)	Oblique	Perpendicular	Straight	Oblique	Perpendicular	Straight
Nov-96	Gulf 3.5 m	c[a]	abc	ab	a	bc	bc	bc
	Gulf 1 m	b	a	a	a	ab	ab	a
	Bay/Sound 1 m	b	a	ab	ab	a	ab	a
	Bay/Sound 3.5 m	b	a	ab	ab	ab	ab	ab
Feb-97	Gulf 3.5 m	b	ab	ab	a	ab	ab	ab
	Gulf 1 m	b	a	a	a	a	a	a
	Bay/Sound 1 m	c	ab	ab	ab	a	b	ab
	Bay/Sound 3.5 m	b	a	ab	ab	a	ab	a
Nov-97	Gulf 1 m	d	bc	ab	a	c	c	c
	Bay/Sound 1 m	c	a	a	a	b	b	b
	Bay/Sound 3.5 m	c	a	ab	ab	b	b	b
	Bay/Sound 6 m	b	a	a	a	a	a	a
Mar-98	Gulf 1 m	d	abc	ab	a	bcd	cd	abcd
	Bay/Sound 1 m	d	ab	ab	a	bcd	cd	bc
	Bay/Sound 3.5 m	c	a	ab	a	abc	bc	abc
	Bay/Sound 6 m	b	a	a	a	ab	ab	ab
	Bay/Sound 11 m	b	ab	ab	ab	a	ab	ab
Oct-98	Gulf 1 m	c	abc	ab	a	c	bc	c
	Bay/Sound 1 m	c	ab	a	a	bc	bc	bc
	Bay/Sound 3.5 m	c	ab	a	a	bc	abc	abc
Mar-99	Gulf 3.5	b	ab	a	a	ab	ab	ab
	Gulf 1 m	c	ab	a	a	bc	bc	c
	Bay/Sound 1 m	b	a	a	a	b	b	b
	Bay/Sound 3.5 m	c	a	ab	ab	c	abc	bc
	Bay/Sound 6 m	c	ab	a	ab	bc	abc	abc

[a] Means within a row followed by the same letter do not differ ($p \leq 0.05$).

Table 6. *Mean survival, ramet number, tiller number, basal width, height and number of inflorescence of sea oats and bitter panicum planted in non-fenced controls in fall 1996 and spring 1997 and measured October 1997.*

Season of Planting	Survival (%)	Ramet Number	Tiller Number	Basal Width (cm)	Height (cm)	Inflor-escence Number
			Sea oats			
Fall	79.40	1.00	3.00	1.83	58.89	0
Spring	84.20	1.00	4.00	2.76	69.86	0
p-value	0.7229	0.1839	0.0925	0.0259	0.0024	—
			Bitter panicum			
Fall	66.40	1.00	5.00	2.19	34.42	1.00
Spring	82.40	1.00	9.00	5.20	51.37	4.00
p-value	0.3018	0.4838	0.0019	0.0002	0.0001	0.0001

Table 8. *Mean percent survival, ramet number, tiller number, basal width, height and number of inflorescence of sea oats and bitter panicum planted fall 1996 and spring 1997 and measured in May 1999 for one site only.*

Season of Planting	Survival (%)	Ramet Number	Tiller Number	Basal Width (cm)	Height (cm)	Inflor-escence Number
			Sea oats			
Fall	72.56	2.00	12.00	27.70	82.00	—
Spring	80.07	2.00	11.00	37.80	88.00	—
p-value	0.2413	0.3023	0.7774	0.1632	0.224	—
			Bitter panicum			
Fall	62.78	1.00	9.00	—	37.00	—
Spring	81.57	1.00	15.00	—	38.00	—
p-value	0.2236	0.758	0.2823	—	0.9043	—

contrast to the first experiment, 6 and 9 months post planting, sea oats planted in November were taller with a greater number of ramets and tillers than sea oats planted in April.

DISCUSSION

Our experiment demonstrated the usefulness of sand fence for rapid sand accumulation following hurricane overwash that removes extant vegetation. Sand from dunes (6–12 m high) was deposited North of monitored sites by Hurricane Opal. This large pool of sand was redistributed gulfward by northerly winds and accumulated around fences. In contrast, adjacent non-fenced sites became blowouts. Also, accumulated sand associated with fence treatments contributed to the protection of State Highway 98 in 1998 when Hurricane Georges overwashed much of Santa Rosa Island. Where fences were in place, water did not reach this inland highway, while gulf water moved through non-fenced areas and negatively impacted the roadway. On Timbalier Island, Louisiana, an island considered to be sand poor, annual rate of accumulation for non-fenced areas was greater than that measured on Santa Rosa Island, Florida (MENDELSSOHN *et al.,* 1991). Yet, with similar fencing our annual accumulation was greater than reported on Timbalier Island.

Dune restoration success increases with fence placement in a secondary dune position. Because fences were located 100–120 m inland, dune building continued even with frequent tropical storm and hurricane activity. Hurricane Georges, the strongest storm since Opal, destroyed additional fences placed 50–60 m inland. Restoration projects in North Carolina, Texas and the Netherlands also concluded success increased and dune building required less inputs when plantings or fences were placed 100–200 m inland (BLOMETHAL, 1964; DAHL and WOODARD, 1977).

Overall, initial sand accumulation rates across Santa Rosa Island were intermediate between rates reported with single row fences in Louisiana, North Carolina and Massachusetts and less than rates reported in Texas (MENDELSSOHN *et al.,* 1991) (Table 10). However, on Santa Rosa Island, initial sand accumulation rates were 2.4–3.6 times greater on eastern sites compared to western sites. The 4.50–6.19 m^3/m accumulation recorded on east Santa Rosa Island after 6 months were comparable to the accumulation of 4.53–6 m^3/m in 8 months along the North Carolina coast. Western sites were more comparable to findings in Louisiana (MENDELSSOHN *et al.,* 1991) where the first year of accumulation ranged from 2.6–4.2 m^3/m. Similar to findings reported for North Carolina, one half of the accumulation in our study took place in the first 6 months following fence installation. Fences filled with sand in less than two years and thereafter, the rate of sand accumulation diminished. Because fences were not lifted or additional fences added, as initial fences filled with sand, accumulation rates were not sustained as in North Carolina, Massachusetts and Texas with multiple fence lifts and vegetation plantings (DAHL and WOODARD, 1977; MENDELSSOHN *et. al.,* 1991).

Variation in sand accumulation rates appeared to be associated with location of the mainland in relation to sites.

Table 7. *Mean survival, ramet number, tiller number, basal width, height and number of inflorescence of sea oats and bitter panicum planted in all treatments in fall 1996 and spring 1997 and measured in October 1998 for one site only.*

Season of Planting	Survival (%)	Ramet Number	Tiller Number	Basal Width (cm)	Height (cm)	Inflor-escence Number
			Sea oats			
Fall	72.56	2.00	5.00	—	66.00	0.05
Spring	80.07	2.00	5.00	—	72.00	0.23
p-value	0.2155	0.9938	0.1223	—	0.3723	0.395
			Bitter panicum			
Fall	63.16	3.00	7.00	—	39.00	3.00
Spring	81.96	4.00	11.00	—	50.00	5.00
p-value	0.1834	0.0176	0.009	—	0.1346	0.0984

Table 9. *Mean survival, ramet number, tiller number, basal width, height and number of inflorescence of sea oats and bitter panicum planted in November (1998) and April (1999) and measured September 1999.*

Season of Planting	Survival (%)	Ramet Number	Tiller Number	Basal Width (cm)	Height (cm)	Inflor-escence Number
Fall	83.05	1.18	4.07	77.04	76.00	0
Spring	82.68	1.07	2.66	70.25	69.00	0
p-value	0.5245	0.0003	0.0006	0.0013	0.0013	—

Table 10. *Comparison of annual dune growth and sand accumulation rates in Massachusetts, North Carolina, Louisiana, Texas, Oregon, and Florida (after* MENDELSSOHN *1991).*

Location	Sand Accumulation (m^3/m)
Nauset Beach, Cape Cod, MA[a]	8.3
Ocracoke Island, NC[b]	8.4
Timbalier Island, LA[c]	0.7–4.2
Padre Island, TX[d]	10.8
Clatsop Pains, OR[e]	13.7
Santa Rosa Island, FL[f]	−3.93–8.48

[a] KNUTSON (1980), 7 years' growth
[b] SAVAGE and WOODHOUSE (1969), 3 years' growth
[c] MENDELSSOHN (1991), 3 years' growth
[d] DAHL et al. (1975), approximately 4 years' growth
[e] MYER and CHESTER (1977), 30 years' growth
[f] Present study (2000), 3 years' growth

While sand supply and texture did not vary consistently from east to west, northerly winds were less obstructed at eastern compared to western sites. Strongest winds during the first 6–8 months after fence construction were predominantly out of the north, resulting in greater sand movement on eastern sites during this period. Variation in dune building within a region and site have been attributed to differences in sand supply, sand texture and the presence of obstruction to sand movement such as vegetation and dune ridges forming between sand supply and monitored sites (DAHL and WOODARD, 1977).

Overall, we found no advantage or disadvantage to fence orientations different from the conventional straight fence parallel to the Gulf. Differences in total sand accumulation among configurations were not significant at anytime during the nearly three-year study. However, the oblique and perpendicular fence showed transient increased accumulation and elevation peaks during the rapid accumulation during Tropical storm Josephine and in fall and winter. On Timbalier Island, Louisiana a transient advantage to perpendicular sand fence was also reported (MENDELSSOHN *et al.,* 1991). But, in Louisiana, as in our study, no differences in accumulation were reported with various fence configurations after three years.

Geojute deteriorated within a year to 18 months and we cannot consider it as a long-term alternative to conventional wood sand fence. However, before deterioration, accumulation with this material was equal to that of wood sand fence. Geojute is less expensive than wood fence and where some vegetation remains following a storm, Geojute may serve to increase accumulation until extant vegetation recovers and begins to contribute to sand accumulation.

Vegetation can be as effective as fencing in sand trapping and has the additional advantage of continuing to accumulate sand through upward and lateral growth without additional inputs. However, because of the slow establishment and growth of sea oat and bitter panicum transplants, planting alone would have delayed sand accumulation for two years. These results support similar findings in North Carolina and Massachusetts where the slow growth of sea oats, bitter panicum and beach grass initially resulted in delayed sand accumulation compared to fenced sites (MENDELSSOHN *et. al.,* 1991).

While sand fence was necessary where vegetation was removed by Opal, sea oats that survived the storm became effective at trapping sand after two growing season. Through qualitative and quantitative means, we noted that where sea oats survived, extant sea oat growth did not contribute to sand accumulation for the first 8 months after fence installation (1 year after the storm). However, during the second growing season post storm, surviving sea oats began to accumulate sand at a rate similar to sand fence. Thus, it is important to prevent damage to surviving sea oats that may not be visible after hurricane overwash. On more developed portions of the islands, heavy equipment was used to scrape beaches of storm debris immediately after Opal. This practice probably removed any remaining sea oats rhizomes. Because of the potential for sea oat regrowth and contribution to future sand accumulation we recommend this practice be eliminated where possible.

Where wind excavation was minimal, planting in November, December, March and April of sea oats and bitter panicum without supplemental water was successful at levels considered excellent in Texas where only 3 of 70 plantings had a survival rate greater than 75% (DAHL and WOODARD, 1977). While DAHL and WOODARD (1977) found bitter panicum to be more successfully transplanted than sea oats in Texas, planting sea oats was as successful as bitter panicum in our study.

Planting within 1.5 m of fences was successful where accumulation before planting was less than 0.5 m and accumulation rates were less than 0.4 $m^3/m/y$. However, because of sand movement, planting within 1.5 m of fences was not successful when initial elevation was greater than 0.24 m. With this much sand accumulation before planting, successful plantings required placement 16 m in front of fences. Thus, recommendation for placement of plantings must be made based on accumulation rates for a particular site.

While planting date did not effect survival, growth was greater when bitter panicum and sea oats were planted in March than in December. Yet, sea oat growth in the second experiment was greater when planted in November compared to April. Research in Texas suggested planting season to be less important than rainfall after planting (DAHL and WOODARD, 1977). In our study, while December 1996, and March and November 1997 plantings were followed by average to above average rainfall, planting in April 1998 was followed by three months of below average rainfall. Greater growth for plantings in November compared to April may have resulted from low rainfall during high temperature months of April, May and June 1998 (Figure 2). While there were initial differences in sea oat growth between December and March plantings, plant size was similar after two years regardless of planting dates. DAHL and WOODARD (1977) suggested planting sea oats and bitter panicum on the Gulf Coast any time there is sufficient soil water and low salinity. In the Florida panhandle, November and April on average are low rainfall months. While planting in these months without supplemental water may offer more risk and lead to less than optimum growth than associated with December and March plantings, lack of differences in survival suggest this risk is not great. However, as evapotranspiration rates increase the risk associated with planting without supplemental water increases. Thus planting without supplemental water during May, on average the lowest rainfall month, and during hot summer months is not recommended.

ACKNOWLEDGEMENTS

We wish to thank the Natural Resource Division of Eglin Air Force Base and U.S. Fish and Wildlife Service for their financial and logistical support, in particular, Carl Petrick, Lorna Patrick, Bruce Haggedorn and Dennis Teague. We would also like to thank our field and computer lab assistance: Gary Jacobs, Jimmy Jarrett, Perrin Penniman, Amy Compton, Mica Blackwell and Dawn Pucci. Bob Kinloch and Shibu Jose provided helpful comments on earlier drafts.

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