U.S. Army
Coast. Eng. Res. Ctr.

MP 9-75

(AD-A018 065)

Construction and Stabilization of Coastal Foredunes with Vegetation: Padre Island, Texas

by

Bill E. Dahl, Bruce A. Fall,
Alan Lohse, and S. G. Appan

MISCELLANEOUS PAPER NO. 9-75
SEPTEMBER 1975

WHOI
DOCUMENT
COLLECTION

Approved for public release;
distribution unlimited.

Prepared for
U. S. ARMY, CORPS OF ENGINEERS
COASTAL ENGINEERING
RESEARCH CENTER
Kingman Building
Fort Belvoir, Va. 22060

GB
450
.U3
no. 9-75

Reprint or republication of any of this material shall give appropriate credit to the U.S. Army Coastal Engineering Research Center.

Limited free distribution within the United States of single copies of this publication has been made by this Center. Additional copies are available from:

National Technical Information Service
ATTN: Operations Division
5285 Port Royal Road
Springfield, Virginia 22151

Contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products.

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

WHOI DOCUMENT COLLECTION

MBL/WHOI
0 0301 0089753 4

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER MP 9-75	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* Construction and Stabilization of Coastal Foredunes with Vegetation: Padre Island, Texas		5. TYPE OF REPORT & PERIOD COVERED Miscellaneous Paper 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR*(s)* Bill E. Dahl, Bruce A. Fall, Alan Lohse, and S.G. Appan		8. CONTRACT OR GRANT NUMBER*(s)* DACW 72-69-C0012 DACW 72-72-C-0013
9. PERFORMING ORGANIZATION NAME AND ADDRESS Gulf Universities Research Consortium 16821 Buccaneer Lane Houston, Texas 77058		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS G 31265
11. CONTROLLING OFFICE NAME AND ADDRESS Department of the Army Coastal Engineering Research Center (CERRE-EC) Kingman Building, Fort Belvoir, VA 22060		12. REPORT DATE September 1975 13. NUMBER OF PAGES 188
14. MONITORING AGENCY NAME & ADDRESS*(if different from Controlling Office)*		15. SECURITY CLASS. *(of this report)* UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release, distribution unlimited

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Barrier island
Beach grass
Dune stabilization
Padre Island, Texas
Sand dunes
Shore protection
Storm surge barrier

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

Experiments were conducted from 1969 to 1974 on Padre Island, Texas, to establish technical specifications and methodologies for the use of beach grasses to construct and stabilize foredunes as storm surge barriers along the gulf coast. Conclusions are based on 2.5 linear miles of experimental plots, consisting of beach plantings and fence-built dunes. Additional experiments on the effects of nutrients and salinity on beach grass growth were conducted in a greenhouse.

(Continued)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

Bitter panicum and sea oats were the best adapted species for beach plantings. The most successful method of establishing a vegetated dune ridge was transplanting these grasses on the backshore, where they trapped, grew through, and stabilized accumulating sand. Barren dunes built with sand fencing were stabilized with grasses, but the process was more difficult and costly. Most beach plantings were made with a tobacco transplanter, with single culms spaced on 2-foot centers and planted or seated 8 inches deep. A 50-foot-wide planting trapped all available blowing sand. Transplant survival of 20 percent or greater was sufficient for maximum dune growth after the first year. Beach plantings accumulated an average of 3.3 to 5.2 cubic yards of sand per linear foot of beach per year. In 5 years, a sea oats planting created a dune 11.4 feet high (15.4 feet MSL) which contained 24.9 yards per cubic foot of beach. Time-costs for establishing a 1-mile-long, 50-foot-wide beach planting (2-foot centers) of sea oats and bitter panicum were 500 and 287 man-hours, respectively.

Both grasses were successfully transplanted year round, but winter through spring was the most favorable period. Transplant survival was influenced by many factors, but mostly by soil moisture and salinity. Fertilization of plantings during the first year improved initial sand-trapping ability, but subsequent fertilization was unnecessary. Postplanting irrigation did not improve transplant survival, but preplanting irrigation was essential for fence-built dunes.

Foredunes were established across overwash channels by creating an elevated, flat, relatively salt-free surface using parallel rows of 2-foot-high sand fencing, and then transplanting both grasses. Fence-built dune slopes were stabilized by transplanting by hand after irrigation. Mulch-netting over the transplants eliminated wind erosion.

PREFACE

This report, containing results of a 5-year field study, is published to assist coastal engineers in developing cost-effective methods for using natural grasses to build and stabilize foredunes as effective barriers against storm surge, and to enhance the environmental quality and productivity in the coastal zone. The work was carried out under the coastal ecology research program of the U.S. Army Coastal Engineering Research Center (CERC).

The report was prepared by Dr. Bill E. Dahl (principal investigator) and Mr. Bruce A. Fall, of the Department of Range and Wildlife Management, Texas Tech University (TTU), Lubbock, Texas; and by Drs. Alan Lohse and S. G. Appan, of Gulf Universities Research Consortium (GURC), Houston, Texas, under CERC Contract Nos. DACW72-69-C-0012 and DACW72-72-C-0013. Drs. Dan E. Feray and Alan Lohse, and Mr. Thomas W. Bilhorn of GURC were the project coordinators. Messrs. Bruce A. Fall, Lee C. Otteni, and Donald W. Woodard, TTU field supervisors during the study, were primarily responsible for successful conduct of the overall project.

The authors express appreciation to the following individuals and organizations for their assistance: Mr. R. P. Savage and Dr. D. W. Woodard, CERC; Chester L. Pawlik, Bard O. Gage, and R. Sarabia, U.S. Army Engineer District, Galveston; Gene Stanley, Lorraine Carlisle, and other staff members, South Padre Investment Corporation; J. McLaughlin, Ernest Borgman, and others of the Padre Island National Seashore; Rodger L. Baker, TTU; W. W. Woodhouse, Jr., and Ernest D. Seneca, North Carolina State University; J. Philip Dering and Fred B. Jones, Corpus Christi, Texas; Arnuflo Guajardo, Hilario Gonzalez, and other personnel of north Padre Island; the Rob and Bessie Welder Wildlife Refuge, Sinton, Texas; and the U.S. Soil Conservation Service, Plant Materials Center.

Dr. D. W. Woodard, who made constructive and significant improvements to the manuscript, was the CERC contract monitor for the report, under the general supervision of R. M. Yancey, Chief, Ecology Branch, Research Division.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79*th* Congress approved 31 July 1945, as supplemented by Public Law 172, 88*th* Congress, approved 7 November 1963.

JAMES L. TRAYERS
Colonel, Corps of Engineers
Commander and Director

CONTENTS

TABLES

FIGURES

FIGURES—Continued

FIGURES—Continued

CONSTRUCTION AND STABILIZATION OF COASTAL FOREDUNES WITH VEGETATION: PADRE ISLAND, TEXAS

by

Bill E. Dahl, Bruce A. Fall,
Alan Lohse, and S.G. Appan

I. INTRODUCTION

Flood damage from hurricanes is a constant concern of inhabitants in the Atlantic and gulf coastal zones. Coastal barrier islands provide significant protection against high water through the damming effect of foredunes which characteristically form parallel to the beach. Foredunes on the gulf coastal barrier islands vary in height from less than 10 feet to over 35 feet above mean sea level (MSL). An unbroken foredune ridge affords natural protection to the mainland and back-island from seasonal high tides, storm surges, and hurricane-generated waves. However, the combined effects of man's destructive influence (e.g., overgrazing by cattle and sheep), fire, droughts, and storm surges have denuded large expanses which allow accelerated erosion in areas lacking a vegetative cover (Harris, 1965). Eventually, storm surges breach the foredunes and allow floodwaters to wreak havoc. On Padre Island, these processes have destroyed the foredunes in numerous places. Storm surge erosion also moves considerable sand inland from the beach onto lowland vegetation, into bays and lagoons, and accumulates on roads and in navigation channels adjacent to the islands. After severe flooding from Hurricane Carla in 1961, mainland residents agitated for restoration of the natural dams and even suggested constructing a seawall on Padre Island.

Increasing elevations of the barrier islands by restoring foredunes would yield obvious benefits. However, except for preliminary trials by a Padre Island National Seashore landscape architect (Tauscher, 1966) and by personnel of the U.S. Army Engineer District, Galveston (Gage, 1970), there is no information on foredune restoration for barrier islands along the Texas coast.

Sand fences, fences used in combination with grasses, and grasses, have all been effective in sand dune restoration and stabilization along the Atlantic and Pacific coasts (Brown and Hafenrichter, 1948a, b; Davis, 1957; Jagschitz, 1960; Woodhouse, 1963; Zak and Bredakis, 1963; Woodhouse and Hanes, 1967; Savage and Woodhouse, 1968).

This study provides tested specifications on how to use vegetation in the restoration of destroyed or denuded parts of foredunes of gulf coast barrier islands. Primarily, grasses were evaluated for their ability to trap moving sand to restore and stabilize dunes. Also, the study evaluated the potential of grasses to stabilize sand accumulated by fences.

II. LITERATURE REVIEW

Programs to maintain a protective, vegetated coastal barrier dune line have long been in existence (King, 1959). A general review of techniques and materials used in Europe is covered in Chapman (1949) and Van der Burgt and Van Bendegom (1949). Similar research has been conducted in Israel (Tsuriell, 1966), Australia (Barr, 1971) and South Africa (Walsh, 1968). European beachgrass (*Ammophila arenaria*) is the species most widely used for stabilization.

In the United States, attempts at coastal dune stabilization were made in the early 18th century. The colonists of Cape Cod caused accelerated erosion as early as 1703 by deforesting sand areas (Westgate, 1904). These settlers soon realized their error and attempted to control the eroding sand with grasses.

Efforts to vegetate dunes in the United States began early in this century along the Pacific Northwest coast (McLaughlin and Brown, 1942). Information gained from these and later efforts are summarized in papers by Brown (1948), and Brown and Hafenrichter (1948a, b; 1962); mostly European beachgrass, American beachgrass (*Ammophila breviligulata*), and American dunegrass (*Elymus mollis*) were used in these dune stabilization studies.

Dune stabilization research along the Atlantic seaboard began later, mostly with American beachgrass (Kucinski and Eisenmenger, 1943; Jagschitz, 1960; Zak and Bredakis, 1963; Augustine, et al., 1964; Zak, 1965; Jagschitz and Bell, 1966a, b; Hawk and Sharp, 1967). By transplanting, the natural distribution of this grass was extended along the North Carolina coast (Stratton, 1957; Gibbs and Nash, 1961; Woodhouse and Hanes, 1967; Savage and Woodhouse, 1968), and into South Carolina (Graetz, 1973). Dune stabilization with sea oats, a barrier island grass of the southeastern Atlantic and gulf coasts, was studied by Davis, 1957, and by Woodhouse, Seneca, and Cooper, 1968. The only report on dune stabilization research in coastal Texas has been by Gage (1970).

Studies of barrier island dune vegetation, especially those relating vegetation and environmental processes, have been conducted for years. Wells and Shunk (1938), and Oosting and Billings (1942), studied the effects of salt spray on coastal plants; Boyce (1954) conducted extensive research on the same topic. Seneca (1969; 1972a, b) tested the effects of substrate salinity and temperature on several species of dune grasses, and offered further explanations of distribution and zonation. Oosting (1954) synthesized all pertinent literature since 1900, concerning the vegetation and environment of the southeastern United States coast. Cooper (1958) and Chapman (1964) present succinct reviews of the role of vegetation in dune development. Comprehensive autecological studies of U.S. dune grasses are of sea oats (Wagner, 1964) and American beachgrass (Laing, 1958).

III. STUDY AREA

Padre Island in south Texas was selected as a study site because it is easily accessible from the mainland, and has many denuded areas suitable for experimentation. The island is about 110 miles long, extending from the south end of Corpus Christi Bay south to the Brazos Santiago Pass, near the mouth of the Rio Grande (Fig. 1). The island is unbroken except for Mansfield Channel, a manmade pass. Padre Island is 2 miles or more wide over

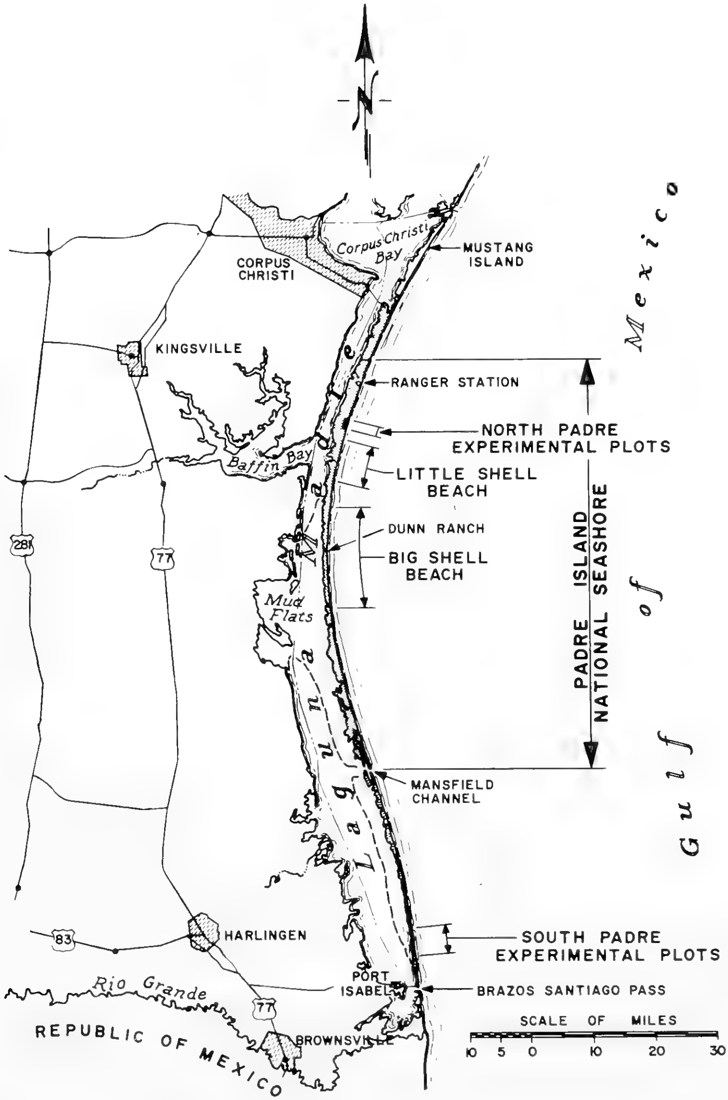


Figure 1. Map of Padre Island, Texas.

most of the north end, but narrows to less than one-half mile at the south end. Similar barrier islands (Mustang, San Jose, and Matagorda) to the north are defined by natural passes. Therefore, a nearly continuous chain of barrier islands extends along the central and south Texas coast.

Most of Padre Island is separated from the mainland by Laguna Madre, a shallow, often hypersaline bay; in the central part, extensive mudflats connect the island with the mainland. Padre Island is accessible by vehicle from the extreme north and south ends. A beach is the only roadway along all but the northern 15 miles and the southern 13 miles.

Two physiographically different study sites were selected about 85 miles apart on the north and south ends of Padre Island (Fig. 1); north Padre and south Padre refer to the experimental plots. For convenience, the island is subdivided in three nearly equal sections: southern Padre, the area south of Mansfield Channel; central Padre, the area from the north end of Big Shell beach to Mansfield Channel; and northern Padre, the remaining section.

1. Modern History of Padre Island.

Padre Island was named for the Portuguese priest, Padre Nicolas Balli, who first grazed the island with cattle during the early 1800's while he attempted to convert the indigenous Karankawa Indians (Harris, 1965). His ranching operation was short lived. Following Balli's attempts, a family named Singer established a ranch on the south end of the island, but it was abandoned during the Civil War; the extent of the Singer livestock operation is unknown. The Kenedy ranch, operating primarily in Kenedy County, Texas, possibly used a part of the island adjacent to their mainland ranch for cattle grazing. According to Price and Gunter (1943), Kenedy said the island was "green as a garden" in the 1850's. Padre Island ranching operations of Patrick Dunn, which began about 1879, probably reached a maximum of 4,000 animal units. Sheep were introduced on the island during the 1880's, but removed shortly thereafter due to a combination of extended drought and overgrazing. This is the first indication of abuse activating the island "sand seas" (Rechenthin and Passey, 1967).

On the northern 20 miles of Padre Island, 1,200 head of cows with calves grazed at one time (Harris, 1965). Livestock gradually decreased to one-half this number from the 1880's to 1940, and were halved again by 1966 (Rechenthin and Passey, 1967). After the 1933 hurricane, the southern half of the island was so denuded of vegetation that it was abandoned for ranching (Price, 1956). The last grazing contract with the Padre Island National Seashore (PAIS), which expired in 1970, limited the number of animal units to prevent excessive use. Except for cripples and excessively wild or wary animals, 1,287 head have been removed from Padre Island National Seashore (Jim Arnott, PAIS District Ranger, personal communication, 1971).

Large areas of the island were burned regularly to enhance growth of saltmeadow cordgrass (*Spartina patens*). However, since the National Park Service gained jurisdiction over a part of the island, planned burning has ceased. The combination of close grazing, burning, drought, and hurricanes has altered the species composition and reduced cover. A hint of the rapid recovery possible with the exclusion of cattle is reported by Price (1971) in comparing a photo of a 1-acre cattle exclosure with adjacent heavily grazed grassland on northern Padre. After only 10 months, the exclosure had a well developed stand of grass (apparently saltmeadow cordgrass), while the grazed part was mostly barren. Combined effects of burning and overgrazing on some east coast barrier islands have been denudation and activation of shifting, barren dunes, which previously were vegetated and stable (Oosting, 1954).

Construction of a causeway in 1927 connecting northern Padre Island with the mainland brought tourism to the island. Developers interested in the tourist potential sought new causeways and legal title to the island. In the 1950's, with the opening of new causeways at each end of the island, land investment increased with development of parks, hotels, and homes.

The National Park Service recommended Padre Island as a national seashore, and in 1963, following approval from Congress and later transfer of State lands and acquisition of private property, Padre Island National Seashore was established. The national seashore extends from about 10 miles south of the northern end of the island to Mansfield Channel (62 miles), and an additional 12 miles south of the channel (beach strip only). Private development of the extreme ends of the island is continuing rapidly, and a community of about 50,000 persons is planned for the north end (Price, 1971). However, the national seashore, comprises more than half of the island and is mostly undeveloped, except for Malaquite Beach near the north end of the park. Since 1963, several million tourists have visited the national seashore, including nearly one million in 1973. Visitors are expected to increase as land bordering the park becomes further developed.

2. Geological Processes of Padre Island.

a. General Processes. The barrier islands of the gulf coast have been formed by natural processes (water and wind) transporting and depositing sand. The specific origin of barrier islands is a source of controversy. An early theory of upward building of offshore bars to become islands has been questioned by Hoyt (1967) and Fisher (1968). Instead, Hoyt proposed a theory of relatively rapid submergence of a mainland shoreline with a well developed dune ridge. Fisher disagreed with this hypothesis, and postulated that barrier islands originated predominantly as complex spits under the action of longshore currents.

Padre Island began forming about 4,500 years ago, when the modern standstill of sea level was established from a previously rising sea level associated with the melting of continental glaciers (Bernard and LeBlanc, 1965). The islands grew seaward by beach and shoreface accretion; and landward into the bays by washover of sand during hurricanes and by eolian drift of sand (Hayes, 1967). Deposition of sediments during storms occurs from the storm surge floodtide, and also from the surge ebbtide (Andrews, 1970).

Lohse (1955) showed that longshore currents move sand southward from Mustang Island and along the upper Texas coast to Big Shell beach area in central Padre Island. Off Big Shell, at the westernmost bend of the northwest gulf shoreline, sedimentary material moving counterclockwise along the upper coast combines with sand and shell moving clockwise along the lower coast from the apex of the Rio Grande Delta. The convergence of material off central Padre Island creates an abundance of terrigenous sediment and shells; thus, large volumes of sand are available to eolian transport inland, while shell detritus is concentrated on the beach by eolian deflation of the sand (Watson, 1971). The shoreface is characterized by shell debris and excessive loose sand in steep beach profile. Little Shell, located farther northward on Padre Island, is a secondary nodal point of sediment accumulation.

In the littoral transport convergence area, there is a positive correlation between shell content and foredune development. In this area high continuous foredunes and very high backshore shell content occur together and are self-reinforcing. The dunes retard overwash and the shell cannot be removed and accumulates; while at the same time the high, steep backshore prevents all but the severe storms from damaging the foredunes (Watson, 1971).

The littoral processes which converge in central Padre Island consist of longshore currents and waves impinging upon the shoreface. These, in turn, are basically controlled by energy from surface winds which have a resultant net energy almost uniformly from east to west, or obliquely along the upper and lower Texas coasts into the westernmost bend (Lohse, 1955). Littoral transport, as seasonally modified by winter and summer (i.e., offshore and onshore) sand movement, provides the sedimentary material to maintain the barrier islands and the equilibria of their subenvironments.

Lohse and Cook (1958) described the relationship of south Padre Island to the development and destruction of Rio Grande subdeltas during the past 3,500 to 4,500 years. This study shows that Padre Island south of Mansfield Channel is geologically younger than the part north of the channel. The narrow width and generally lower elevations of the southern part are directly related to a shorter period of growth. Fisk (1959) describes the geologic history of central Padre Island, and presents data based on numerous borings and cores.

Mason and Folk (1958), Hayes (1964), and Milling and Behrens (1966) described the characteristics of beach and dune sands of Mustang and Padre Islands. They showed that the sands of Padre Island can be divided into three groups according to geographical location and petrologic province: (a) southern Padre Island (Rio Grande source), (b) central Padre Island, and (c) northern Padre Island (northern rivers source). The southern province has slightly coarser sand (mostly fine sand) than the northern province (mostly very fine sand), and the sand of the central area is a bimodal mixture of the two sources. Because the beach sand of Padre Island is well sorted, dune sands from this source represent the same grade-size characteristics with little increase in sorting. The major difference between the beach and dune sediment is the progressive decrease in shell and opaque mineral content from the beach in an inland direction.

b. Specific Processes: South Bird Island Quadrangle. A schematic cross section of northern Padre Island (South Bird Island Quadrangle) is shown in Figure 2; Figures 3 and 4 are aerial photos of the northern and southern parts of the island. The geological processes operating in the northern 10 miles, are discussed by Hunter and Dickinson (1970), and Hunter, et al., (1972). In this area, immediately north of the north Padre Island study sites, a well developed foredune ridge exists 15 to 30 feet above MSL with several maximum elevations over 45 feet. The ridge is mostly continuous and is broken by only a few narrow gaps. West of the foredune ridge is a plain of lower elevation, with an irregular pattern of ridges and troughs. A westward-migrating, longitudinal dune field, mostly barren, lies west of the plain. Bordering the Laguna Madre on the east is a relatively narrow flat strip periodically inundated by wind-driven water.

Surface configuration of the northern area was different in the middle to late 1800's. The foredune ridge was present and similar in shape; however, the mid-island consisted of an irregular pattern of vegetated dunes, while the western part of the island was a low vegetated flat. There was no back-island dune field, nor a low plain in the middle part, and the island was one-fourth mile narrower on the western side. During 1948-67, the migrating back-island dune field advanced along the western edge of the island into the Laguna Madre, an average of 700 feet; this advance is still continuing. Before 1948, the western shoreline was relatively stable.

Hunter and Dickinson (1970) attribute the present condition to the following sequence of events. In the late 1800's and early 1900's, much of the vegetation was destroyed by overgrazing and droughts (Price and Gunter, 1943). The previously vegetated dunes in the middle of the island, and probably the foredunes, became subject to wind erosion. These barren dunes then migrated westward to form the present back-island dune field. As the dunes migrated past a given point, they left behind a low deflation plain, which is now well vegetated. Where the migrating dunes more recently passed (since 1948), plant succession is in an initial stage; this area is termed a *young deflation plain*. During wet cycles, the westward advance of the dune field was slowed, and the trailing ridges became vegetated. During dry cycles, barren sand on the trailing edge was wind-eroded to a lower elevation, forming a trough which in subsequent wet years became a semipermanent pond. This pattern of troughs and ridges can be traced, on aerial photos from 1937 to present, through wet and dry cycles.

Blowout dunes occur in various stages of activity along the mostly continuous foredune ridge. Where the vegetative cover is locally weakened or destroyed, the wind-activated sand moves northwest. Beach sand is continually added to the barren area as long as it remains connected with the beach. When a new foredune is formed in its place, the sand supply is choked off completely. The original active dune continues migrating westward, and leaves behind a low deflation plain which eventually becomes vegetated (Hunter and Dickinson, 1970). Several active blowouts are evident in Figures 3 and 4.

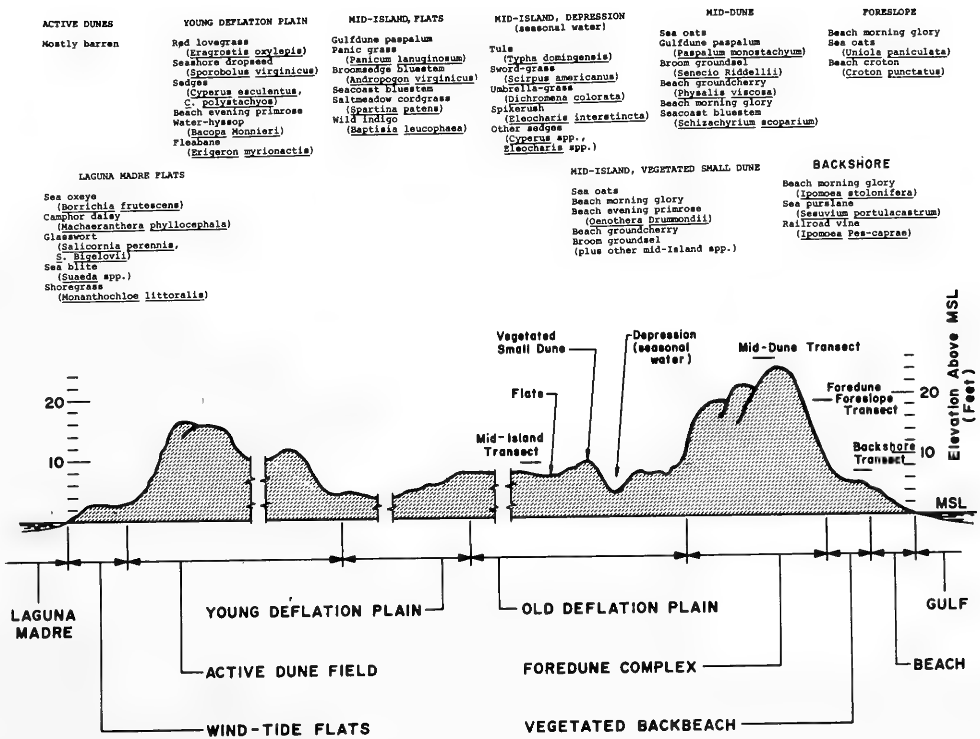


Figure 2. Schematic cross-sectional profile of north Padre Island and some dominant plants of major communities (vicinity of Ranger Station, Padre Island National Seashore).

Figure 3. Aerial photo (1969) of north Padre Island.

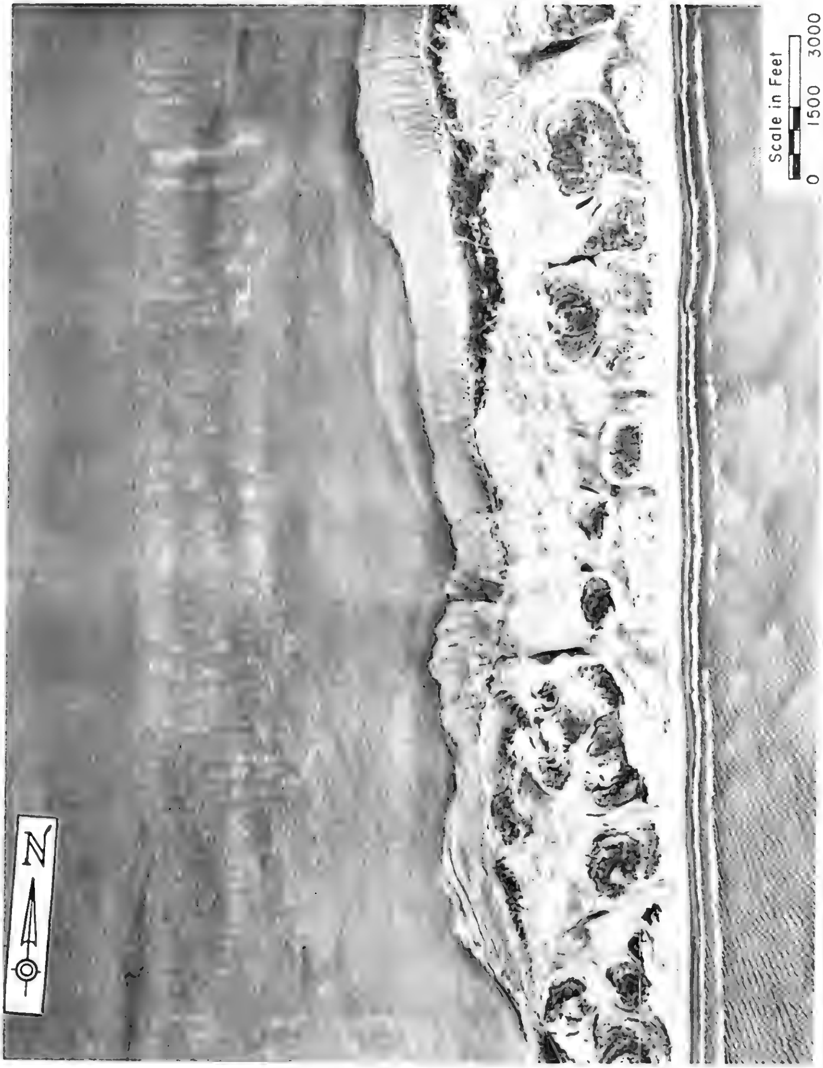


Figure 4. Aerial photo (1970) of south Padre Island, north of Andy Bowie Park.

The dunes now migrating across northern Padre originated almost entirely by devegetation of once-stabilized dunes (Hunter, et al., 1972). However, studies by Hayes (1967) in the central part south of Big Shell beach indicate that hurricane washovers supply sand to the back-island sand fields. In the northern part, washover fans and other effects of hurricanes are small because the foredune ridge is high and broken by only a few narrow gaps (Hunter and Dickinson, 1970). At Big Shell beach, a continuous, unbroken, well vegetated dune ridge and vegetated flats exist with very little change since 1937 (Hunter, et al., 1972). This 12-mile-long section at the westernmost bend of the shoreline has not been breached by recent hurricanes.

3. Hurricanes and Storm Surges.

During the first 63 years of this century, 42 tropical cyclones have struck the Texas coast. Of these, 28 were classed as hurricanes, an average of one every 2.3 years (Hayes, 1967). However, associated storm surges varied. Hurricane Celia (1970), with extremely high and damaging winds, caused a maximum surge of about 5.5 feet on the gulf beaches. Old washover channels were briefly reopened, and small coppice dunes of the backshore were removed, but the surge caused no erosion to the foredunes (McGowen, et al., 1970). Hurricane Carla (1961), with lesser winds but a more erratic track, had an open gulf surge of over 12 feet (Bodine, 1969). Foredunes in central Padre Island were cut back an average of 100 feet, and were completely leveled along some stretches of beach. Associated flooding from the surge was the most severe on record in Texas. On Mustang Island, 50 to 100 yards of dunes were eroded, and some steep-faced dune cliffs were 10 to 15 feet high (Hayes, 1967). The ability of a well vegetated primary dune line to minimize hurricane surge effects in this area has been noted by several authors (Price, 1956; Hayes, 1967; Behrens, 1969; McGowen, et al., 1970; Hunter and Dickinson, 1970).

Without a dune barrier, even minor surges of weak storms may cause damage to manmade structures. In February 1969, a high-pressure system surge washed out several sections of road on south Padre, and bridge approaches on Mustang Island. The surges of Hurricanes Camille and Laura (1969) and Hurricanes Celia and Ella (1970) left drift lines on the experimental plantings, but caused no serious dune erosion.

Observations by the U.S. Army Engineer District, Galveston (1962, 1968, 1971) for Hurricanes Carla, Beulah (1967), and Celia, revealed that barrier islands of the Texas coast were breached in about 100 places, averaging a storm surge breach every 3 to 4 miles along the island chain. In each storm, sizable volumes of sand were transported from the beach and foredune across the island. Hayes (1967) described three types of breaches in the foredunes caused by Hurricane Carla in central Padre Island: (a) major hurricane channels which erode below mean sea level and maintain an open connection with the gulf for several weeks after the storm. These channels usually leave a persistent cut through the foredunes that is opened during every major storm; (b) minor hurricane channels or high-level channels which cut through the foredune ridge during high water stage of the storm, but does not erode below mean sea level. These channels are quickly healed; and (c) broad overwash where the foredune ridge is completely breached for 1 mile or longer. These breaches are mostly evident in central and southern Padre Island, but are less significant in the northern part.

Bodine (1969) analyzed data from 19 Texas hurricanes, and presented models of expected frequency of storm surges for various heights at different coastal locations. These data are presented in Table 1. The frequency of surges for a given height decreases from the northeast coast to the southern tip. A surge equal to or greater than the Mustang Island surge of Hurricane Celia can be expected to reoccur, on the average, every 10 years at the same location. As noted, the natural dune line in that area was hardly affected by Celia, although low, duneless areas (old hurricane channels) were scoured out by the surge floodtide and ebbtide. In contrast, the surge of Hurricane Carla is shown in Table 1 as the storm surge of the century; the 12.3-foot recorded surge near the eye of the hurricane has been exceeded only once in Texas during this century—the 1915 storm at Galveston with 12.7 feet (Bodine, 1969). As discussed earlier, the well developed foredune ridge of Mustang Island and northern Padre survived Hurricane Carla, and although severe erosion of the dune face occurred, it kept the surge from broadly overwashing the island. Whether an artificial dune line can do the same is conjectural, and would depend greatly on dimensions of the dune line at the time of the storm. The 5-year-old dunes would not have withstood the more than 100-foot dune-face erosion associated with Carla, since the dune ridge is narrow at present although its height is over 14 feet MSL. However, the effects of a 10- or even a 20-year storm surge would be minimal.

Table 1. Average expected height of storm surges on open beaches for selected yearly intervals at certain Texas gulf coast localities.

Intervals (years)	Surge height (feet)					
	Sabine	Galveston	Freeport	Port O'Connor	Mustang Island	Port Isabel
2	3.7	3.1	2.8	2.8	2.7	2.6
5	5.4	4.5	4.4	4.4	3.9	3.7
10	8.0	7.0	6.0	6.0	5.5	5.5
20	10.3	9.4	8.2	8.2	7.8	7.4
50	13.5	11.5	10.3	10.3	9.8	9.2
100	15.0	12.6	11.4	11.5	11.0	10.2
1,000	17.0	14.1	12.8	13.0	12.0	11.3

(Bodine, 1969)

4. Natural Barrier Island System.

Godfrey and Godfrey (1972) and Dolan (1972a, b) stated that for some east coast barrier islands, e.g., the Outer Banks of North Carolina, a well developed and continuous vegetated foredune system is not a natural condition, and that the islands have always been sparsely vegetated. These authors believe that a foredune zone exists, consisting of low, unconnected hummock dunes, and that during storm surges, the island is uniformly overwashed, and water flows between the dunes and across the island with the result that wave energy is rapidly dissipated. With extremely high surges, large waves occasionally succeed in eroding completely the low-lying foredunes, and carry sediment across the island into the salt marshes of the bay. Overwash is considered important for marsh formation and in allowing the barrier island to retreat and maintain its level during the currently rising Atlantic coast sea level. They believe that an artificial dune line does not simulate the natural condition, and that the net results of such a dune line are: (a) erosion of the beach and loss of fine sediments to sea; (b) narrowing and steepening of the beach; (c) elimination of overwash, resulting in suppression of natural island growth; and (d) an undesirable succession of plants behind the dunes, allowing less salt-tolerant species to become dominant, which could result in serious denudation should overwash eventually occur. Godfrey and Godfrey (1972) and Dolan (1972a, b) cast serious doubts on the wisdom and value of constructing artificial dunes on east coast barrier islands, and state that such a beach and dune stabilization program may be detrimental to the long-term equilibrium of these barrier islands.

These conclusions do not seem applicable to the northern half of Padre Island, nor to Mustang Island. The present condition of these islands, even after more than a century of human abuse, is generally a well developed vegetated foredune ridge, and a wide grassland prairie to the lee. In a schematic diagram of the effects of hurricane surges on northern Padre and Mustang Islands, McGowen, et al., (1970) showed that surge is channeled through old permanent passes (e.g., Corpus Christi Pass), which partially heal between storms. During severe storms, such as Hurricane Carla, new channels are cut at other weak locations, and foredunes act as an effective barrier. In two extensive areas of well developed foredunes (South Bird Island Quadrangle, and central Padre-Big Shell), few washovers exist, even from Carla. Here, the effects of Carla on this natural system were as described by Dolan (1972a), and Godfrey and Godfrey (1972) as "unnatural," i.e., the cutting back or erosion of the dune face from 50 to 100 feet or greater, without broad overwash. The beach was planed off to a long and gradual slope (without a berm) with considerable loss of sediment (McGowen, et al., 1970; Davis, 1972). However, the healing process of the foredune and backshore is rapid. McGowen, et al., (1970) stated: "Observations of the beach zone shortly after the passage of Celia indicated that sand was being transported landward and that the normal beach profile was already being restored."

By 1974, the foredunes have largely healed by a shoreward migration from this erosional cut. The process is adversely affected by the constant and heavy vehicular traffic on Mustang and northern Padre Islands, which prunes off the shoreward-growing rhizomes of dune-forming plants and kills emergent seedlings. The most natural foredune system is probably along a 4-mile stretch of beach on the national seashore which has been closed to vehicular traffic since 1968. Backshore vegetation in this area has migrated shoreward 100 to 200 feet farther than contiguous areas north and south where traffic is heavy.

There is no evidence that beaches are eroding in areas of artificial or long-stabilized natural foredunes although artificial foredunes have existed for 5 years or less and no severe storm surges have occurred during this time. To the north, the shoreline level on San Jose and Matagorda Islands has prograded seaward (Hunter, et al., 1972). On central and northern Padre Island and on Mustang Island, the shoreline has remained stable for the past century, and probably since the origin of the island (Fisk, 1959; Hunter, et al., 1972). The condition of stability extends to south of Big Shell beach.

Specific net rates of shoreline change, from surveyed turning points in the middle to late 1800's, were presented by Seelig and Sorensen (1973), and were mostly +3 to –3 feet per year for Padre Island north of Mansfield Channel; an exception was a 2-mile-long area around Packery Channel, a hurricane channel complex at the north end of Padre Island, where a former shoreline bulge has eroded 36 feet per year since 1882. The north Padre study site has experienced no net change during the same period. In contrast, the southern part, with no continuous foredune ridge, has experienced shoreline erosion of about 1,000 feet in less than a century (Hunter, et al., 1972). Near the south Padre study sites, the shoreline eroded a net average of 10 feet per year since 1880 (Seelig and Sorensen, 1973).

There is no evidence that a stabilized foredune ridge on Padre or Mustang Island allows succession to salt-intolerant woody plants that are unable to withstand a storm surge flood, as described by Godfrey and Godfrey (1972) for Cape Hatteras, North Carolina. On these islands, woody plants are rare, even leeward of the long stabilized and washover-free Big Shell natural foredunes. The grassland leeward of the foredune ridge is apparently well adapted to recover from saltwater flooding. Mustang Island was flooded by saltwater from the bay during Hurricane Celia which left a drift line on the rear of the foredune ridge. Most of the low back-island was well vegetated before the flood, and was not damaged by wave action or saltwater inundation (McGowen, et al., 1970); the area is still an extensive midheight grassland. However, the unvegetated sandflats in the western part of the island were subjected to severe scouring by the storm surge.

In summary, the overwash theory of barrier island equilibrium and retreat (Dolan, 1972a, b; Godfrey and Godfrey, 1972) does not apply to Mustang Island or the north half of Padre Island. A mostly continuous and well vegetated foredune ridge which minimizes storm surge effects, and a stable shoreline are the natural condition, and none of the events described by these authors for a stabilized foredune system is occurring.

The present condition on Padre Island south of Big Shell is more similar to the supposed pristine condition of part of the North Carolina Outer Banks, i.e., low, mostly unconnected hummock dunes. Broad overwash (unchanneled) has been shown for the area immediately north of Mansfield Channel (Hayes, 1967). However, even in southern Padre, discontinuous stretches of stablilized foredunes occur. In the extreme southern part, where the island is youngest and generally low and narrow, hurricane washover passes and overwash fans are a dominant feature; between these low areas, a foredune ridge often occurs with associated grassland flats (Fig. 4).

In early 1846, Lt. J.E. Blake made a reconnaissance trip along the entire length of Padre Island to assess its suitability as a troop transport route compared with the mainland. Blake's (1846) report contained brief statements on vegetation and geology. These statements, vague as to island location, were undoubtedly influenced by the purpose of his trip. Additionally, his journey was only a year following a hurricane (1844) severe enough to have destroyed a settlement near Brazos Santiago Pass. Blake stated that "little grass is found on the island, and that a very inferior quality [for grazing]," and concluded the island was unsuitable for troop and livestock transport due to "the want of grass . . . and the difficulty of getting off [the island] at its southern termination. . . ." He also noted that toward the south end of the island, "the sandhills are less elevated and more broken . . .," and described hurricane washovers where driftwood had been carried into the center of the island. In contrast, he reported "good water on the western side of the sandhills" and driftwood on the east side, apparently from more northern island locations. Blake's (1846) statements describing the lack of grass seem inconsistent with the fact that in the mid-1800's, the Singer cattle ranch was headquartered about 26 miles north of Brazos Santiago (Harris, 1965). Later, southern Padre was also grazed by Dunn livestock, although by 1940 the southern 50 miles no longer supported cattle since little vegetation remained (Rechenthin and Passey, 1967).

5. Climate.

Padre Island has a subtropical, semiarid climate, moderated by maritime tropical air from the Gulf of Mexico. Only two seasons predominate, summer and winter, while spring and fall are short transitional periods. The summer months, May through September, are hot with little daily or weekly variation. Winter, from December through February, is generally mild, but fluctuates widely in temperature.

Freezing temperatures are infrequent; Corpus Christi (inland) experiences about 10 occurrences of 32° Fahrenheit or below each year, but the island extremes are more moderate. Port Isabel on the mainland coast adjacent south Padre Island, averages only 1 year out of 3 with freezing weather (Orton, et al., 1967). Similarly, maximum summer temperatures are usually cooler than the mainland, and rarely exceed 95° Fahrenheit. The 1973 monthly temperatures for Padre Island are given in Table 2; long-term temperature and precipitation means for Corpus Christi and Port Isabel are given in Table 3. South Padre has a warmer climate in every month, averaging from 7° to 8° warmer in winter, and from 3° to 5° warmer in summer, although the two stations are less than 100 miles apart.

Precipitation in coastal south Texas is characteristically irregular, both monthly and annually, with no sharply defined seasons. Within the last century, annual precipitation at Corpus Christi has ranged from 5.38 inches (1917) to 48.16 inches (1888). During the period 1931-60, Port Isabel had a maximum of 44.62 inches and a minimum of 12.33 inches. Excessive precipitation associated with hurricanes, usually in late summer and early fall, biases the annual average upwards. Without this boost, the averages would be lower and

Table 2. Monthly temperature for Padre Island.

1973	Temperature (°Fahrenheit)					
	$\bar{X}$ maximum	$\bar{X}$ minimum	$\bar{X}$	High	Low	Number of Days ≤ 32°F
North Padre (Padre Island National Seashore Ranger Station)						
Jan.	58	44	51	73	29	3
Feb.	62	47	54	73	30	2
Mar.	73	61	67	84	52	
Apr.	74	62	68	84	49	
May	82	68	75	93	58	
June	86	74	80	90	65	
July	89	77	83	94	72	
Aug.	89	76	82	94	70	
Sept.	88	75	81	93	62	
Oct.	83	70	77	90	61	
Nov.	81	66	73	87	47	
Dec.	71	53	62	81	27	2
South Padre (U.S. Coast Guard Station, Isla Blanca)						
Jan.	65	51	58	83	31	2
Feb.	69	56	62	82	34	
Mar.	78	66	71	93	60	
Apr.	78	66	72	87	61	
May	85	74	79	93	67	
June	88	78	83	94	70	
July	93	79	86	97	77	
Aug.	91	80	85	97	76	
Sept.	91	80	86	99	73	
Oct.	88	77	82	99	68	
Nov.	87	74	80	95	59	
Dec.	76	62	69	90	39	

Table 3. Climatological data for Corpus Christi and Port Isabel, Texas.[1]

Month	Corpus Christi		Port Isabel	
	Temperature 1887 to 1970 (°Fahrenheit)	Precipitation 1887 to 1970 (inches)	Temperature 1931 to 1962 (°Fahrenheit)	Precipitation 1931 to 1960 (inches)
Jan.	56.4	1.48	61.8	1.66
Feb.	59.0	1.57	64.4	1.35
Mar.	64.7	1.40	67.8	1.15
Apr.	71.4	1.86	73.3	1.69
May	76.7	3.09	78.5	1.98
June	81.0	2.69	82.5	2.49
July	83.1	1.80	83.7	1.21
Aug.	83.4	2.26	83.8	2.19
Sept.	80.5	4.53	81.9	4.97
Oct.	73.8	2.46	77.2	3.05
Nov.	64.8	1.85	69.5	1.75
Dec.	58.4	1.73	64.3	2.31
Annual	71.1	26.72	74.1	25.80

1. Averages. (Data from Orton, et al., 1967, and Department of Commerce, 1970)

more indicative of the stress associated with semiarid lands where droughts are neither infrequent nor regular (Carr, 1966). Carr's summary of probability for Texas droughts indicates that the precipitation for Corpus Christi and Port Isabel will be less than or equal to the long-term average, 6 years out of 10. Year to year precipitation occurs in irregular cycles, as shown in Figure 5 for Corpus Christi during the past 43 years. Except for 1 year, this study (1968 to 1974) has been conducted during a wet cycle. Monthly precipitation data for north and south Padre for the period of this study are given in Table 4. In the last 6 years, precipitation on northern Padre has slightly exceeded that on the mainland at Corpus Christi (38.10 versus 36.91 inches per year average).

In north Padre, prevailing winds (disregarding windspeed) are onshore 11 months of the year. The annual resultant vector sum (direction and velocity) of all winds is S 85°W (Boker, 1956). Northerly winds are associated with frontal passages and usually are strong with concurrent precipitation. Due to surface moisture, a higher wind velocity is needed to initiate sand movement. However, some "northers" are dry, and build small dunes along the beach with each passage. This sand is available for the prevailing winds to transport back to the foredunes.

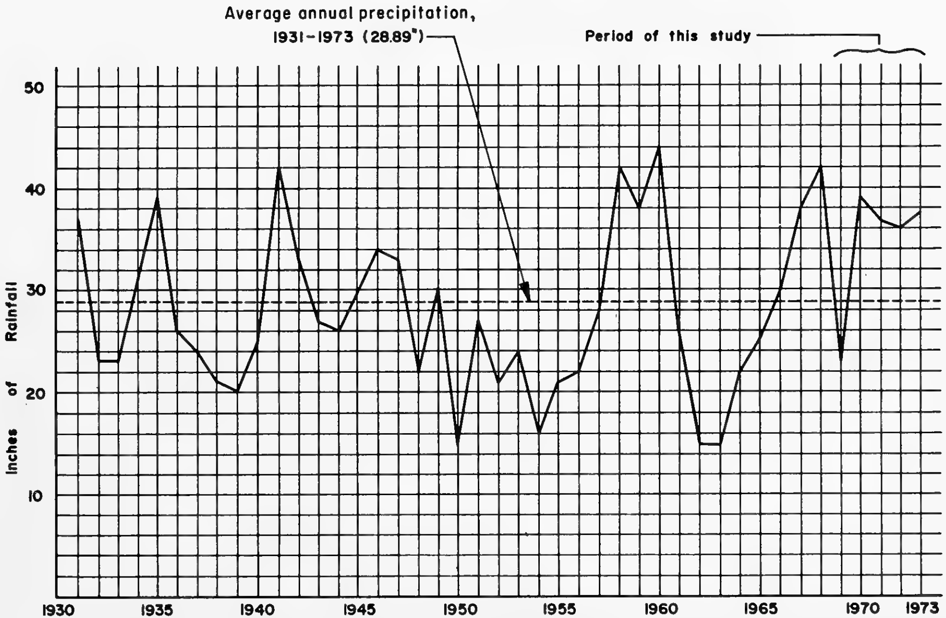


Figure 5. Annual precipitation at Corpus Christi, Texas (1931-73), showing irregular dry and wet cycles (Department of Commerce, 1970).

Table 4. Precipitation (inches) for Padre Island.

Month	1968	1969	1970	1971	1972	1973	1974
North Padre[1]							
Jan.	3.67	0.89	2.45	0.19	0.77	3.65	1.88
Feb.	2.31	3.42	0.64	0.46	4.16	1.16	0.10
Mar.	0.84	0.89	1.23	-------	2.09	0.23	3.92
Apr.	0.91	0.38	0.45	2.49	2.82	0.90	0.03
May	10.47	2.79	4.46	0.89	5.95	1.65	-------
June	10.48	0.14	0.86	0.05	10.31	10.67	-------
July	3.08	0.01	0.87	-------	4.43	0.97	-------
Aug.	0.78	2.47	2.61	6.79	3.81	2.27	-------
Sept.	7.14	2.75	7.62	12.83	7.75	12.40	-------
Oct.	2.37	9.80	3.10	3.07	1.33	9.91	-------
Nov.	1.18	8.84	0.55	1.04	4.95	1.52	-------
Dec.	1.55	0.49	0.45	3.74	0.29	0.16	-------
Totals	44.78	32.87	25.29	31.55	48.66	45.49	
South Padre[2]							
Jan.	---------	---------	-------	0.51	-------[3]	-------	1.04
Feb.	---------	---------	-------	1.15	-------	3.20	0.08
Mar.	---------	---------	0.25	-------	-------	0.16	0.20
Apr.	---------	---------	2.25	1.75	-------	0.72	0.26
May	---------	---------	7.28	0.77	-------	1.32	-------
June	---------	---------	1.64	3.79	-------	6.21	-------
July	---------	---------	0.80	6.00	4.61	0.60	-------
Aug.	---------	---------	0.50	1.69	-------	4.21	-------
Sept.	---------	---------	5.91	11.96	-------	3.44	-------
Oct.	---------	---------	5.31	-------	-------	3.27	-------
Nov.	---------	---------	0.37	-------	-------	0.87	-------
Dec.	---------	---------	0.99	-------	-------	0.31	-------
Totals	---------	---------	25.30	27.62			

1. Data from Padre Island National Seashore Ranger Station.
2. 1970, 71, and 72 data from one mile north of U.S. Coast Guard Station. 1973, 74 data from U.S. Coast Guard Station.
3. 1972 data lost.

Evaporation data are available from two stations near Padre Island. Beeville, about 60 miles northwest of Corpus Christi, had an annual average evaporation of 59.11 inches. Precipitation during the same period averaged 29.48 inches; wind movement was 51,898 miles per year. Weslaco, occupying a similar position relative to Port Isabel as Beeville to Corpus Christi, in 22 years had an average annual evaporation rate of 56.07 inches, and an average annual precipitation rate of 23.80 inches; wind movement was 29,020 miles annually for a 19-year period (Bloodgood, Patterson, and Smith, 1954). Evaporation on the island is less than the mainland due to higher humidity and lower temperatures, although precipitation rates are equal. Nonetheless, there is deficiency in available water.

6. Soil.

The coastal topography of the mainland adjacent Padre Island is relatively flat with soils developed from Pleistocene and Recent unconsolidated clastic sediments. The soils of Padre Island developed on Recent marine and eolian sands. Sand particle size from project samples (Table 5) is dominantly fine to very fine sand, and agrees with other investigators (Hayes, 1964). Garner (1967) states, "The well sorted sands consist of quartz, chert, heavy minerals, and volcanic and plutonic rock fragments . . . Sands on the northern part of the island contain plutonic and volcanic rock fragments; on the southern part of the island they contain relatively more volcanic rock fragments and relatively fewer plutonic rock fragments." The soil is highly variable in salt content with varying amounts of shell and organic matter. The highest percentage of organic matter from beach sands was 0.1 (Table 6). Shell fragments ranged from a trace to 14.9 percent.

7. Vegetation.

The vegetational history of the island is incomplete, but the relative species composition is different today from the pristine condition. The adjacent mainland vegetation is a mixture of live oak (*Quercus virginiana*), sweet bay (*Magnolia virginiana*), and tall prairie grasses such as big bluestem (*Andropogon Gerardi*), tanglehead (*Heteropogon contortus*), switchgrass (*Panicum virgatum*), Indian grass (*Sorghastrum avenaceum*), and four-flowered trichloris (*Trichloris pluriflora*), and associated broadleaf plants. With one exception, none of these prairie grasses occur today on either Padre Island or Mustang Island, although all are well adapted to sandy, moist sites, similar to those of the mid-island prairie. All are excellent forage species, and are termed *decreasers* since they do not persist under heavy grazing pressure. One species (big bluestem) has recently (1973) appeared at scattered locations along the roadside on northern Padre, apparently as waifs; the 30 to 40 individual plants are thriving and spreading.

Padre Island's woody vegetation consists mainly of live oak. Sizable mottes (dense groves surrounded by grassland) exist on the north end of the island and several small mottes occur farther south. On the national seashore, several trees survive in an area once covered by a large motte (Derek Hambly, PAIS Naturalist, personal communication, 1970). Stumps of this motte are occasionally uncovered during hurricanes. Within the remaining mottes on the

Table 5. Sand-size fractions (percent) from various locations on Padre and Mustang Islands.

Area	Depth (inches)	Coarse[1] ≥ 0.50 mm	Medium ≥ 0.25 mm	Fine ≥ 0.10 mm	Very fine ≥ 0.05 mm
		1969 Samples			
North Padre	Surface	1.1[1]	19.7	77.9	1.1
	12	-------	38.4	59.8	1.7
Nursery	--------	-------	0.8	97.2	1.9
South Padre	Surface (windblown)	-------	8.7	90.2	0.4
	Surface	-------	1.3	95.4	3.2
	12	-------	15.9	83.5	0.4
	Surface	-------	0.9	96.4	2.5
	6	-------	3.6	94.7	1.6
	12	0.9	3.9	93.7	1.3
	26	14.9	11.9	71.4	1.6
		1970 Samples			
Mustang					
foredune			1.7	96.3	1.9
interdune			1.5	96.3	2.2
hind dune			1.6	96.4	2.0
North Padre					
foredune			0.3	97.7	1.9
interdune			1.0	97.1	1.9
hind dune			0.1	98.6	1.3
Seashore					
foredune			0.5	98.2	1.3
interdune			1.4	96.4	2.2
hind dune			0.6	97.5	1.9
Twin Batteries, 1,200-foot sea oats			0.9	97.8	1.3

(Using U.S.D.A. Size Standards)

1. Coarse sand was mostly shell particles. In 1970, these particles never exceeded a trace and were not measured. Particles less than 0.05 mm belong in the silt and clay fractions and never exceeded a trace; although measured, the values are omitted.

Table 6. Average nutrient content of sand from various locations on Padre Island.

Area	pH	Organic matter (percent)	NO_3	P_2O_5	K_2O	CaO	Soluble salts	Na
			(pounds per acre)					
Suggested level for agricultural lands[1]	8.3	----	80	80	500	----------	2,000	--------
Nursery	7.4	0.7	----	30	155	700	-------	42
Twin Batteries	8.6	0.1	21	15	188	4,739	3,840	1,995
South Padre Pass	8.9	0.0	24	18	480	14,000	4,420	4,140
South Padre sea oats	9.2	0.0	10	25	580	15,000+	2,219	5,000+
Mustang foredune	8.0	0.0	----	17	48	2,576	52	60
Mustang interdune	7.3	0.8	2	26	84	1,344	52	60
Mustang hind dune	6.6	1.1	5	24	72	1,344	104	60
North Padre foredune	8.5	0.1	2	18	48	6,300	52	60
North Padre interdune	7.8	0.5	2	12	84	1,036	52	40
North Padre hind dune	7.4	0.1	----	11	60	376	52	60
PAIS foredune	8.1	0.1	20	15	96	3,500	1,716	640
PAIS interdune	7.8	0.6	----	19	96	1,036	52	80
PAIS hind dune	7.5	0.2	----	13	60	616	52	60
1,200-foot sea oats	8.3	0.1	47	19	204	2,940	4,940	1,620
South Padre 400-foot sea oats	9.0	0.1	5	28	144	14,000	416	480

Area	Micronutrients (pounds per acre)					
	Fe	Mn	B	Ca	Zn	Mo
Suggested level for agricultural lands[1]	200	40	40.0	4.0	24	1.0
Nursery	84	12	0.3	7.3	3	0.1

1. Courtesy of Dr. William F. Bennett, Associate Dean, College of Agricultural Sciences, Texas Tech University.

extreme north end of the island are sweet bay, common lantana (*Lantana horrida*), prickly-ash (*Zanthoxylum Clava-Herculis*), and huisache (*Acacia Smallii*). Scattered clumps of huisache are also found throughout the island, and willows (*Salix nigra*) are occasionally encountered. Salt-cedars (*Tamarix* spp.) were introduced on the north end of the island and near the Dunn ranch headquarters. Considerable planting of Australian-pine (*Casuarina equisetifolia*) is now underway in the development area. However, with the exception of some common plants of sub-shrubby habit (e.g., *Croton punctatus*, *Senecio Riddellii*, *Borrichia frutescens*), woody plants are of little importance to the vegetation structure of the island.

North Padre Island, south to southern Big Shell beach, is predominantly grassland of midheight. Seacoast bluestem (*Schizachyrium scoparium* var. *littoralis*), seashore dropseed (*Sporobolus virginicus*), gulfdune paspalum (*Paspalum monostachyum*), and saltmeadow cordgrass (*Spartina patens*), occur from the foredune across the island. These, plus broomsedge bluestem (*Andropogon virginicus*), and several species of panic grasses (*Panicum* subgenus *Dicanthelium*) are the dominant grasses in the vegetated middle part of the island.

Broomsedge bluestem is dominant in a 15-mile-long area surrounding the PAIS ranger station, while seacoast bluestem forms an extensive midheight grassland to the south (especially in the Big Shell area) and on the extreme northern end of the island. On southern Padre, which has suffered more extensive hurricane surge damage, the grassland is discontinuous, and entirely absent in some large stretches. However, the composition is similar to the north end, except broomsedge bluestem and the *Dicanthelium* panicums are absent. Bordering the mudflats on the Laguna Madre shores, on both north and south Padre Island, shoregrass (*Monanthochloe littoralis*) is dominant.

The spring flora is characterized by many showy forbs. Beach evening primrose (*Oenothera Drummondii*), whitestem wild indigo (*Baptisia leucophaea*), and gentians (*Eustoma exaltatum*, and *Sabatia arenicola*) are among the conspicuous and widespread species. In fall, wooly croton (*Croton capitatus*), gulf croton (*Croton punctatus*), prairie senna (*Cassia fasciculata*), scarlet pea (*Indigofera miniata*) beach groundcherry (*Physalis viscosa*), western ragweed (*Ambrosia psilostachya*), and camphorweed (*Heterotheca subaxillaris*) comprise many of the dominant forbs.

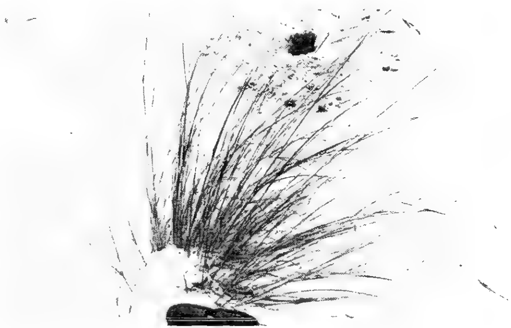
Most mid-island hummock dunes and ridges have remnants of sea oats in addition to the above-listed species. Swales and shallow depressions vary in size from small potholes to extensive marshes with typical aquatic vegetation. Although there are few permanent freshwater marshes, in wet years extensive ponds may be present year around. Shallow depressions are often covered with saltmeadow cordgrass, but those with longer-standing water often have tule (*Typha domingensis*), rattlepod (*Sesbania Drummondii*), and the tall sedges *Eleocharis interstincta* and *Scirpus americanus*, plus other species of small sedges (*Eleocharis* spp. and *Cyperus* spp.). Seashore dropseed usually covers the exposed ground surface when the depressions are dry. Lagunal saline mudflats, subject to periodic inundation, develop a cover of glasswort (*Salicornia perennis*, and *S. Bigelovii*), and sea blite (*Suaeda* spp.). On slightly more elevated areas, shoregrass, sea oxeye (*Borrichia frutescens*), and camphor daisy (*Machaeranthera phyllocephala*) are found.

The number of species on the shoreface of the dunes is limited, with sea oats the dominant sand-trapping plant (Fig. 6). Other species capable of trapping or binding sand are saltmeadow cordgrass, seashore dropseed, bitter panicum, railroad vine (*Ipomoea Pes-caprae*), and gulf croton. After dunes have been started by pioneer vegetation, forbs such as beach groundcherry, beach evening primrose, and prairie senna often become common.

To supplement a visual description of the island vegetation, and to help document changes after livestock removal, quantitative vegetation measures were made in August 1971, and repeated in August 1973. Transects were established in four zones: (a) backshore, about 100 feet shoreward of the foredunes; (b) foredune foreslope (windward slope); (c) middune area, leeward of the primary dune crest, but in the foredune complex; and (d) mid-island prairie, mostly flat grassland, with occasional scattered dunes and depressions.

Sea oats

Bitter panicum



Saltmeadow cordgrass

Shoredune panicum

Figure 6. Native grasses used in test plantings.

The transects were 1 mile long on a north-south axis parallel with the beach, and extended north from the PAIS ranger station to the Chevron Oil Company installation. A 1-meter-diameter hoop was tossed at 10-pace intervals from the previous sample. Frequency and cover-class data were taken. One hundred samples along each transect were obtained each year. An importance index was calculated for each species by multiplying percent frequency by percent cover (Dyksterhuis, 1946) for a maximum possible value of 10,000.

These transects were located in the central part of the South Bird Island Quadrangle. The mid-island prairie transect extended from 500 feet west of the PAIS ranger station north to 500 feet west of the Permian Tank-main road junction. This area is termed an older deflation plain by Hunter and Dickinson (1970). The backshore transect was in the center of the 4-mile-long pedestrian-only beach. The two foredune transects were along a continuous and well-developed foredune ridge. Representative photos of parts of the four transects are shown in Figure 7.

Results of the vegetative survey are shown in Tables 7 and 8, and generalized in Figure 2. There was little difference in frequency of most species between the 2 years, but generally a consistently higher cover value for these same species in 1971 (Table 8); this apparently represents differences in observer bias in the estimation of cover classes, rather than a decrease in cover. Several species frequently found in the 1973 mid-island transect were scarce or absent in the 1971 transect, e.g., a sedge, (*Fimbristylis caroliniana*), yellow-eyed-grass (*Xyris Jupicai*), *Centella asiatica*, pencil-flower (*Stylosanthes viscosa*), and fleabane (*Erigeron myrionactis*). Species composition of the mid-island grasses changed little in 2 years, but backshore vegetation changed dramatically during the interval. Hurricane Beulah (1967) planed off the beaches on northern Padre to the foredune line. Since Hurricane Beulah, the backshore vegetation at the pedestrian-only beach has rapidly advanced seaward.

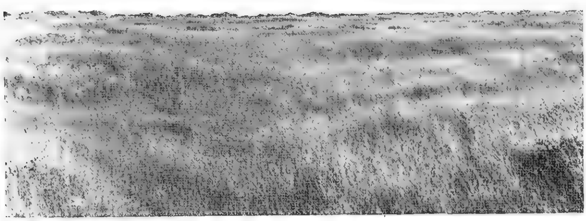
Species diversity increases inland (Table 9), with the greatest number occurring on the mid-island transect (old deflation plain). Although similar transects were not made within the younger deflation plain or Laguna Madre flats, species diversity also decreased in these areas. The total number of vascular plant species on Padre and Mustang Islands (including roadside waifs and some exotic plantings, such as five species of salt-cedar) is about 370 (Fred B. Jones, Corpus Christi botanist, personal communication, 1973).

Of particular interest is the vegetation of the backshore and the foredune foreslope, and the natural succession of plants from a barren, hurricane-planed backshore to a continuous, mature foredune ridge. The following sequence of these events was based on information from vegetative surveys, observation of areas of natural formation, and examination of sequential aerial photos dated 1937 to 1974.

Sea purslane, one of the first species to reappear on the denuded backshore, is vegetatively dispersed by wave and wind action. Clumps of sea purslane trap sand, forming small dunes which usually rise only a few feet above the beach surface. Beach

Backshore (center) and foredune foreslope (left)

Mid-dune of foredune complex



Mid-island prairie (old deflation plain)

Figure 7. Locations of four vegetative-survey transects, north Padre Island. Photos taken July 1974.

Table 7. Dominant plant species of four major plant communities, north Padre Island.[1]

August 1971	Importance Index	August 1973	Importance Index
Backshore			
Ipomoea Pes-caprae	53	*Ipomoea stolonifera*	371
		Sesuvium portulacastrum	299
		Ipomoea Pes-caprae	113
		Amaranthus Greggii	25
		Sporobolus virginicus	19
		Spartina patens	13
Foreslope of Foredune			
Uniola paniculata	1,159	*Ipomoea stolonifera*	1,411
Ipomoea stolonifera	899	*Uniola paniculata*	714
Croton punctatus	765	*Croton punctatus*	249
Ipomoea Pes-caprae	19	*Oenothera Drummondii*	24
Physalis viscosa	14	*Senecio Riddellii*	18
		Cassia fasciculata	11
Mid-dune			
Uniola paniculata	2,549	*Uniola paniculata*	908
Paspalum monostachyum	1,578	*Paspalum monostachyum*	740
Physalis viscosa	125	*Senecio Riddellii*	525
Senecio Riddellii	95	*Physalis viscosa*	127
Ambrosia psilostachya	66	*Ipomoea stolonifera*	76
Ipomoea stolonifera	58	*Paspalum setaceum*	74
Oenothera Drummondii	38	*Oenothera Drummondii*	67
Croton punctatus	37	*Cyperus esculentus*	48
Paspalum setaceum	36	*Ambrosia psilostachya*	29
Leptoloma cognatum	31	*Leptoloma cognatum*	25
Panicum spp.[2]	12	*Schizachyrium scoparium*	13
		Hydrocotyle bonariensis	11
		Vaseyochloa multinervosa	10
Mid-island			
Paspalum monostachyum	2,024	*Paspalum monostachyum*	949
Panicum spp.[2]	1,035	*Panicum lanuginosum*	876
Panicum angustifolium	441	*Andropogon virginicus*	441
Schizachyrium scoparium[3]	266	*Panicum angustifolium*	124
Baptisia leucophaea	156	*Xyris Jupicai*	98
Spartina patens	43	*Stylosanthes viscosa*	86
Hydrocotyle bonariensis	22	*Paspalum setaceum*	53
Dichromena colorata	14	*Spartina patens*	52
		Centella asiatica	33
		Croton capitatus	26
		Fimbristylis caroliniana	20
		Erigeron myrionactis	17
		Croptilon divaricatum	10

1. Species with an Importance Index $\geqslant 10$. Product of relative frequency (percent) times percent cover (Table 8); maximum = 10,000.
2. Probably *P. lanuginosum*, *P. sphaerocarpon*, and *P. portoricense*.
3. Confused with *Andropogon virginicus*, the dominant bluestem in this area in 1973.

Table 8. Composition of vegetation along four transects, north Padre Island.

Family	Species[1]	Backshore		Foredune Foreshore		Mid-dune		Mid-island		Backshore		Foredune Foreshore		Mid-dune		Mid-island	
		F	PC	F	PC	F	PC	F	PC	F	PC	F	PC	F	PC	F	PC
		August 1971								August 1973							
Gramineae	*Andropogon virginicus*															49	9.0
	Leptoloma cognatum					17	1.8	3	0.2			5	0.2	25	1.0	1	T
	[*Panicum* sp. (*Dicanthelium* subgen)]					9	1.3[2]	79	13.1[2]								
	Panicum lanuginosum													1	0.2	63	13.9
	Panicum angustifolium					6	0.2	42	10.5					4	0.2	31	4.0
	Paspalum monostachyum			2	0.4	68	23.2	88	23.0			1	T	87	8.5	93	10.2
	Paspalum setaceum			2	0.4	24	1.5	8	0.4			3	T	35	2.1	35	1.5
	Schizachyrium scoparium					3	0.2	36	7.4[3]					6	2.1	1	0.9
	Spartina patens	9	0.3	7	0.6	4	0.8	17	2.5	10	1.3	4	0.2	6	0.6	14	3.0
	Sporobolus virginicus	4	T	5	0.1					21	0.9	3	0.2				
	Uniola paniculata	6	0.7	84	13.8	87	29.3	1	T	3	0.2	70	10.2	75	12.1	6	0.5
	Vaseyochloa multinervosa													7	1.4		
Cyperaceae	*Cyperus esculentus*											6	T	34	1.4		
	Dichromena colorata					2	T	15	0.9							4	0.2
	Fimbristylis caroliniana															34	0.6
Xyridaceae	*Xyris Jupicai*															35	2.8
Amaranthaceae	*Amaranthus Greggii*									18	1.4	2	T				
Aizoaceae	*Sesuvium portulacastrum*	1	0.2							65	4.6						
Leguminosae	*Baptisia leucophaea*							30	5.2							16	0.1
	Cassia fasciculata											6	1.9	8	0.8	21	0.2
	Stylosanthes viscosa															33	2.6
Euphorbiaceae	*Croton capitatus*							1	T					7	0.1	26	1.0
	Croton punctatus			55	13.9	17	2.2	1	T	1	T	53	4.7	1	T		
Onagraceae	*Oenothera Drummondii*			1	0.2	15	2.5	1	T	1	0.2	14	1.7	12	5.6		
Umbelliferae	*Centella asiatica*															22	1.5
	Hydrocotyle bonariensis					3	0.3	16	1.4					10	1.1	9	0.3
Convolvulaceae	*Ipomoea Pes-caprae*	14	3.8	12	1.6	2	0.3			39	2.9	12	0.7			1	T
	Ipomoea stolonifera	1	T	81	11.1	24	2.4			57	6.5	96	14.7	21	3.6	11	0.3
Solanaceae	*Physalis viscosa*			13	1.1	48	2.6	1	T			11	0.6	49	2.6	4	0.2
Compositae	*Ambrosia psilostachya*			5	0.3	39	1.7	2	T			7	0.6	21	1.4	8	0.5
	Croptilon divaricatum													1	0.2	10	1.0
	Erigeron myrionactis													4	0.6	24	0.7
	Senecio Riddellii			3	0.3	22	4.3					25	0.7	41	12.8		
Unknown Forb								24	0.9								

1. Only those species with an importance index (F × percent cover) of ⩾ 10 for any one or more of the 8 transects are included.
2. Originally reported as *P. portoricence.* Probably represents several *Dicanthelium Panicums* (*P. lanuginosum*, the commonest species by far; *P. sphaerocarpon; P. portoricence*).
3. Confused with *Andropogon virginicus*, a vegetatively similar species (both flower later in October and November).

Notes: F = relative frequency (percent occurrence in 100, 1-meter-diameter plots). Maximum = 100 per species per transect.
PC = percent cover: sum of cover per plot per 100. Maximum = 100 per transect.
T = trace = <0.1 percent.

Table 9. Species diversity in each of four plant communities, August 1973.

Number of species sampled per 100 plots.	
Backshore	10
Foreslope	20
Mid-dune	36
Mid-island	58
Total species sampled (400 plots)	74

morning-glory, railroad vine, gulf croton, sea oats, saltmeadow cordgrass, and seashore dropseed are early colonizers. Establishment of seed-dispersed species may be aided by the temporarily stable sea purslane dunes. Bitter panicum, an important early colonizer and apparently dispersed only vegetatively, failed to appear on the transects.

Rhizomatic growth and tillering of these grasses, especially sea oats and bitter panicum, is stimulated by the accumulation of fresh sand continually blown inland from the shore. Windblown sand is trapped by exposed grass blades and eventually stabilized by the root and rhizome system. The morning-glories generally do not function in dune building, but rapidly grow over barren sand and partially stabilize the dunes. Single plants of sea oats and bitter panicum, and to a lesser degree saltmeadow cordgrass and gulf croton, continue trapping and growing through accumulating sand, forming isolated hummock dunes that grow vertically and horizontally in all directions (Fig. 8). Few other species can survive on rapidly growing dunes, but the protection afforded the backshore leeward of the hummock dunes from wind, salt spray, sand accumulation, and minor surges, allows several species of forbs to exist.

Fed by fresh beach sand blowing inland, the unconnected hummock dunes of sea oats, bitter panicum, and saltmeadow cordgrass continue growing and eventually interconnect, forming a dune ridge. New hummock dunes begin forming shoreward, and in this manner, the foredune grows toward the gulf. This shoreward growth eventually eliminates fresh sand accumulation on the rear of the dune ridge, and affords additional protection from wind and salt spray. Less salt-tolerant species and species not adapted for growing in accumulating sand then become established, e.g., seacoast bluestem, thin paspalum, gulfdune paspalum, broom groundsel, and beach groundcherry.

At this stage, the foredune system is relatively stable, but is vulnerable to storm surges and wind-activated blowouts. Minor hurricane surges, e.g., Hurricane Celia, periodically destroy the young, early successional backshore dunes, but the foredunes remain undamaged. The backshore vegetation remains at a lower successional level due to its vulnerability. During infrequent severe storms, front parts of the foredunes may be destroyed, but eventually reform shoreward by the processes previously described.

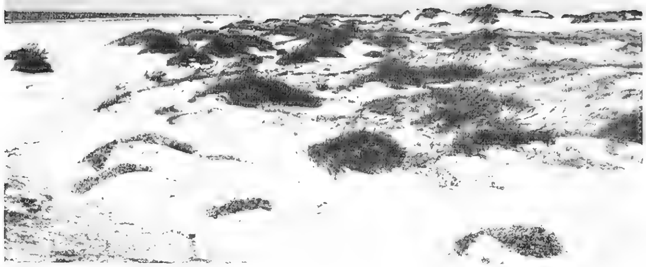


Figure 8. Unplanted (control) area (upper photo), 0.5 mile north of 1,200-foot sea oats dune, north Padre Island, July 1974; area was barren in 1969 when the sea oats site, also barren, was planted. Bottom photo shows another unplanted area in central Padre Island, July 1973; the naturally reforming dune line, mostly of sea oats hummock dunes, was barren in 1968.

The time scale for these sequences is mostly dependent upon the intervals between storms, the severity of previous storm damage, the proximity of undamaged colonizing species, and the precipitation cycle. Sequential aerial photos of Padre Island were examined at the U.S. Geological Survey office, Corpus Christi, at the PAIS headquarters, and at the University of Texas Marine Institute, Port Aransas. The photos showed that the area presently containing the north Padre study plots was barren in 1937, presumably as a result of the 1933 hurricane. However, by 1948, a fairly well developed vegetated foredune ridge had appeared with a vegetated plain to the west. The ridge and plain were more pronounced in 1950, but by 1961 (before Hurricane Carla), they were less distinct but still present. By 1967, after Hurricanes Carla and Beulah, the dune ridge was absent, and the area was again barren with a field of active sand dunes migrating west. Today (1974), in an unplanted one-half-mile section north of the study plots, the dune field is reforming naturally, and consists of mostly unconnected hummock dunes of sea oats, saltmeadow cordgrass and gulf croton which are still actively growing (Fig. 8). Another area, extending south from 1 mile south of the present Pan Am road, was also barren in 1937. In 1950, a foredune ridge was forming from interconnected hummock dunes, but there was little evidence of a leeward vegetated plain. In 1961, both ridge and vegetated plain were distinct; they apparently weathered Hurricanes Carla and Beulah since both were present in 1967, although with some active blowouts. The ridge is now mostly continuous and well vegetated.

In mid-island, there is plant colonization and succession from the westward-migrating barren dune fields, partly activated early in this century by a combination of overgrazing and drought. The dunes are so unstable that colonization by any species does not occur.

After the dune has migrated past a given point, it leaves behind a zone of barren, moist sand, usually about 5 feet above MSL. The rapidity with which a newly exposed young deflation plain can be colonized during a wet cycle and after the elimination of grazing is shown in Figure 9. Ten months after the second photo was taken, the area was sampled quantitatively for species composition; the results are given in Table 10. The most important colonizing species were feral bermuda grass (*Cynodon dactylon*) and red lovegrass (*Erogrostis oxylepis*), with several species of sedges and forbs frequent. It is expected that succession eventually will trend to a composition similar to the older deflation plain to the east (mid-island transect).

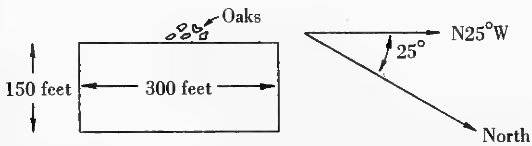
Foredune blowouts actively migrate and often encroach on the mid-island prairie and smother the vegetation. When the barren dune field advances onto a vegetated mid-island dune or dune ridge, it is often buried only to the crest, and species such as sea oats, gulf croton, beach evening primrose and beach groundcherry, which can withstand moderate to great amounts of sand deposition, continue to grow and even thrive as a vegetative island in the midst of a sand sea. The dune may be partially stabilized in this manner, or it may continue to migrate, eventually leaving behind the "island" as the top of an inverted cone of barren sand, which usually erodes.

Figure 9. A surviving live oak motte near Permian Tank road, Padre Island National Seashore. Upper photo (1970) shows a deflation plain left by a barren, migrating dune field; plant colonization was inhibited by cattle grazing. Bottom photo taken November 1972, shows condition 2 years after removal of cattle.

Table 10. Composition of vegetation at "Oak Grove," Permian Tank Area, Padre Island National Seashore, 13 September 1973.[1]

Family	Species	F	Percent cover	Index[2]
Gramineae (Grasses)	*Cynodon dactylon*	92	9.4	862
	Eragrostis oxylepis	82	4.6	379
Cyperaceae (Sedges)	*Cyperus polystachyos*	56	0.9	49
	Cyperus esculentus	23	0.9	21
	Cyperus surinamensis	33	0.3	9
Juncaceae (Rushes)	*Juncus scirpoidea*	17	0.3	5
Loganiaceae	*Polypremum procumbens*	51	0.7	37
Onagraceae	*Oenothera Drummondii*	33	0.4	14
Scrophulariaceae	*Bacopa Monnieri*	52	1.4	74
Compositae	*Erigeron myrionactis*	44	0.8	35

1. Sample consisted of 100 1-meter-diameter hoops systematically thrown in a 300- by 150-foot area. The location is as follows:



2. Importance Index = Product of frequency × percent cover. Maximum = 10,000.

IV. METHODS: EXPERIMENTAL PLOTS

The experiments and experimental methods performed during 1969 to 1974 at study plots on Padre Island, and their subsequent monitoring, are discussed in this section and in Section V and Appendix A; individual topics are discussed in detail in the following section. Early in the study, emphasis was on selection of suitable species of dune-building plants and the basic techniques of establishment. Problems encountered during the initial phase were studied and methods tested for circumventing them. In the later project stages, refining of planting techniques continued, with a further study of environmental parameters critical to plant establishment, of modified techniques for planting problem areas (washover passes, fence-built dunes), and a continued monitoring of dune growth and its effect on the surrounding area.

A summary of the experimental plots with successes and failures is given in Table 11; the table corresponds with the study site-map in Figures 10 and 11. The maps show only successful sites presently growing.

Table 11. Experimental planting sites on Padre Island.

Description	Planting	Comments
North Padre		
1,200-foot sea oats (Twin Batteries).	Mar. 1969	Original planting 3/4 saltmeadow cordgrass and 1/4 sea oats. Percent survival: cordgrass, 14; sea oats, 46. Cattle grazing an early problem. Supplemental fill-in plantings of sea oats, cordgrass, and panicum (shoredune and bitter).
1,500-foot monthly planting-species comparisons.	1969 to 1970	Test plantings in small blocks of bitter panicum, sea oats, saltmeadow cordgrass, and seashore dropseed; planted over 2 years. Survival: irregular; dune not uniform.
400-foot dune-width extension plot.	Apr. 1973	3:1 mixture of bitter panicum to sea oats. Percent survival: panicum, 62; sea oats, 1.
1,100-foot bitter panicum	Feb. 1970	Bitter panicum alternated with sea oats seed. Percent survival: panicum, 17; sea oats, unsuccessful. Subsequent patchwork planting.
1,200-foot dune-width bitter panicum.	Feb. 1972 and Apr. 1972	North half planted with bitter panicum; 76 percent survival. South half planted with sea oats but destroyed by jackrabbits. Replanted in April with bitter panicum; 17 percent survival.
700-foot monthly plantings (north section) plus 400-foot monthly plantings (southernmost plot).	1973 to 1974	Site originally planted in January 1971, as mixed sea oats-bitter panicum planting. Failure due to drought and wind excavation. Monthly plantings in 1973 (700-foot section) and 1974 (southernmost plot) of sea oats and bitter panicum; mostly successful.
Pan Am panicum (500 feet).	Apr. 1970	Planted with sea oats, but destroyed by rabbits. Replanted with bitter panicum; 47 percent survival. Further panicum plantings in December 1970.
South Padre		
Pass No. 1.	Mar. 1971	North 400-foot section of 4-foot sand-fence dune planted with bitter panicum.
	Mar. 1973	South 800-foot section of beach west of fence planted to sea oats and bitter panicum. South half: failure due to sand burial. North half: successful. Percent survival: panicum, 53; sea oats, 21.

Table 11. Experimental planting sites on Padre Island.—Continued

Description	Planting	Comments
South Padre—Continued		
Pass No. 2	Feb. 1969	1,100-foot planting of saltmeadow cordgrass buried by sand of storm surge; total failure. Replanted with cordgrass following month.
	Mar. 1971	2-foot sand-fence dune (erected spring 1970) planted with bitter panicum. Mostly successful, but some recent washed-out areas in center.
	Feb. 1973	400-foot section leeward of Highway Department picket sand fence planted with sea oats, bitter panicum, shoredune panicum. Mostly failure due to high soil salinity and burial by sand drifts.
Pass No. 3	Mar. 1971	Shoredune panicum planted in furrows on original elevation. Planting failure due to high salinity.
	May 1972	2-foot sand-fence dune (400-foot-long fence erected November 1971) planted with sea oats. Seeds wind-excavated. Survival: none.
	Nov. 1972 to Sept. 1973	Monthly plantings of sea oats and bitter panicum. Survival: irregular; mostly good.
	Feb. 1973	400-foot section leeward of Highway Department picket sand fence planted with sea oats, bitter panicum, shoredune panicum. Mostly failure due to high soil salinity and burial by sand drifts.
Pass No. 4	Mar. 1971	Planted on original elevation with sea oats and bitter panicum. Planting failed due to high salinity.
	Dec. 1971	2-foot sand-fence dune (400-foot-long fence erected November 1971) planted to bitter panicum. Planting mostly washed out by surge and buried by drifting sand.
	Feb. 1973	Replanted after fence filled with sand with bitter panicum and sea oats. Percent survival: bitter panicum, 48; sea oats, 22.
North Section Fence. South 400-foot beach.	Feb. 1971	Planted with bitter panicum. Failure due to surge.
North Section Fence. North 400-foot sea oats (beach).	Feb. 1969	Survival: 1 percent due to surge.
	Mar. 1971	Leveled and replanted with sea oats and bitter panicum. Failure due to surge.

Table 11. Experimental planting sites on Padre Island.—Continued

Description	Planting	Comments
South Padre—Continued		
North Section Fence. Middle 400-foot sea oats (beach).	Feb. 1969	Survival: 2 percent, due to surge.
	Mar. 1971	Leveled and replanted with sea oats and bitter panicum. Failure due to surge.
South 400-foot sea oats (beach).	Feb. 1969	Survival: 8 percent but sufficient for uniform dune growth. Not replanted.
North Section Fence, sand-fence dune. 1,800- to 2,200-foot section.	Feb. 1962	Planted with bitter panicum. North half badly wind-eroded, mostly destroyed. South half (mulched and irrigated). Survival: good.
North Section Fence, sand-fence dune. 0- to 400-foot, 800- to 1,800-foot, and 2,000- to 2,400-foot sections.	Feb. 1973	Planted with sea oats and bitter panicum; mulched and irrigated. Survival: good on foreslope; irregular elsewhere.

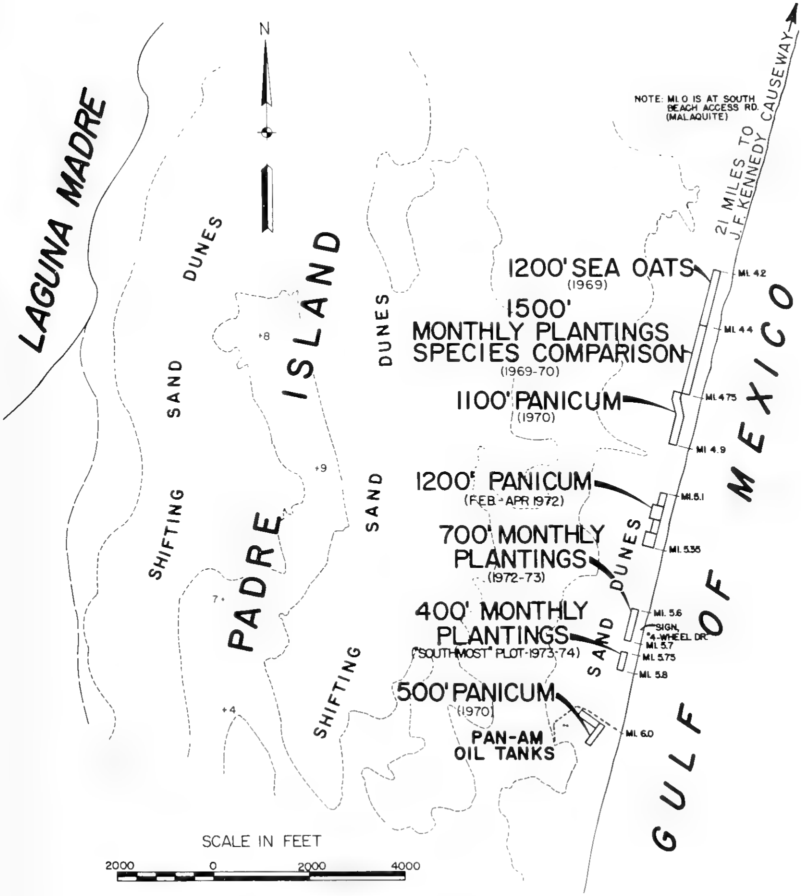


Figure 10. Location of north Padre Island experimental plantings (Map courtesy of U.S. Army Engineer District, Galveston).

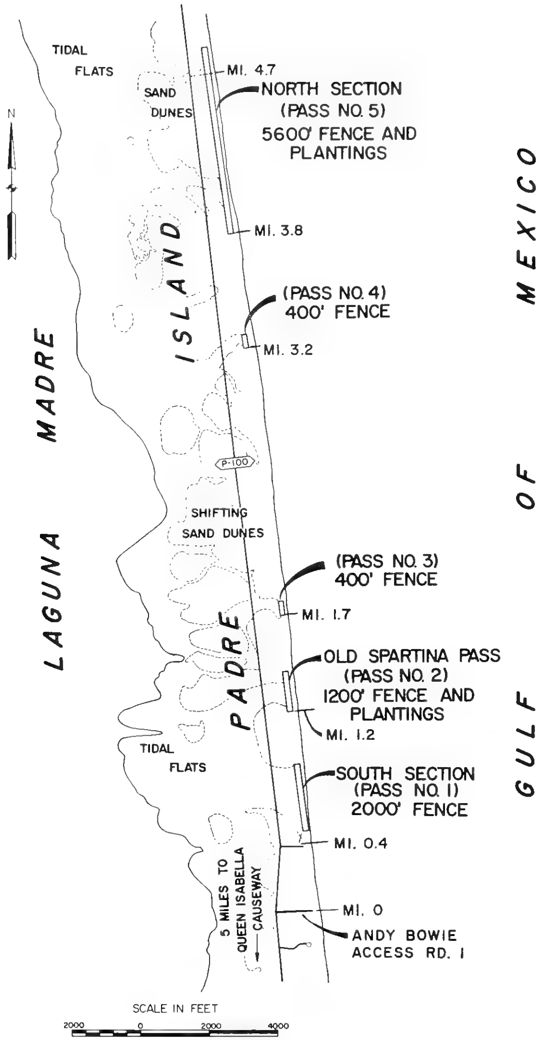


Figure 11. Location of south Padre Island experimental plantings (Map courtesy of U.S. Army Engineer District, Galveston).

At the time this study was completed, the growth of nearly 2.5 linear miles of dune line, from 50 to 100 feet wide and from a few months to over 5 years old, was being monitored. This excludes many areas of failure which were replanted once or several times using more refined methods gained through experience. On south Padre, there are five general sites of about 5,800 linear feet of planted dune line, consisting of beach plantings, hurricane washover-pass plantings with low sand fencing, and two-tiered sand-fence dunes planted after construction. On north Padre, all plantings were on the beach, without sand fencing, and now consists of about 7,000 linear feet.

V. EXPERIMENTAL RESULTS AND DISCUSSION

Experimental results are presented by flow diagrams (Figs. 12 through 18) in a sequence of experiments to establish a dune line in various areas. Numbers in the flow diagrams refer to text subsections of this section; the major steps are shown in bold letters. Guidelines and specifications for establishing a dune line are outlined in Appendix A.

1. Selection of Species.

The first phase of this study was to test and select the plants best suited for constructing foredunes. Since this required simulating as closely as possible the natural dune-building process, native Texas barrier island species were given the most consideration. In addition, many exotic (nonnative) species were also tested.

a. Necessary Attributes. Plant species for foredune construction must possess many adaptations to the harsh barrier island environment. Tolerance of salt spray and of occasional inundations by saltwater are essential attributes. The semiarid climate requires a resistance to low moisture and occasional drought conditions. Adaptations to withstand abrasion by sand particles, smothering by sand drifts, high soil temperatures, and low soil nutrient content, are also essential.

In addition to being able to survive in the backshore salt-spray zone, the plants must grow through accumulating sand quickly, stabilizing it as the dune builds. A perennial species is essential, especially a grass with a deep, fibrous root system. The ideal plant would have the capability of growing through the greatest amount of drifting sand on the backshore without being smothered.

b. Screening. Four species of grass which occur naturally on the backshore and foredunes initially were thought to possess many or all of these desired attributes. These include sea oats, bitter panicum, saltmeadow cordgrass, and seashore dropseed (Fig. 6). Many other species which occur infrequently to abundantly on the backshore and foredunes were rejected as unsuitable. Some of these, with reasons for rejection, are: (a) railroad vine and beach morning-glory; shallow root system with little ability to grow through drifting sand, and die back almost completely in cold weather; (b) sea purslane; lacks ability to form high dunes and easily fragmented by surf action; (c) seacoast bluestem; not resistant to salt spray nor tolerant of drifting sand; and (d) gulfdune paspalum; little sand trapping capacity and not very tolerant to sand burial.

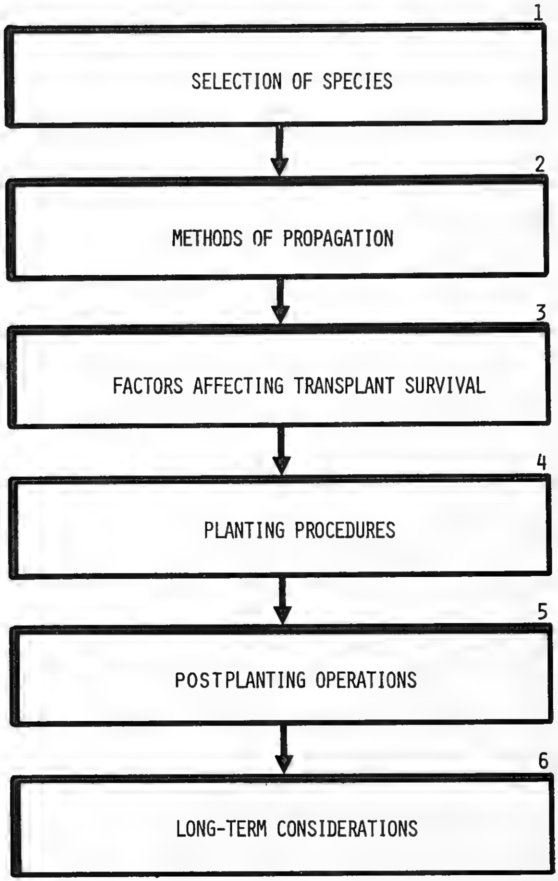


Figure 12. Flow diagram: six major aspects considered in dune stabilization. Flow represents general sequence of events in stabilizing dunes.

1. SELECTION OF SPECIES

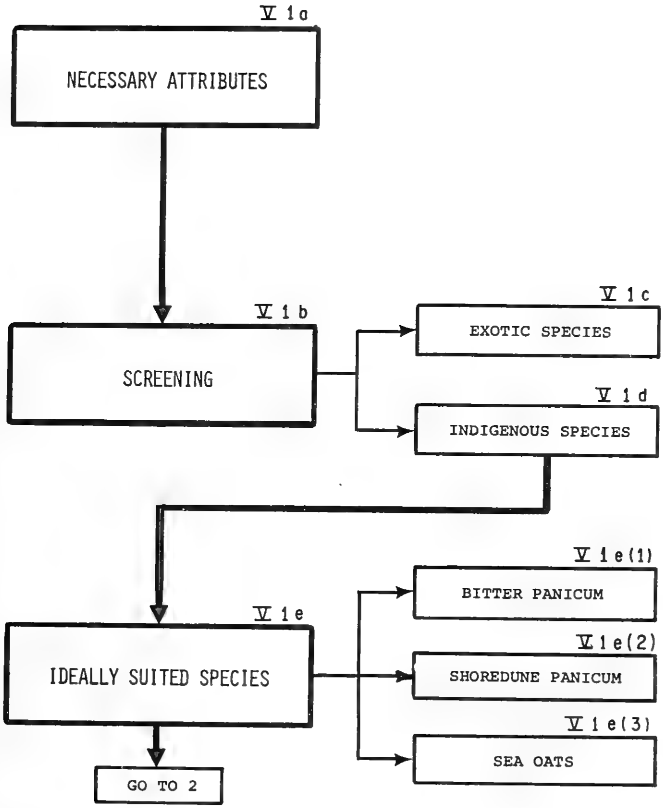


Figure 13. Flow diagram: selecting the best suited species for dune stabilization.

2. METHOD OF PROPAGATION

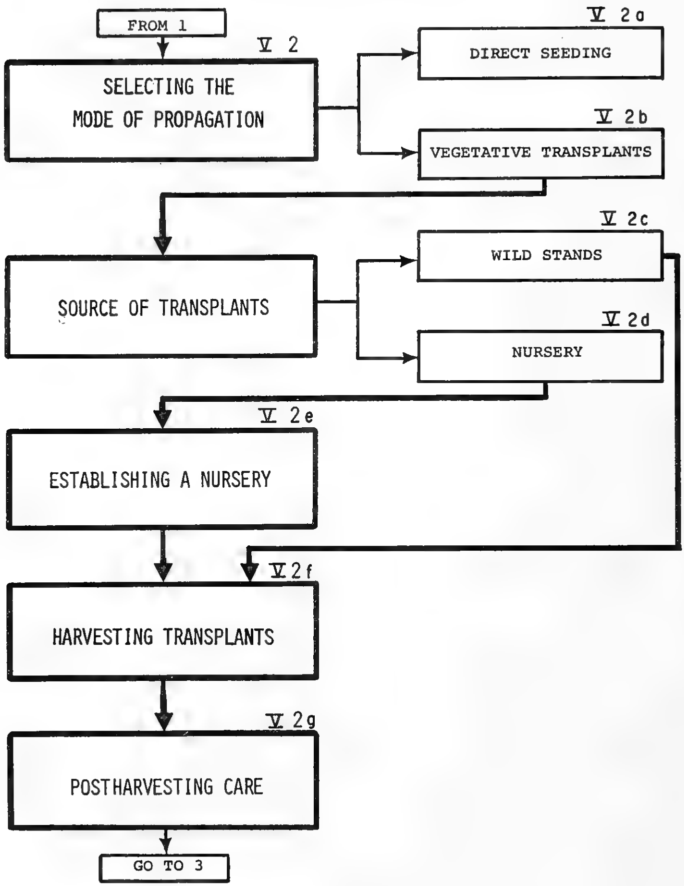


Figure 14. Flow diagram: sequence of events in propagating grasses for dune stabilization.

3. FACTORS AFFECTING TRANSPLANT SURVIVAL

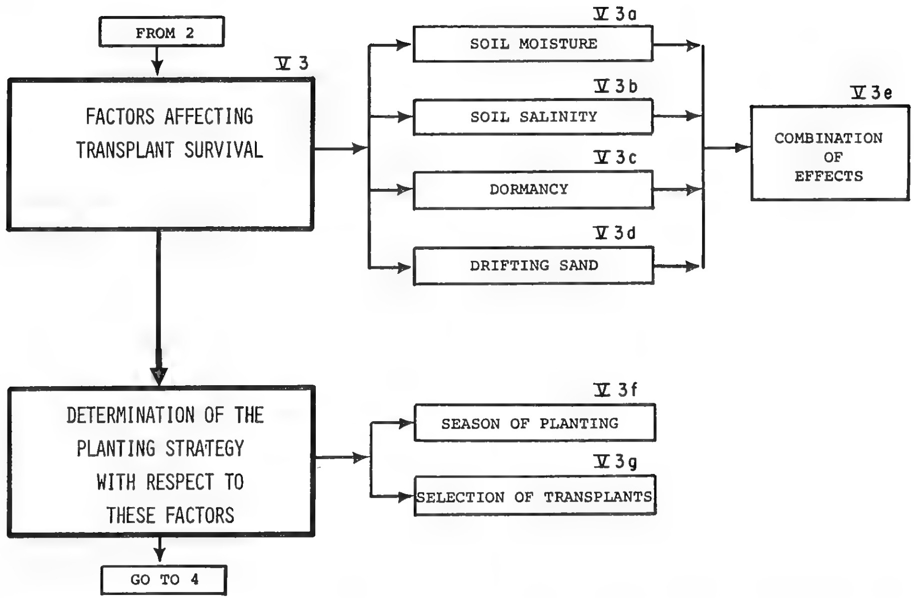


Figure 15. Flow diagram: factors affecting transplant survival of grasses planted for dune stabilization.

4. PLANTING PROCEDURES

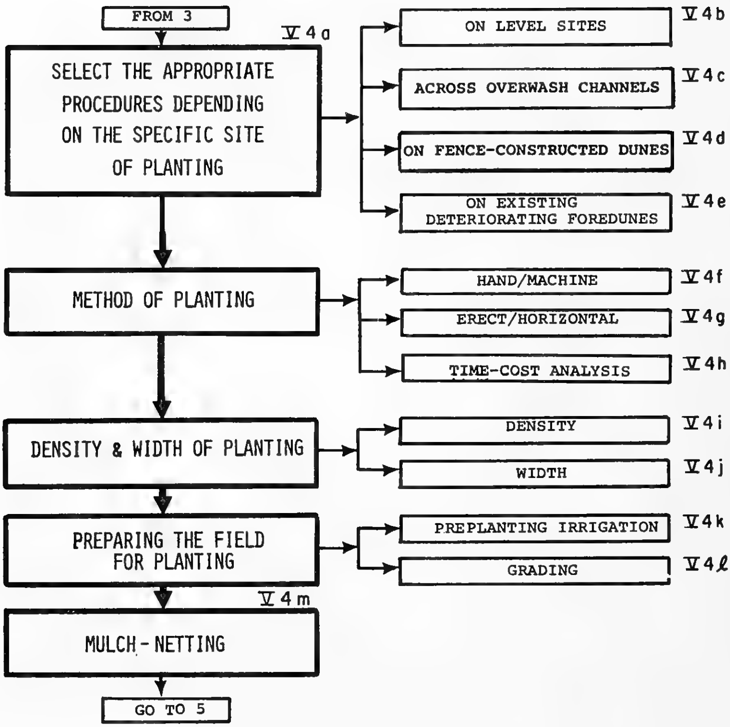


Figure 16. Flow diagram: methodology of planting grasses for dune stabilization.

5. POSTPLANTING CARE

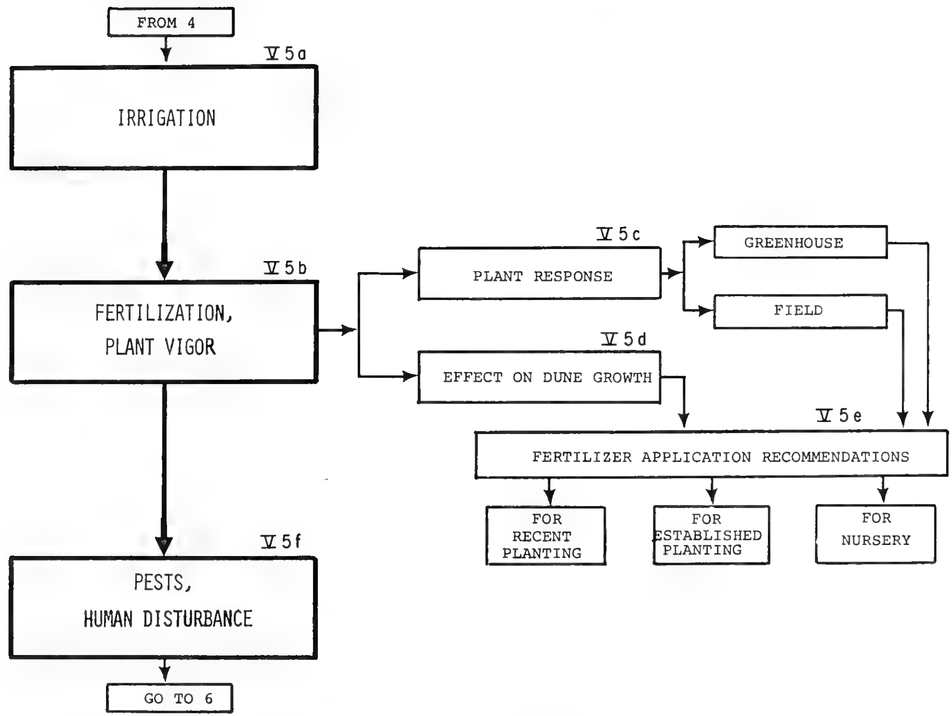


Figure 17. Flow diagram: postplanting care of grasses planted for dune stabilization.

6. LONG-TERM CONSIDERATIONS

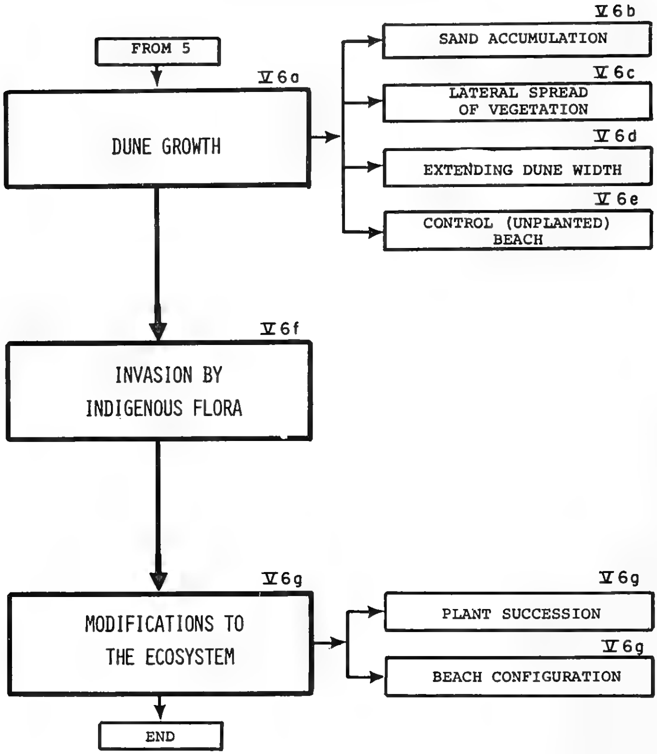


Figure 18. Flow diagram: long-term considerations in dune stabilization with grasses.

c. Exotic Species. Several exotic species were tested, through the courtesy of the U.S.D.A. Soil Conservation Service Plant Materials Centers at Pullman, Washington; Experiment, Georgia; and Knox City, Texas. Both seeds and plants were obtained for trial plantings. Results from the plantings were mostly negative (Table 12). No plants emerged from the seeds except for one species native to the area, *Indigofera miniata* (synonym is *I. leptosepala*). Survival of transplants was variable and those surviving lacked vigor except for the Japanese wild indigo (*Indigofera pseudotinctoria*). Of all lots received, only the Japanese wild indigo shows promise as a sand trapper or binder on Padre Island. Further evaluation of exotic plants was terminated in 1972 by landfill operations of the Padre Island Investment Corporation. Other plants received during 1971 were planted on backshore areas near the north Padre 1,200-foot sea oats plot. Saltwater inundation and sand abrasion prevented these species from becoming established.

American beachgrass (*Ammophila breviligulata*), a cool season grass used widely on the east coast for dune stabilization, has been successfully introduced from a more northern range into the Carolinas and used as an exotic for dune construction (Woodhouse and Hanes, 1967; Graetz, 1973). In 1970, transplants supplied by the North Carolina State University, Raleigh, North Carolina, were planted on Padre Island. The south Padre plants died within a short period, while on north Padre some plants persisted nearly 2 years before succumbing. Apparently, the hot and dry south Texas climate was unsuitable for American beachgrass. European beachgrass (*A. arenaria*) was tested on PAIS by Tauscher (1966). Early results were generally successful, and a few individual plants persisted for over 5 years.

Additionally, 113 plants of *Scaevola Thunbergii* (an exotic forb) were supplied in 1972 by the New Crops Research Branch, Agricultural Research Services, U.S.D.A., Beltsville, Maryland. The plants were transplanted to protected sites in the north and south parts of the island. After 2 years, three plants are still living on north Padre, and appear healthy although growth is slow (all are less than 2 feet high). A native species of this genus (*S. Plumieri*) is rare in this area, but one sizable clump on a north Padre foredune shows it may be useful as a dune-builder. These trials concluded that none of the exotic species tested was suitable for dune construction.

d. Indigenous Species. Testing the four most promising grasses by monthly plantings to determine survival rates and block (50 by 50 feet) plantings to assess dune-building potential, was started in 1969 (Table 13). Two species, seashore dropseed and saltmeadow cordgrass, were later eliminated. Although successfully transplanted, seashore dropseed lacked adequate sand-trapping potential; poor survival, lack of vigor, and less than optimum sand-trapping capability eliminated saltmeadow cordgrass. Saltmeadow cordgrass is very salt-tolerant, but also has a high moisture requirement (Oosting and Billings, 1942), and grows most successfully on low dunes and the backshore.

Table 12. Exotic plants tested for growth and vigor on north Padre Island.

Species[1]	Accession number	Survival 1970	Survival 1971	Survival 1972
Agropyron distichum	299457	1		
Elymus giganteus	272133	1		
	313965	1		
	314928	1		
	315079	1		
Sporobolus fimbriatus	185576	1		
	196373, 75	1		
	198596, 97	1		
	203382, 83	1		
	208950	1		
	209219	1		
	209405, 06, 07	1		
	300123	1		
Sporobolus fimbriatus var. *latifolius*	156095, 96	1		
Dactyloctenium australe	299588	1		
Digitaria macroglossa	299645, 46, 47, 49	1		
Myrica cordifolia	300032	1		
Panicum amarulum (plants)	1410, 13	2	2	
Panicum amarulum	1411	2	2	
	1412	1		
Desmostachys bipinnata (plants)	1351	2	1	
Calamovilfa gigantea	704	1		
	1416	1		
	1667, 68, 69, 70, 71	1		
	1785, 86	1		
	1979	1		
Sporobolus fimbriatus	1422	1		
Panicum Havardi (plants)	1480	2	2	
	1059	2	2	
Indigofera leptosepala	1051	3	2	
Indigofera pseudotinctoria (plants)	325	3	1	
Scaevola Thunbergii (plants)	325			2
Hemarthria altissima (plants)	299039			1
	299993			1
	364877			1

1. Seed unless indicated.

Notes: 1. No germination or growth.
2. Survived but vigor reduced.
3. Vigorous plant.

Table 13. Survival of monthly plantings of four test species on Padre Island.[1]

Species	1969 Oct.	1969 Nov.	1969 Dec.	1970 Jan.	1970 Feb.	1970 Mar.	1970 Apr.	1970 May	$\bar{x}$
North Padre									
Bitter panicum	39	66	39	60	17	20	15	65	
Saltmeadow cordgrass	23	12	9	32	13	2	1	85	
Seashore dropseed	7	26	7	30	27	10	65	41	
Sea oats	15	4	38	69	27	2	8	30	
South Padre									
Bitter panicum	11	26	61	72	69	10	10	----	
Saltmeadow cordgrass	0	0	0	10	49	0	3	----	
Seashore dropseed	4	1	25	13	44	32	9	----	
Sea oats	0	2	6	62	29	5	1	----	
North and South Padre									
Bitter panicum	25 e, f, g[2]	46 b, c	50 b	66 a	43 b, c, d	15 f, g, h	12 g, h	----	37 q
Saltmeadow cordgrass	12 h, i	6 i	4 i	21 e, f, g, h	31 c, d, e	1 i	2 i	----	11 r
Seashore dropseed	6 i	14 g, h, i	16 f, g, h, i	22 e, f, g, h	36 b, c, d	21 e, f, g, h	37 b, c, d, e	----	22 r
Sea oats	8 i	3 i	22 e, f, g, h	66 a	28 d, e, f, g	4 i	4 i	----	19 r

1. N = 100 plants.
2. Locations, species, or survival values with the same letter as another location, species, or survival value are not different at the $P_{0.05}$ level of significance.

e. Ideally Suited Species. The two remaining grasses, sea oats and bitter panicum, were selected as the most ideal species of either natives or exotics. Bitter panicum is more desirable because of higher transplant survival rates, longer planting season, ease of harvesting, and the tendency to form a uniform dune profile. The general life history, morphology, and ecology of these species in south Texas are summarized below:

(1) Bitter Panicum (*Panicum amarum*).

(a) Geographic Range. Occurs along the Atlantic and gulf coasts from Connecticut south to the Rio Grande, and has been reported from every intermediate State including both coasts of Florida (Palmer, 1972).

(b) Morphology. Bitter panicum is a strongly rhizomatous perennial grass, growing by branching at the nodes which are scattered along the length of the culm (see App. B for definitions of grass terminology). The internodes are long (Fig. 19); the sheaths are longer than the internodes and are not strongly overlapping. The inflorescence is a contracted panicle, with appressed main branches. Sheaths and blades are usually dark green, somewhat glaucous and glabrous. Blades are up to 1.5 feet long but are usually about half this length.

(c) Growth. Growth is from primary shoots, lateral shoots (aerial nodes), or tillers (subterranean nodes). In a typical foredune habitat, drifting sand often covers part of the exposed culm, and the covered lateral shoots root at the nodes as do rhizomes or stolons. In areas of light sand accumulation, the exposed parts of a mature primary culm are over 1 yard long and include 10 or more nodes; in areas of heavy sand accumulation, only the terminal leaves are visible. Schematic growth of a single-culm vegetative transplant of bitter panicum is shown in Figures 20 and 21. The clump will eventually expand vertically and horizontally in all directions by a continuation of the same process. At the perimeter are the laterally spreading tillers, while in the center of a clump are the more vertical mature primary culms. Mature primary culms may persist more than 1 year with little additional growth if not buried.

Greatest vigor occurs where blowing sand accumulates around the plant. The sand either mechanically or nutritionally stimulates the growth of new shoots and tillers which keep pace with the accumulation. If the sand supply is choked off, as on the leeward parts of a foredune, the plants appear nutrient-deficient after several years. Cover decreases, and the plants appear semidormant even in summer, putting out a minimum of new growth. Although such a stand appears to be declining, a new deposit of sand will quickly stimulate growth.

The growing season in south Texas coincides with the prevailing weather for that particular year. During the warm winter of 1973-74, some active growth occurred in all months although from mid-December to mid-February most plants in areas of light sand accumulation appeared dormant. Most leaves died, leaving only the exposed culm with perhaps a few green apical leaves. Tillering and shoot growth from old culms generally

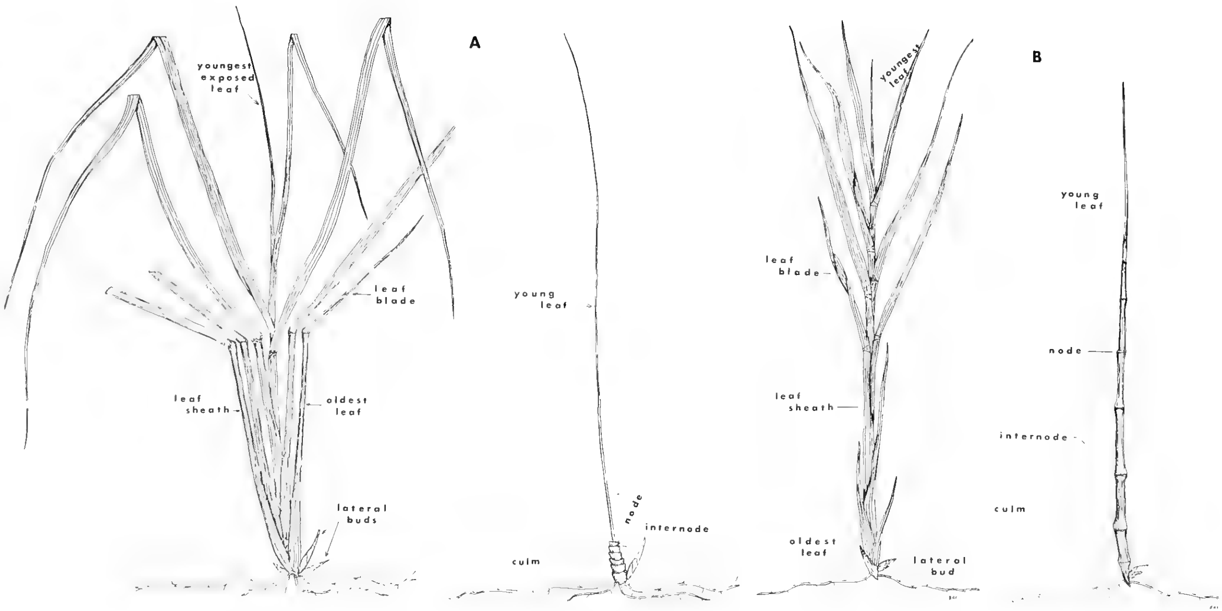


Figure 19. Vegetative culms (transplants) of sea oats (A) and bitter panicum (B). Culms are intact (left); leaf blades and sheaths removed except very young center leaves at right.

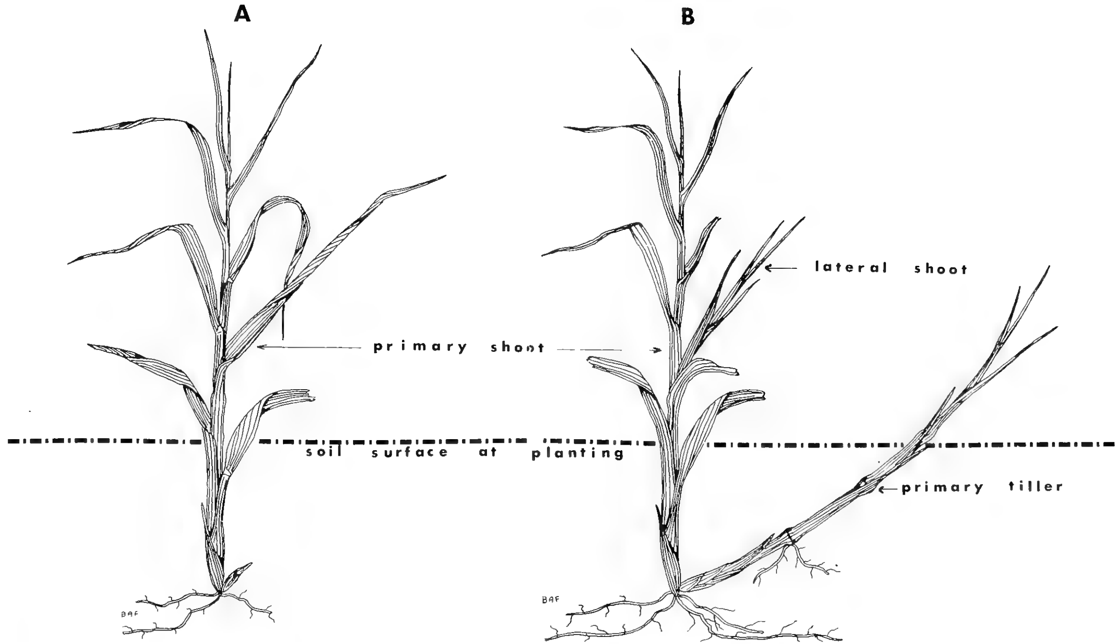


Figure 20. Growth habit of bitter panicum. Vegetative culm (A) soon after transplanting; spring growth (B) several months after planting. Growth is from a lateral shoot and a primary tiller.

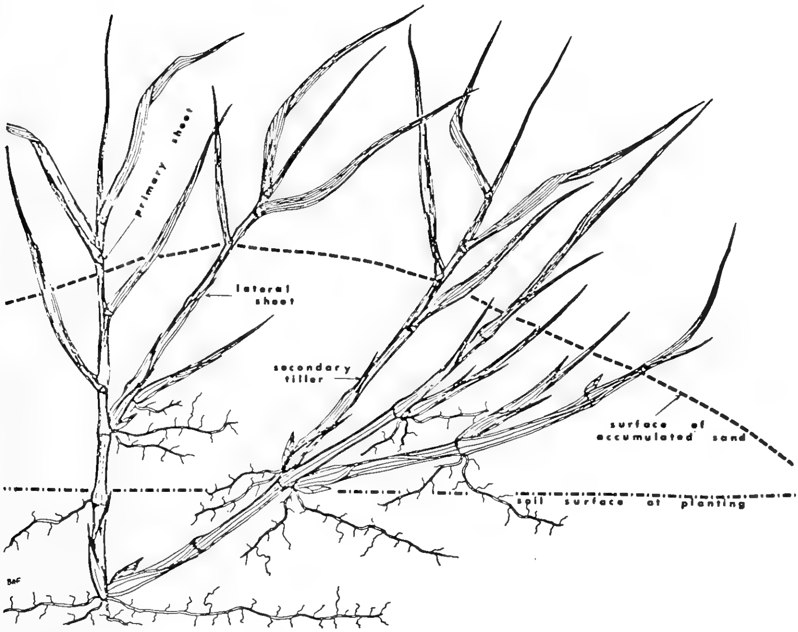


Figure 21. Bitter panicum growth at end of first summer. Lateral growth is shown in one direction only. Initial transplant has grown vertically and horizontally, accompanied by sand accumulation. Lateral shoot is buried, has rooted, and has formed a tiller and new buds. Primary tiller has given rise to secondary tillers which are in turn forming new tillers at the buried nodes.

begins in late February to March, and continues throughout the summer and fall. Where sand is actively accumulating on top of the plants, year-round growth occurs even in mid-winter. However, winter cover is more sparse.

Flowering begins in September, and continues through December. The seed is apparently sterile (Palmer, 1972), thus reproduction is entirely vegetative by lateral tillering from established clumps or by mechanical disarticulation of primary culms, which is of great importance in recolonization after hurricanes. It is theorized that culms dislodged by a storm surge are scattered in the saltwater, and redeposited as drift by the receding waters. Culms have the ability to root at the nodes even when on top of moist sand. Also, foraging by jackrabbits (*Lepus californicus*) and possibly ground squirrels (*Spermophilus spilosoma*) are important; the culms, chewed off at the base, are scattered by strong winds.

(d) Ecology. Bitter panicum is most common on the backshore and windward slope of the foredunes where few other species compete with it. Bitter panicum occurs regularly with other species less adapted to blowing sand on the lee parts of the foredunes, usually on the crest or slopes. It also occurs at widely scattered locations on the mid-island grassland prairie, and at Corpus Christi Bay shore at Port Ingleside.

Bitter panicum is highly preferred by livestock, which likely is the main reason for its scarcity on northern Padre during the early part of this study. Since grazing stopped, it is rapidly reappearing and is now locally abundant on newly formed foredunes, especially in a 5-mile area south of Bob Hall Pier; it also is common on Mustang Island. Bitter panicum is regular on the long-stabilized foredunes of the Big Shell area in central Padre, and is appearing regularly on the backshore of the PAIS pedestrian-only beach, as well as in the foredunes south to Twin Batteries. On south Padre, it is locally common in similar areas, especially on the foredunes at Boca Chica at the mouth of the Rio Grande. Similarly, Woodhouse and Hanes (1967) reported a recent increase of bitter panicum on the North Carolina Outer Banks after cattle were excluded. On some islands off the Mississippi and Alabama coasts, bitter panicum comprised about 75 percent of the foredune vegetation (Lloyd and Tracy, 1901).

(2) Shoredune Panicum (*Panicum amarulum*).

(a) Geographic Range. This species is briefly discussed because of its close taxonomic relationship to *P. amarum*. Shoredune panicum occurs along the Atlantic and gulf coasts from New Jersey to Mexico (Palmer, 1972) and southeast around the gulf to Quintana Roo (Sauer, 1967).

(b) Morphology. Shoredune panicum is considered by Palmer (1972) as conspecific with bitter panicum, the two being varieties. Palmer states that *P. amarum* and *P. amarulum* are morphologically indistinguishable in Texas and elsewhere along the gulf coast, although they become divergent and easily distinguishable in northeastern U.S. However, this study found the two taxa quite distinct, both in growth habit and ecologically.

(c) Growth. Shoredune panicum is only weakly rhizomatous. It is a bunchgrass with mostly erect culms up to 7 feet high; some of the largest culms may become basally decumbent. Sand burial does not stimulate tillering and production of rhizomes like in bitter panicum; instead, this species remains a dense, tall bunchgrass (Fig. 5). Morphological differences other than growth habit are slight, and are discussed by Palmer (1972).

(d) Ecology. Shoredune panicum is common on south Padre, particularly in moist, lowland sites leeward of the foredunes. On the national seashore it occurs north of Mansfield Channel for a short distance, but is apparently absent from the remainder, although it has been planted at Twin Batteries and Pan Am sites. Reproduction from seed is common, and this is presently occurring leeward of planted areas on the national seashore. The growth habit of this species is of little value as a dune-building grass, but it appears satisfactory for sand stabilization. If planted culms are closely spaced in a row, it offers considerable protection as a windbreak.

(3) Sea Oats (*Uniola paniculata*).

(a) Geographic Range. Sea Oats range from Cape Henry, Virginia (Wagner, 1964), south along the Atlantic and gulf coasts into Mexico, and as far south as Tabasco (Sauer, 1967); it is also found in Cuba and the Bahamas (Wagner, 1964).

(b) Morphology. Sea Oats is a strongly rhizomatous perennial grass, with the culms attached in bunches at the rhizome nodes. Internodes are short and congested at the culm base (Fig. 19), except for one or two internodes which may elongate with age as shown in Figures 22 and 23. Sheaths are strongly overlapping and clasping, and are much longer than the congested internodes. Blades are long, and in some culms are over 1 yard. The nodes are nearly always buried, and only the top of the sheaths and the blades protrude aboveground. The inflorescence is a large, open panicle of numerous many-flowered laterally compressed spikelets.

(c) Growth. The growth of a newly planted culm is shown in Figures 22 and 23. Buds at the nodes, which are congested at the culm base, elongate, and form tillers. Tillers reach the surface at an angle to the primary culm, and form additional culms. New buds, continually produced at the culm base, become oriented at nearly a 90° angle to the primary culm. Tillers grow more horizontally, and become rhizomes, which elongate, form a node at the terminal end, and produce new buds and tillers. Later, a series of culm clumps forms, interconnected by rhizomes. Vertical growth of the individual culms occurs by elongation and addition of leaves from the apical meristem. As sand is deposited on top of the plants, both tillering and apical growth are stimulated; the oldest leaves, on the outside of an individual culm, eventually become buried and die. When 3 or 4 years old, the vegetative culms may begin to elongate and flower (Wagner, 1964); after flowering, they die, but are replaced by new tillers from the nodes.

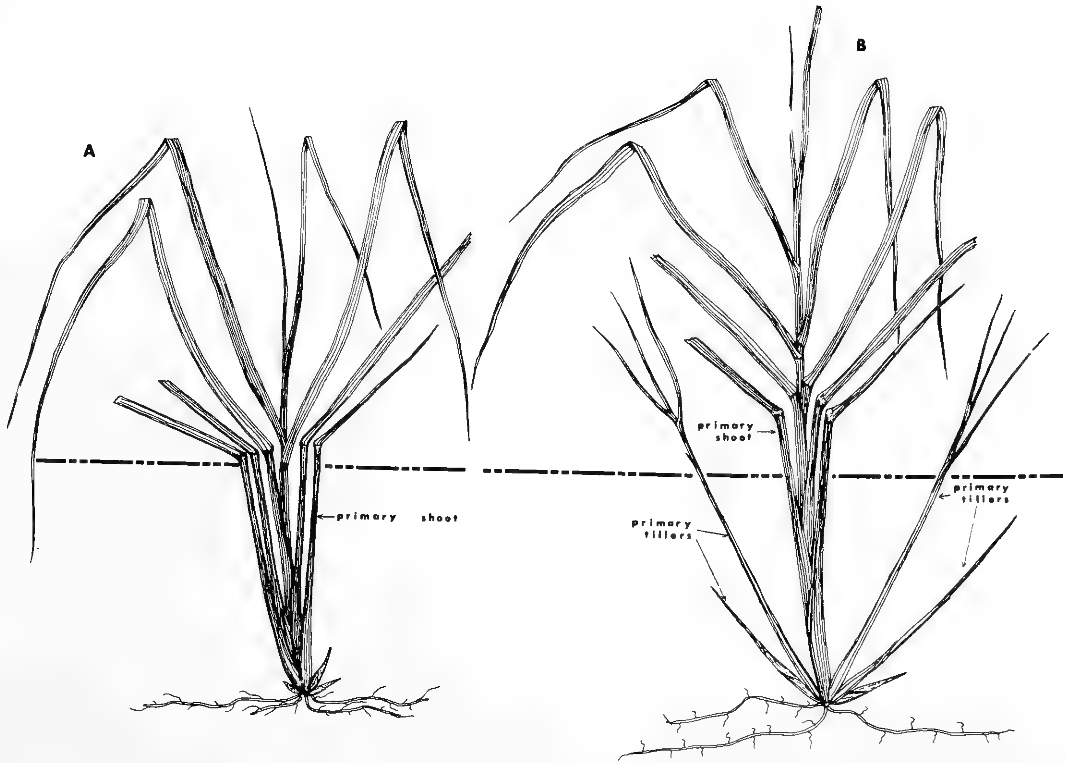


Figure 22. Growth habit of sea oats. Vegetative culm at planting (A); and same transplant after several months (B). Growth is from primary tillers arising from basal nodes and elongation and development of young (centermost) leaves. All growth tissue is subterranean.

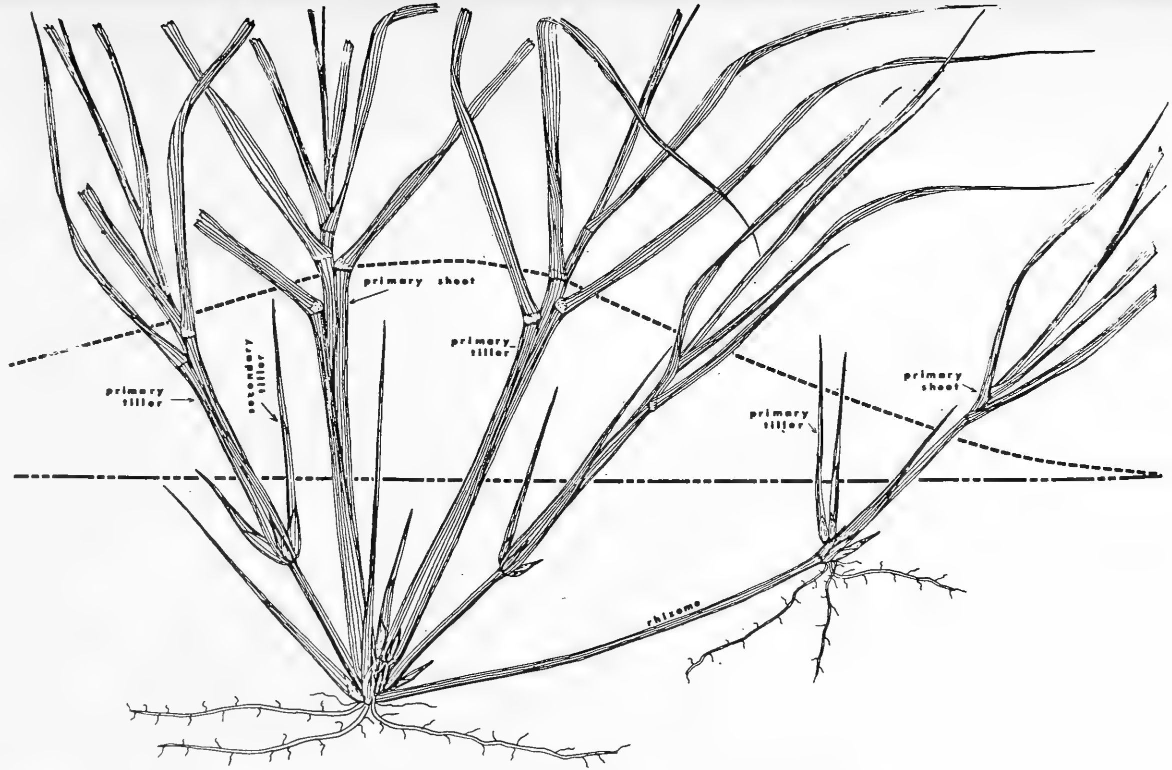


Figure 23. Sea oats growth at end of first summer. Basal nodes have given rise to a complex of primary tillers. In two of these, single internodes have elongated, and the remaining congested nodes at the top have developed secondary tillers. Note the one rhizome with a primary shoot and tillers which will later form another clump.

In the northern part of its Atlantic coast range, sea oats becomes dormant in winter. The leaves appear as if dying, and in spring they are replaced by new leaves (Wagner, 1964). In south Texas there is no such obvious period of dormancy, although some loss of color occurs in winter as aging leaves become senescent; generally, the plants remain green year round. There is a noticeable greening-up in early March, as new tillers are produced in abundance. Tillering may occur in any month, particularly as a response to burial by sand.

In May, flowering culms begin rapid growth and mature during summer; the spikelets remain on the panicle until removed by the wind in fall and winter. Wind also plays a dominant role in distributing the spikelets. The seed has a period of dormancy; cold-layering over winter overcomes two inhibitors to germination (Wagner, 1964). However, many of the ovules abort, and on the average, only two caryopses are found per 10 to 12 flowered spikelet (Westra and Loomis, 1966).

(d) Ecology. Sea oats is abundant on the foredune complex, from the backshore and foredune foreslope leeward to the backslope, all along the south Texas coast. It is one of the most characteristic plants of Padre Island. On the foreslope and backshore, it occurs alone or with a few other species adapted to accumulating sand; on the middle and behind the dune, it is found with a variety of less specialized species. Sea oats also occurs regularly in disjunct populations on low, vegetated hummock dunes in mid-island, and on dunes near the Laguna Madre shore.

Wagner (1964) reported that uptake of the chloride ion by sea oats leaves is minimal, due to a thick cuticle and other xeromorphic features. Oosting and Billings (1942) explained the zonation of three dune species of the east coast (sea oats, seacoast bluestem, and saltmeadow cordgrass) with respect to tolerance to windborne salt and moisture requirements. Sea oats, which grows on the highest elevations and on the windward slopes, has the lowest water requirement of the three species and is resistant to salt spray. Cordgrass is more resistant and can withstand total saltwater immersion with no apparent effects. However, saltmeadow cordgrass has the highest water requirement of the three species. Seacoast bluestem is the least resistant to salt spray, which explains why it is found on the foreslope in more protected depressions. These three species are similarly zoned in Texas. Seneca (1972a) found an inverse linear relationship between seedling growth and substrate salinity. Based on seedling growth response, he showed that the order of decreasing salt tolerance of four east coast dune grasses is saltmeadow cordgrass, shoredune panicum, sea oats, and American beachgrass.

2. Methods of Propagation.

a. Mode of Propagation: Direct Seeding. A substantial reduction in stabilization cost could be realized if direct seeding would produce a stand of grass. Seeding was attempted for 3 years using sea oats and bitter panicum seed. Bitter panicum seed is reportedly sterile, although one trial planting in April 1972, germinated 6 weeks later. Seeding tests included: (a) planting at different locations on the beach, hurricane overwash channels, and areas of broad overwash; (b) planting on fence-built sand dunes; and (c) use of irrigation and burlap mulching in conjunction with beach and dune plantings. The most useful areas for harvesting sea oats seed were from isolated clumps in the midst of a barren dune field. Insect and ground squirrel use was so pronounced in areas of continuous vegetation that little viable seed could be obtained. Even isolated clumps downwind of a large vegetated area showed moderate insect use. Harvested inflorescences were stored in burlap bags suspended from a ceiling in an enclosed warehouse at ambient temperatures. Seed heads were threshed by hand to the spikelet and stored in burlap bags in the warehouse until planted.

Comparison between the 1970-71 and 1971-72 plantings show a 3-week difference in seedling emergence—during the first week in June 1970-71, and the second week in May 1971-72. This difference apparently corresponded to the difference in available soil moisture between years. Even with more favorable environmental conditions in 1971 and 1972, emergence was too sporadic to ascertain conclusive results, but they did reveal other problems in direct seeding methods. They were:

(a) Seeding attempts on elevated surfaces, such as fence-built dunes and without irrigation and burlap, yield few seedlings due to wind erosion of seeds. Frequent drying of the surface sand also prevents germination.

(b) Burlap covering of seed on elevated slopes stabilized the sand but did not sufficiently retard surface water loss. Irrigation in conjunction with burlap covering did not produce a stand of grass due to the low germination rate of sea oats seed.

(c) Seeding was more successful behind fence-built dunes where seeds were protected from saltwater inundation and shifting sand. Best stands resulted when seed was broadcast at high rates, covered with burlap, and irrigated when the surface sand dried out.

(d) Since two growing seasons are required for full establishment of sea oats seedlings, but only one-half year for transplants, direct seeding is not useful on critical areas such as fence-built dunes, and is not recommended for beach plantings for the same reasons.

b. Mode of Propagation: Vegetative Transplants. All of the successful experimental dunes were established with vegetative transplants, dug from a nursery or from wild stands and replanted on the beach sites.

c. Source of Transplants: Wild Stands. Both bitter panicum and sea oats transplant stock may be acquired successfully from naturally occurring stands. At the start of this study, bitter panicum was scarce on north Padre, and establishment of a nursery was necessary to ensure enough material. However, adequate wild stock of both species now exists on both ends of the island. The most suitable site for obtaining wild sea oats culms is from an early successional, young deflation plain, where sea oats seedlings are established and growing as clumps. Such a site has a limited amount of blowing sand, so that the culms are usually not deeply seated. The poorest site is the foredune, since accumulating sand buries the culms and increases harvesting time. Similarly, bitter panicum should be sought from sites where accumulating sand is not actively growing a dune. Although bitter panicum and sea oats are vigorous and dense on these sites, the culms must be individually excavated. Natural bitter panicum stands on the lee slopes of foredunes and on a low plain behind a forming dune line are the best locations.

d. Source of Transplants: Nursery. Woodhouse, Seneca, and Cooper (1968) felt that nursery-produced sea oats culms were superior to wild stock because of a better developed root system. Several nurseries of both species were established on north Padre early in the study to test the superiority of nursery stock. The first nursery was established in February 1969, with sea oats, bitter panicum and shoredune panicum (Fig. 24). The advantages of a nursery are that they: (a) produced a stand of uniform transplant material; (b) reduced harvest time since the plants were dense, localized, and shallowly buried; and (c) provided more uniform material for mechanical transplanting.

Sea oats transplants from 2-year-old plants had more mass per tiller, which aided i handling and transplanting. Transplants from 1-year-old plants were highly variable, an many tillers were too small for machine planting. Sea oats nursery production average 20.9, 28.9, and 20.8 transplants per original culm planted after 8, 10, and 22 month respectively. Comparisons of wild harvest versus nursery-produced transplants revealed n significant survival differences between the two sources of planting stock (Table 14).

After 15 months, bitter panicum yielded an average of 20.9 transplants per original cul planted. However, these transplants had to be further subdivided to allow machine plantin consequently, the number of usable transplants per original nursery plant exceeded 20. Planting stock was vigorous with large culms from the first year, and unlike sea oats, r advantage is evident for transplanting from 2-year-old plants.

e. Establishing a Nursery. Experience from nurseries allows the following conclusio for establishment:

(a) A moist, loose sand is best. Ideally, the site should be protected by natural dunes or vegetation from encroaching sand.

(b) If not weed-free or if virgin land, fumigation with methyl bromide will reduce maintenance costs. Clearing and leveling the site with a bulldozer before fumigation may be necessary.

(c) An area of barren, moist sand exposed by a migrating dune field is a good location for a nursery if protected from beach sand drifts and high tides by a mid-island location or reformation of a dune line. Advantages over virgin land are leve surface, lack of vegetation to be cleared, and moist surface sand without irrigation.

(d) Supplementary irrigation may be necessary to wet the surface before plantin and to maintain moisture at the root zone during the first few months, and to retar excavation of plants during periods of high wind.

Sea oats, August 1969

Sea oats, July 1970

Panicum, October 1969

Panicum, July 1970

Figure 24. Photo sequence of sea oats nursery planted March 1969, and bitter and shoredune panicum nursery planted October 1969.

Table 14. Percent survival of nursery versus wild sea oats.[1]

Sea oats	1969			1970			
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
North Padre Island							
Nursery	18	14	13	23	22	1	3
Wild	21	2	16	47	27	1	5
South Padre Island							
Nursery	0	1	3	34	1	13	1
Wild	0	1	1	32	8	17	1

1. Number of plants: 150. No significant difference found between source of transplants for any month.

(e) Row spacing should be wide enough to allow mechanical cultivation.

(f) Only 1 year is required to produce an outstanding crop of both panicums. Sea oats is more variable after the first year with prime transplants coming from 2-year-old plants. Fertilization of the nursery is essential for maximum density and size of transplants. Fertilization rates are discussed in Section V, 2e.

(g) Panicums may be planted from late fall to spring for production the next winter. Early winter planting of sea oats may produce suitable material after the first year; late winter plantings will produce suitable material after the second year. Planting methods are similar to beach plantings, and are discussed later.

(h) Sea oats plants established from seed require at least 2 years for transplant production. Results from seed were highly variable and nursery establishment from seed is not recommended.

f. Harvesting Transplants. Sea oats culms, either nursery or wild stock, were harvested by excavating individual clumps with a shovel. Culms normally cannot be pulled from the ground without damaging the root system or breaking or bending the basal part of the culm above the internodes. The most expedient method is to dig around the clump perimeter (an ideal clump is less than 1 yard in diameter), angling the shovel slices toward the center and about 1.5 feet deep. The clump is then lifted from the soil, shaken free of sand, and individual culms separated. Culms damaged during digging should be discarded. A part of the clump of several culms and rhizomes should be left intact for regrowth. Harvesting wild stock from a large dune usually requires excavating individual culms rather than clumps, and is time consuming. Wild stock in small clumps on a low flat surface can be harvested at the rate of 200 to 300 culms per man-hour. Although not tested, it may be possible to mechanize sea oats wild-harvesting using a backhoe to dislodge clumps or larger dunes, and then separating the culms by hand. Cost savings probably would be minimal, since five to seven laborers can be hired for the cost of backhoe rental.

The fastest method to harvest bitter panicum culms is to pull the culm from the ground or break it off at ground level. In winter, culms are dry and brittle, and can easily be broken near the surface. Winter primary culms have also been successfully harvested with a serrated grass scythe, although this is more advantageous in areas of dense, tall growth. In spring and summer the culms are succulent and pliable, and it is easier to pull the culm from the ground with the roots and rhizomes attached than to break it off at ground level. Either method is satisfactory, as rootless broken culms can be as successfully transplanted as rooted ones. Harvesting by hand can usually be done at the rate of 600 to 1,000 or more culms per man-hour.

g. Postharvesting Care. During winter, it usually is unnecessary to give special care to transplants after harvesting if replanted the same day. Transplants should be bundled in groups of several hundred and tied, or packed base first in bushel baskets. If planting is delayed until the following day, or if the weather is hot and dry, plants should be placed in trenches dug in moist sand, and partially buried until planting.

At times, it is convenient to procure transplants on one day, and plant them at a later date, particularly if the planting site is far from the nursery. In January 1974, an experimental plot was planted to determine the feasibility of long-term storage of transplants in freshwater. Six hundred culms of each species were dug in one day, thoroughly mixed, and grouped in bundles of 100. One bundle of each species was planted immediately; the others were stored in a freshwater pond by immersing the lower half of the bundle. The stored transplants were removed and planted after 1, 4, 9, 17, and 28 days of storage; survival data are shown in Table 15. Bitter panicum was successfully stored for 4 weeks, but could have sustained a longer storage period. After 2 to 3 weeks, the culms began to turn reddish-brown, and most green leaves withered, but this did not affect survival after planting. After 4 weeks, some stored transplants were sprouting new shoots from the immersed culm.

Table 15. Percent survival of bitter panicum and sea oats transplants after storage in freshwater.[1]

Transplants	Days of storage					
	0	1	4	9	17	28
Bitter panicum	93, a[2]	95, a	94, a	88, a	95, a	94, a
Sea oats	49, b	41, b	40, b	19, c	13, c	3, c

1. Number of plants: 100. Transplant stock (600 culms per species) procured 9 January 1974, and planted from 9 January to 6 February at a protected beach site.

2. Figures sharing common alphabet are not significantly different ($P_{0.05}$).

Storage of sea oats was less successful. Four days of storage had little effect on survival, but at some point between 4 and 9 days of storage, the culms lost considerable survival potential. After 4 weeks, nearly all failed to survive.

3. Factors Affecting Transplant Survival.

In the backshore test plantings at monthly intervals of sea oats and bitter panicum during the past 5 years, transplant survival was variable (Table 16). Since establishment of transplants is the most important phase of dune construction, it was necessary to examine the factors affecting transplant survival to determine optimum planting conditions. Factors which are potentially important or can influence transplant survival are: soil moisture, soil salinity, plant dormancy and vigor, air and soil temperatures, sand inundation, and salt spray. All but sand inundation and salt spray were measured for each planting, and related to survival of the transplants by multiple correiation analysis. Although salt spray is an important factor, it was not measured.

Table 16. Transplant survival of monthly planting of sea oats and bitter panicum.[1]

Location	Years	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June
						Sea Oats							
North Padre	1969, 70	----	----	----	----	5	30	68	25	5	7	27	----
	1970, 71	----	----	----	----	12	28	8	2	0	4	----	----
	1971, 72	----	----	----	7	46	xx[2]	64	xx[3]	76	27	75	----
	1972, 73	----	----	6	0	6	2	26	60	0	34	8	18
	1973, 74	37	5	22	20	12	3	19	21	6	29	41	10
South Padre	1969, 70	----	----	----	0	5	60	30	10	xx[2]	----	----	----
	1970, 71	----	----	----	----	0	0	9	2	0	xx[2]	----	----
	1971, 72	----	----	----	29	xx[3]	76	73	61	59	0	22	----
	1972, 73	----	----	----	----	5	26	43	81	0	4	15	41
	1973, 74	46	----	32	38	22	17	62	24	----	----	----	----
						Bitter Panicum							
North Padre	1969, 70	----	----	----	----	60	50	55	15	20	15	70	----
	1970, 71	----	----	----	----	8	37	10	0	2	10	----	----
	1971, 72	----	----	----	34	22	xx[2]	37	84	88	58	80	----
	1972, 73	----	----	4	0	30	24	10	34	62	68	70	78
	1973, 74	93	89	81	37	53	78	77	78	72	50	67	----
South Padre	1969, 70	----	----	----	----	25	60	70	68	10	10	----	----
	1970, 71	----	----	----	----	32	7	32	22	34	xx[2]	----	----
	1971, 72	----	----	----	28	xx[3]	39	21	26	35	0	51	----
	1972, 73	----	----	----	----	0	12	40	33	38	46	40	97
	1973, 74	83	----	12	36	32	19	59	39	----	----	----	----

1. 100 plants per species per site. Months in which no planting was made are indicated by dashes (----).
2. Destroyed by vehicles (xx).
3. Destroyed by storm surge (xx).

a. Soil Moisture. Subsurface (6 inches) moisture of sand on the backshore (about 4.5 to 5.0 feet MSL) varies widely and depends on rainfall and on inundations by surges. The range of moisture content, from data collected since 1970, is from about 22 percent to no less than 2 percent, but is usually above 5 percent even after moderate droughts. Field capacity of the sand, i.e., water retained by the sand under well-drained conditions, without the effects of evapotranspiration, is about 3 to 4 percent; laboratory-determined saturation extract is 21.5 percent. Thus, the usual backshore soil moisture varies from greater than field capacity to saturation. Moisture remains high because the water table is usually within 2 feet of the surface except during prolonged droughts when it is deeper, and after heavy rains when it is at or above the surface. Only when the water table recedes does complete drainage of soil pores occur. Soil moisture at the beach surface varies more widely, from 0.1 percent to saturation. In a south Padre hurricane pass, of lower elevation and hence closer to the water table, soil moisture was even higher.

On elevated surfaces, drainage is less restricted, and both surface and subsurface moisture contents are lower than on the beach. Near-saturation occurs only briefly, during and immediately after heavy rains. The typical subsurface moisture content range of an elevated dune is between field capacity and 10 percent.

Moisture values taken at monthly intervals in 1973 from 15 stations along an artificial dune line on Padre Island are shown in Table 17. "Beach toe" and "bay toe" samples were

Table 17. Percent soil moisture at the surface and at 6 inches from three locations on artificial dunes.[1]

North Padre							South Padre						
1973	Beach toe (inches)		Center of dune (inches)		Bay toe (inches)		1973	Beach toe (inches)		Center of dune (inches)		Bay toe (inches)	
	0	6	0	6	0	6		0	6	0	6	0	6
9 Jan.	12.2	19.3	7.5	9.4	11.2	18.0	7 Jan.	2.7	7.2	2.7	3.5	6.0	11.2
19 Feb.	6.5	10.6	4.9	6.9	6.5	10.9	17 Feb.	11.7	8.6	11.5	8.7	11.5	7.8
15 Mar.	0.2	4.4	0.1	4.5	0.4	7.4	29 Mar.	0.1	2.7	0.1	2.0	0.1	3.1
14 Apr.	0.5	4.2	0.3	2.4	0.2	3.8	29 Apr.	0.2	2.5	0.2	0.8	0.1	1.6
13 May	0.2	5.9	0.1	5.3	0.3	5.2	31 May	0.2	2.2	0.2	2.0	0.2	1.9
14 June	1.8	7.7	0.2	4.7	11.1	14.9	23 June	8.3	13.1	6.8	8.4	8.7	12.9
16 July	0.2	3.9	0.2	3.0	0.2	4.9	28 July	0.1	2.5	0.1	2.0	0.1	2.8
19 Aug.	1.0	8.4	0.1	5.8	5.6	12.6	Aug.[2]	-------	-------	-------	-----	-------	-------
18 Sept.	8.1	17.9	3.2	5.5	20.9	24.8	12 Sept.	0.2	5.1	0.1	2.7	0.2	7.5
20 Oct.	10.0	22.9	0.1	3.7	18.9	26.6	26 Oct.	1.6	5.3	0.2	2.9	1.6	12.5
18 Nov.	0.3	9.4	0.2	3.2	7.8	23.3	21 Nov.	0.4	4.6	0.4	2.7	0.5	8.9
17 Dec.	0.2	7.7	0.2	3.2	1.7	14.8	14 Dec.	0.2	4.0	0.2	1.9	0.2	6.5

1. Monthly collections. Each is the mean of five samples from fixed stations.
2. No samples taken.

taken in front of and behind the dune line, respectively, on the beach elevation; the "center of dune" samples were taken west of the dune crest, about 5 to 10 feet above the beach samples. Similar data from 1970 through 1972, excluding bay toe samples but including "hurricane pass" samples from south Padre are given in Table 18. During heavy rainfall on north Padre in the summer and fall 1973, water was often ponded behind the dune line. Soil moisture generally remained higher behind the dune line than on the beach (Table 17).

The relationship of subsurface soil moisture to monthly rainfall and surge inundations is shown in Figure 25, for a backshore site (monthly plantings, about 4.5 feet MSL) over a 16-month period. Samples were taken at monthly intervals and also following surge inundations.

b. Soil Salinity. Soil salinity on the backshore varies, and is influenced by inundating surges, salt-laden sand blown inland from the berm, salt spray, and rainfall. Generally, subsurface salinity of the backshore, at elevations above 4.5 feet MSL, is relatively low and usually remains so until a storm surge inundates the area. Hurricane washover passes on south Padre are lower in elevation than a normal backshore, and are more subject to flooding by minor surges which break through the berm. Drainage is also restricted, resulting in frequent ponding of seawater followed by evaporation and concentration of the salts. These processes leave the passes with a greater salt content than the higher backshore.

Salt content is usually much lower on elevated surfaces of artificial or natural dunes, especially beneath the surface where leaching and drainage is more complete, and regular inundation (one source of salt) does not occur. Variations in elevated dune salt content are due to salt spray and salt-laden drifting sand blown from the lower beach, especially after high tides or surges.

Surface salinities are usually higher than in the subsurface since soluble salts are brought to the surface during periods of heavy evaporation. Surface salinity in hurricane passes reach the highest values which explains why seedlings of even the very tolerant saltmeadow cordgrass have not become established after over 2 years of protection by sand-fence barriers from inundation.

Measurements of salt content were made using a conductivity meter on samples of one part ovendry sand thoroughly mixed and diluted with two parts of distilled water at 72° Fahrenheit. The term "soil salinity" is used in this study although conductance was the unit of measurement. Conductance values, given in micromhos per centimeter, may be converted to parts per thousand (ppt) of salt in the soil with the following formula (Jackson, 1958):

$$\text{ppt salts in soil} = (0.00064)\ (L)\ (2)$$

where

$$L = \text{specific conductivity in } \mu\text{mho/cm}.$$

Table 18. Percent soil moisture by topographic position on Padre Island

Date	North Padre				South Padre					
	Beach (inches)		Top of dune (inches)		Beach (inches)		Top of dune (inches)		Hurricane pass (inches)	
	0	6	0	6	0	6	0	6	0	6
Nov. 70	7.6	11.9	5.8	8.6	2.0	6.4	1.7	3.6	3.8	7.6
Dec.	3.0	7.5	2.8	6.8	4.7	7.2	6.2	3.6	5.7	7.2
Jan. 71	4.3	8.4	2.3	3.3	5.1	9.9	2.5	6.7	7.0	15.4
Feb.	1.8	5.8	0.7	3.9	4.9	9.1	1.3	2.3	3.8	8.7
Mar.	1.8	7.0	0.9	3.2	2.5	8.6	1.4	4.3	2.0	7.2
Apr.	2.1	8.4	2.3	5.1	2.2	8.3	0.2	3.9	2.4	11.5
May	2.9	8.9	1.6	4.2	1.4	7.2	0.2	3.6	0.7	9.3
June	1.0	6.8	0.5	1.8	6.0	11.2	4.3	9.7	10.2	13.4
July	0.6	6.6	0.2	3.6	6.7	12.8	1.5	6.0	4.6	10.2
Aug.	8.3	10.3	7.7	6.8	8.6	10.9	8.1	7.5	15.0	19.6
Sept.	4.5	3.5	4.7	5.2	0.3	3.3	0.3	1.0	0.3	4.0
Sept.	11.0	14.6	5.6	7.0	16.9	17.7	6.8	6.9	20.7	19.2
Oct.	19.4	21.9	4.9	8.1	16.1	18.2	7.2	10.1	16.0	20.8
Nov.	5.5	12.0	6.5	9.0	12.0	8.6	0.1	0.1	-------	-------
Dec.	21.6	22.3	11.7	20.3	7.7	8.7	3.7	7.7	10.5	12.5
Jan. 72	16.6	20.6	7.3	10.0	6.6	12.8	8.5	11.8	20.5	18.0
Feb.	17.8	19.8	16.8	17.2	1.6	7.0	-----	6.0	5.0	10.0
Mar.	20.5	22.5	13.8	14.8	10.2	10.4	11.0	6.0	12.5	14.5
Apr.	4.4	13.0	2.0	7.4	0.4	5.4	0.1	2.6	0.3	9.0
May	17.4	21.4	11.8	13.8	8.3	16.3	3.6	8.6	15.3	20.0
June	20.8	21.4	11.6	14.8	18.0	19.6	5.8	7.6	18.0	19.5
July	4.2	13.6	2.5	4.5	0.8	3.6	-------	0.2	1.7	4.3
Aug.	20.3	22.3	7.0	12.2	2.2	8.2	0.2	3.4	2.0	7.0
Sept.	4.6	13.4	0.6	5.4	-------	2.8	0.8	1.6	-------	3.0
Oct.	14.2	18.8	4.8	8.8	3.6	8.2	-------	3.0	4.1	12.0

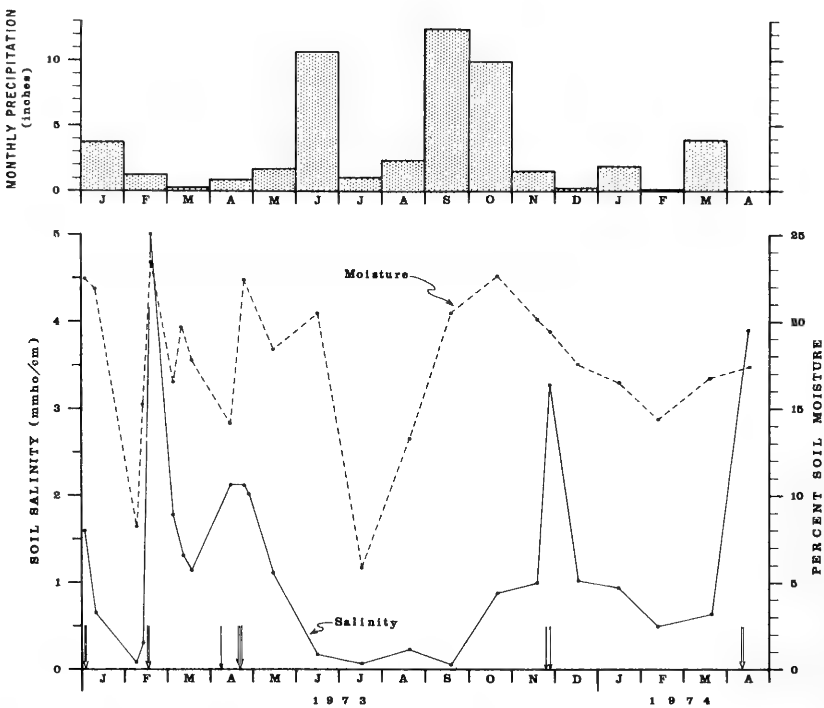


Figure 25. Variation in subsurface soil salinity and soil moisture, as influenced by rainfall and saltwater inundations. Vertical arrows indicate inundations; number of lines per arrow represents number of consecutive days of inundation. Data from the 1973-74 north Padre monthly planting site. Salinity expressed in millimhos per centimeter for 1:2 sand-water ratio.

Salinity data from the artificial dune line are given in Table 19 for 1973, and for 1970-72 in Table 20. The relationship of inundations and precipitation to subsurface soil salinity of a backshore site on north Padre (1973-74) is shown in Figure 25. Periods of high rainfall are related to low salinity, whereas inundations with low rainfall result in the highest values.

Seneca (1969) found that the toxicity of substrate salinity to germination of three dune grasses was due to an osmotic pressure deficit, and only slightly from chloride ion; in sea oats, germination may have been influenced by toxicity of the chloride ion. If osmotic pressure deficit is a primary cause of toxicity, the actual amount of salt in the soil may be less important than the concentration of salt in the available soil water. For example, a given soil salinity content would be twice as concentrated and presumably more toxic in a soil with 10 percent moisture than the same soil with 20 percent moisture. Saline soils are defined as having a saturation extract conductivity of 4,000 micromhos per centimeter. Since saturation is about 21.5 percent for Padre Island sand, this is equivalent to 430 micromhos per centimeter for a 2:1 dilution. Therefore, most soils of the backshore and the elevated foredunes would not be considered saline. Other investigators (Kearney, 1904; Oosting and Billings, 1942; Randall, 1970) have also concluded that beach soils ordinarily contain no higher concentrations of salt than average cultivated soils of the area, and that beach plants need not be obligate halophytes.

To determine critical salinity levels for the survival of transplants, laboratory experiments were conducted in the spring of 1973 with bitter panicum and in the spring of 1974 with shoredune panicum and sea oats.

Transplants (250 to 500) of all species were harvested from a north Padre protected site, and replanted, five culms per pot, in the greenhouse. After about 2 months, when the surviving plants were actively growing, two cups of saline (sodium chloride) solutions of various strengths (from 0 to 6 percent) were added to randomly chosen pots. Subsequently, the pots were watered weekly with one cup of tap water. Since the pots contained no drainage holes, all salt added in the initial treatment remained in the sand. Six weeks after the salinity treatment, relative survival and conductivity of the soil in each pot was determined.

Shoredune panicum was least salt-tolerant, followed by sea oats; bitter panicum was most tolerant. The point where live shoots are reduced 50 percent is a valid means to compare the three species. Salinity values required to reduce survival 50 percent for shoredune panicum, sea oats, and bitter panicum were 1,830, 2,620, and 3,460 micromhos per centimeter, respectively (Fig. 26). Another indication of relative salt tolerance is that point where increasing salt concentration caused a significant ($P_{0.05}$) reduction in grass shoot survival. These levels were 1,540, 2,120, and 2,720 micromhos per centimeter respectively, for shoredune panicum, sea oats, and bitter panicum (Tables 21, 22, and 23). However, Seneca (1972b) found that germination rates and seedling survival of sea oats were more adversely affected by salinity than were these characteristics of shoredune panicum. Nevertheless, their relative habitats on Padre Island would support the evidence that sea oats is more tolerant of saline conditions than shoredune panicum on the south Texas coast.

Table 19. Soil salinity at the surface and at 6 inches from three locations on artificial dunes on Padre Island.[1]

North Padre							South Padre						
1973	Beach toe (inches)		Center of dune (inches)		Bay toe (inches)		1973	Beach toe (inches)		Center of dune (inches)		Bay toe (inches)	
	0	6	0	6	0	6		0	6	0	6	0	6
9 Jan.	46	64	38	61	42	108	7 Jan.	122	78	85	75	90	87
19 Feb.	150	240	103	198	108	82	17 Feb.	61	132	44	83	55	105
15 Mar.	758	107	261	121	505	64	29 Mar.	1110	58	410	70	440	56
14 Apr.	1790	124	1440	358	804	79	29 Apr.	1540	72	1270	469	651	278
13 May	1263	1168	962	1100	497	691	31 May	1580	180	800	322	418	299
14 June	123	40	65	115	88	44	23 June	51	50	50	63	49	67
16 July	2760	89	1044	87	363	74	28 July	306	67	251	69	248	67
19 Aug.	105	187	74	99	115	60	Aug.[2]	--------	------	--------	------	------	------
18 Sept.	83	38	50	32	95	99	12 Sept.	2994	320	293	49	356	49
20 Oct.	133	37	48	28	446	93	26 Oct.	4820	490	222	56	753	53
18 Nov.	546	181	168	76	1430	69	21 Nov.	1098	368	372	227	270	55
17 Dec.	2110	121	411	35	2530	102	14 Dec.	1525	214	746	110	966	3

1. Soil salinity (μmho/cm, using a 1:2 solution of dry sand-distilled water at 72° Fahrenheit). Each monthly collection is the mean of five samples from fixed stations.
2. No samples taken.

Table 20. Soil salinity on Padre Island by topographic position.[1]

Date	North Padre				South Padre					
	Beach (inches)		Top of dune (inches)		Beach (inches)		Top of dune (inches)		Hurricane pass (inches)	
	0	6	0	6	0	6	0	6	0	6
Nov. 70	455	671	434	389	2,264	789	450	570	5,500	2,150
Dec.	310	58	213	118	69	305	50	247	40	80
Jan. 71	583	68	237	64	476	475	65	23	700	525
Feb.	3,850	325	2,733	512	5,458	1,204	1,493	487	4,750	1,400
Mar.	2,108	408	2,117	5,555	2,458	912	1,273	287	2,850	1,350
Apr.	1,358	558	1,325	2,129	6,700	1,470	1,317	453	9,300	2,125
May	3,533	364	3,583	5,300	2,864	4,275	168	135	1,700	1,775
June	1,996	475	3,183	925	168	128	131	62	175	500
July	1,246	692	2,067	1,120	176	75	47	37	270	835
Aug.	40	65	32	147	42	48	43	38	72	500
Sept.	232	359	65	170	423	67	102	75	1,412	2,030
Sept.	81	59	95	87	8,333	5,783	3,883	1,737	8,250	5,250
Oct.	233	108	505	160	478	400	420	340	950	4,000
Nov.	2,275	725	3,000	367	686	482	620	417	6,750	2,400
Dec.	208	166	143	520	1,265	437	367	243	1,800	2,100
Jan. 72	3,283	1,613	1,755	2,732	1,600	1,540	1,700	1,525	5,250	4,750
Feb.	83	640	88	918	1,000	2,160	350	310	2,750	3,000
Mar.	1,150	250	230	72	50	190	50	247	62	700
Apr.	3,920	810	1,335	385	4,190	5,295	530	225	1,600	3,167
Apr.	---------	---------	---------	---------	7,000	9,400	3,930	1,830	8,500	5,000
May	1,290	1,940	730	578	2,683	2,216	470	292	7,167	7,000
June	570	950	290	476	1,950	1,050	140	70	3,500	4,000
July	7,100	1,380	4,088	1,038	5,216	2,900	320	80	14,000	3,986
Aug.	50	43	50	50	180	90	70	50	100	100
Sept.	7,900	1,070	975	912	260	110	130	100	50	100
Oct.	750	400	455	215	700	440	240	60	600	317

1. Soil salinity (μmho/cm, using a 1:2 solution of dry sand-distilled water).

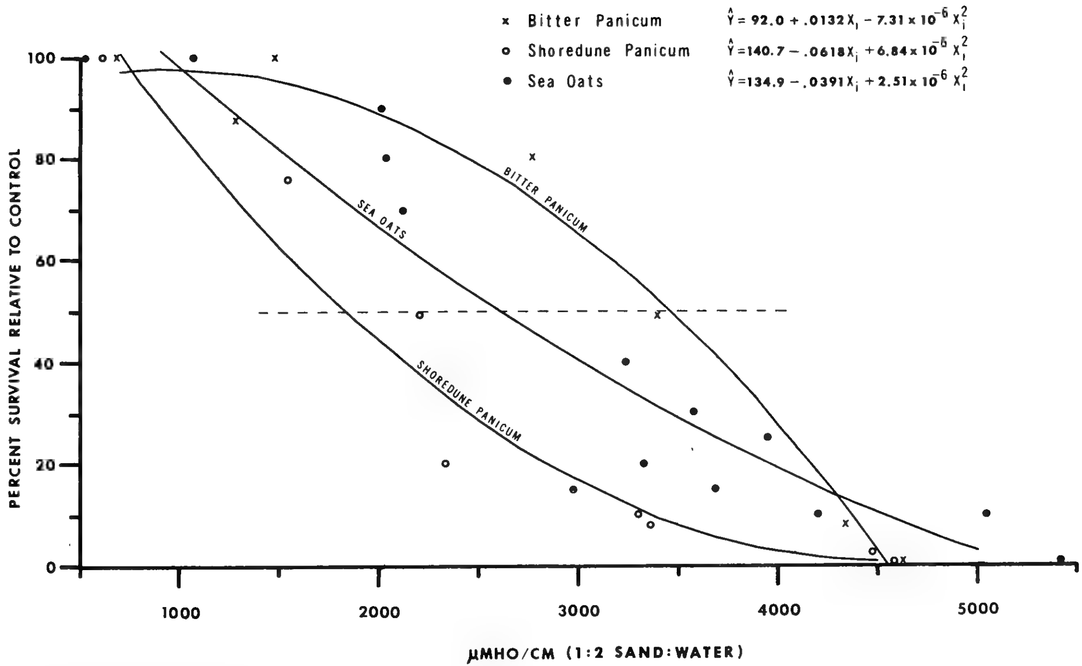


Figure 26. Response of sea oats, bitter panicum, and shoredune panicum transplants to soil salinity level under greenhouse conditions.

Table 21. Response of sea oats transplants to salinity level under greenhouse conditions.

Soil salinity (μmho/cm)[1]	Live shoots per seven pots[2]
520	20 a[3]
1,070	20 a
2,020	18 a
2,030	16 a
2,120	14 a, b
2,980	3 c, d
3,240	8 b, c
3,330	4 c, d
3,580	6 c, d
3,680	3 c, d
3,950	5 c, d
4,200	2 c, d
5,050	2 c, d
5,420	0 d

1. 1:2 sand-water mixture.
2. Five transplants per pot at beginning of study.
3. Values with the same letter are not significantly different at the $P_{0.05}$ level.

Table 22. Response of bitter panicum transplants to salinity level under greenhouse conditions.

Soil salinity (μmho/cm)	Live shoots per six pots[1]
680[2]	25 a[3]
1,280	22 a
1,480	25 a
2,720	20 a
3,400	12 b
4,340	2 c
4,625	0 c

1. 1:2 sand-water mixture.
2. Five plants per pot at beginning of study.
3. Values with the same letters are not significantly different at the $P_{0.05}$ level.

Table 23. Response of shoredune panicum transplants to salinity level under greenhouse conditions.

Soil salinity (μmho/cm)[1]	Live shoots per seven pots[2]
610	51 a[3]
1,540	38 a, b
2,200	24 b
2,330	10 c
3,280	5 c
3,350	4 c
4,480	3 c
4,580	0 c

1. 1:2 sand-water mixture.
2. Five plants per pot at beginning of study.
3. Values with the same letter are not significantly different at the $P_{0.05}$ level.

c. Dormancy. High concentrations of carbohydrates in roots and rhizomes of grasses are indicative of dormancy. During periods of accelerated growth, a plant draws on these reserves, causing a substantial reduction in the amount stored (Weinmann, 1961). Since survival is likely to be influenced by food reserves stored in the transplant, monthly root and rhizome samples were collected from bitter panicum and sea oats from 1970-74, and also from saltmeadow cordgrass, shoredune panicum, and seashore dropseed from 1970-72. The total available carbohydrates (TAC) were extracted from the planting material as described by Smith, Paulsen, and Raguse (1964), except that 0.2 normal hydrochloric acid was used instead of 0.2 normal sulfuric acid. Monthly TAC values for both bitter panicum and sea oats from north Padre, 1972-74, are plotted in Figure 27; complete data are included in Table 24. Month to month TAC variation of both species fails to exhibit a well defined seasonal pattern, since growth may occur year round in this climate, and is influenced by irregular drought and rainfall. A period of winter dormancy in both species is shown by high values in both 1972-73 and 1973-74, followed by a pronounced depletion in spring (Fig. 27). Winter 1973-74 was much milder than the previous winter, and this is probably the reason for the spring TAC decline 1 month earlier than in 1972-73. However, this pattern is not evident in winter 1971-72. Sea oats exhibited a better defined annual cycle than bitter panicum.

d. Drifting Sand. Drifting sand accumulating on actively growing plants is essential for dune growth. Established clumps of sea oats and bitter panicum not only tolerate but thrive under the accumulation of a foot or more of sand deposited during a short period. However, freshly transplanted culms are adversely affected by accumulating sand before active transplant growth has begun. Apparently, this is because a buried transplant must deplete its

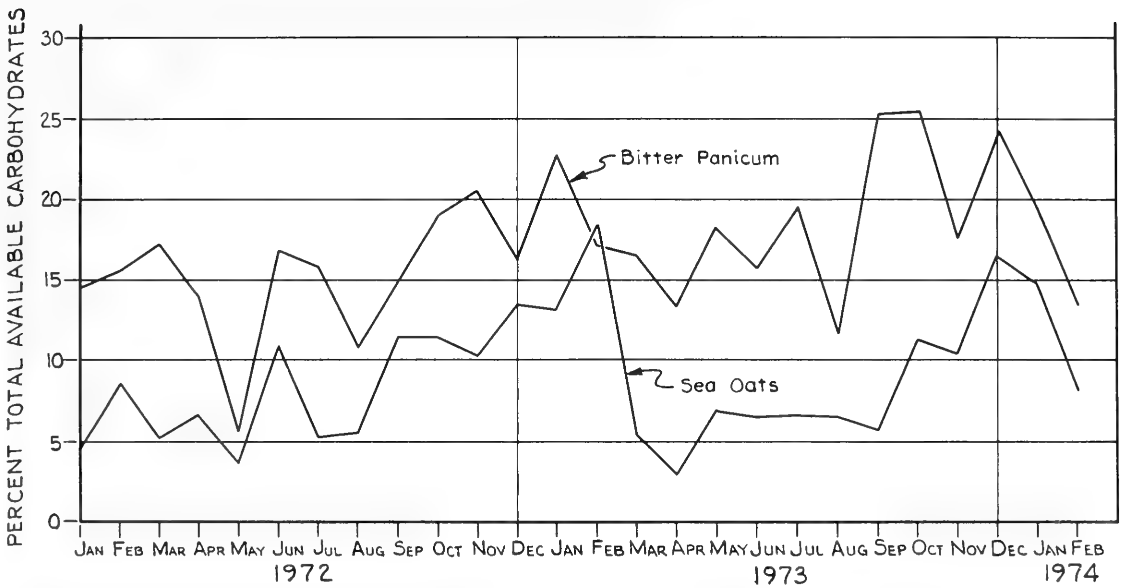


Figure 27. Percent total available carbohydrates stored in roots and rhizomes of bitter panicum and sea oats; from north Padre monthly collections.

Table 24. Percent total carbohydrates available for native test species on Padre Island

North Padre						South Padre					
Date	Sea oats	Bitter panicum	Saltmeadow cordgrass	Shoredune panicum	Seashore dropseed	Date	Sea oats	Bitter panicum	Saltmeadow cordgrass	Shoredune panicum	Seashore dropseed
1970						**1970**					
10 Nov.	13.3	27.6	13.8	——[1]	——[1]	11 Nov.	14.1	13.8	8.3	17.1	——[1]
17 Dec.	10.4	23.0	20.1	11.5	——	14 Dec.	14.9	17.0	16.2	23.0	——
1971						**1971**					
17 Jan.	10.0	14.5	15.8	14.9	——[1]	15 Jan.	12.4	13.2	13.4	19.2	——[1]
16 Feb.	10.8	13.4	13.2	11.6	——	20 Feb.	12.1	14.6	9.6	19.1	——
11 Mar.	9.4	15.4	11.8	12.4	——	10 Mar.	8.1	9.8	12.0	16.6	——
19 Apr.	7.1	11.0	8.6	9.2	——	Apr.	——[1]	——[1]	——[1]	——[1]	——
10 May	7.8	13.4	13.4	7.4	——	21 May	15.7	14.4	10.8	8.0	——
11 June	11.3	13.4	17.3	12.4	——	28 June	9.7	8.5	11.0	10.0	——
2 July	8.1	18.4	18.5	17.3	——	21 July	21.2	22.6	15.3	9.6	——
2 Aug.	7.5	12.6	14.4	9.5	——	5 Aug.	7.4	10.4	10.2	12.0	18.2
4 Sept.	4.5	15.2	11.8	12.2	18.4	6 Sept.	——	11.0	9.7	10.0	18.0
1 Oct.	4.2	12.0	8.0	12.0	8.0	1 Oct.	4.2	6.7	6.2	7.4	23.2
20 Oct.	10.5	28.4	15.0	26.2	——	Oct.	——	——	——	——	——
15 Nov.	14.5	19.9	15.2	14.1	23.2	12 Nov.	19.6	31.7	13.2	17.6	32.2
20 Dec.	11.0	25.7	18.7	23.7	20.6	15 Dec.	15.4	22.0	12.8	18.8	32.9
1972						**1972**					
17 Jan.	4.7	21.5	15.0	22.5	34.1	19 Jan.	8.0	——[1]	14.4	10.2	15.5
10 Feb.	8.4	15.6	14.2	——[1]	30.7	7 Feb.	7.2	14.4	15.6	9.9	20.9
17 Mar.	5.1	17.2	10.5	13.1	24.8	16 Mar.	4.4	9.8	8.8	8.1	23.1
6 Apr.	6.6	14.0	11.8	15.0	35.5	14 Apr.	9.0	16.2	7.4	7.9	21.2
14 May	3.8	5.7	9.7	4.0	25.1	10 May	8.0	9.2	7.8	6.4	22.8
15 June	10.9	16.9	11.1	9.2	36.6	17 June	10.8	15.9	14.0	5.4	28.8
6 July	5.1	15.9	10.7	10.5	23.6	12 July	11.5	12.5	6.9	7.3	20.7
4 Aug.	5.6	10.9	——[2]	——[2]	——[2]	7 Aug.	8.8	11.2	——[2]	——[2]	——[2]
7 Sept.	11.4	14.8	——	——	——	4 Sept.	21.8	13.8	——	——	——
6 Oct.	11.4	19.0	——	——	——	17 Oct.	14.8	19.8	——	——	——
4 Nov.	10.1	20.5	——	——	——	26 Nov.	11.4	22.4	——	——	——
20 Dec.	13.4	16.2	——	——	——	29 Dec.	12.4	20.5	——	——	——

1. No samples available for these dates.
2. No samples taken for these dates.

Table 24. Percent total carbohydrates available for native test species on Padre Island.—Continued

	North Padre						South Padre				
Date	Sea oats	Bitter panicum	Saltmeadow cordgrass	Shoredune panicum	Seashore dropseed	Date	Sea oats	Bitter panicum	Saltmeadow cordgrass	Shoredune panicum	Seashore dropseed
1973						**1973**					
10 Jan.	13.1	22.8	——[2]	——[2]	——[2]	17 Jan.	11.1	16.0	——[2]	——[2]	——[2]
19 Feb.	18.3	17.1	——	——	——	23 Feb.	17.3	12.0	——	——	——
17 Mar.	6.3	16.6	——	——	——	31 Mar.	9.1	8.8	——	——	——
14 Apr.	3.0	13.3	——	——	——	29 Apr.	5.9	10.8	——	——	——
14 May	6.9	18.1	——	——	——	31 May	13.1	13.5	——	——	——
15 June	6.4	15.8	——	——	——	23 June	9.0	17.1	——	——	——
15 July	6.6	19.6	——	——	——	July	——[2]	——[2]	——	——	——
18 Aug.	6.6	11.7	——	——	——	Aug.	——	——	——	——	——
17 Sept.	5.7	25.2	——	——	——	12 Sept.	9.2	19.2	——	——	——
19 Oct.	11.1	25.4	——	——	——	26 Oct.	8.2	19.9	——	——	——
16 Nov.	10.4	17.7	——	——	——	21 Nov.	10.7	20.7	——	——	——
17 Dec.	16.3	24.2	——	——	——	14 Dec.	20.4	19.5	——	——	——
1974						**1974**					
15 Jan.	14.9	19.3	——[2]	——[2]	——[2]	24 Jan.	7.9	16.7	——[2]	——[2]	——[2]
12 Feb.	8.1	13.5	——	——	——	28 Feb.	8.6	12.3	——	——	——

2. No samples taken for these dates.

food reserves by sending shoots through the sand to the surface. Backshore sand drifts are unpredictable, and at times may cover some parts of a planting for several days or weeks, then drift out, or move to another part of the planting. In most beach plantings, sand burial is less than a foot above the original planting surface.

Two similar experiments were conducted to determine the effect of sand burial on fresh transplants of bitter panicum (Table 25). Sea oats also was tested, but none of the plants survived, including the control. The survival ability of bitter panicum transplants was decreased considerably by the accumulation of more than 6 inches of sand on the uppermost living part of the transplant. Accumulation of over 20 inches resulted in total failure. Drifts of this magnitude were not a problem on the backshore, but were a regular occurrence on fence-built dune plantings. Most surprising was the emergence of the shoots of several plants through 12 to 18 inches of sand after 5 months of burial.

Table 25. Survival of bitter panicum transplants with different depths of sand accumulation on Padre Island.

Accumulation[1] (inches)	Transplants (number)	Survival[2] (percent)
North Padre Variable sand fence plot (planted 4 April 1973)[3]		
0	25	68 a
4 to 8	24	29 a, b
8 to 12	24	4 b
12 to 16	24	8 b
16 to 20	24	12 b
20 to 24	30	0 b
South Padre Stabilized dune plot (planted 19 March 1973)[4]		
0	20	45 a
6	20	45 a
12	20	5 b
24	20	0 b

1. Accumulated sand depth refers to inches of sand covering uppermost living part of transplant.
2. Figures sharing a common letter are not significantly different ($P_{0.05}$).
3. Three parallel rows of fabric fence, in the shape of an inclined plane, designed to accumulate sand in a continuum from 4 to 24 inches above the planting surface. Culms planted flush with surface before fence erection.
4. Culms planted horizontally in bottom of trenches at indicated depths, and buried with sand. The planting site was a shallow-sloped dune, stabilized by beach morning glory.

e. Combination of Effects. By multiple regression analyses, environmental parameters were tested for their contributions to the success or failure of transplants. The following monthly measurements for each planting season were evaluated: (a) surface and subsurface (six inches) soil salinity; (b) surface and subsurface (six inches) soil moisture percent; (c) precipitation; (d) total available carbohydrates of bitter panicum, sea oats, and shoredune panicum (percent); and (e) subsurface (4 inches) soil temperature and mean temperatures for day and month of planting. Values used for the analyses are tabulated in Table 26.

The actual contribution of a particular environmental factor to the success of a grass planting is difficult to interpret by this technique. Use of the technique to single out those factors responsible, in combination, would be more significant. Multiple correlation coefficients (R) and coefficients of determination (R^2) are tabulated in Table 27; correlation coefficients (r) for individual factors are shown in Table 28. Correlation coefficients (R and r) showing the relationship of environmental and parameters by season of planting are in Table 29.

These data showed that no one factor accounted for the success of a planting, and that either extreme salinity or extreme drought could cause total failure. The other important variables of soil temperature, air temperature, and plant vigor (as indicated by TAC in the roots and rhizomes), contributed to planting success or failure but the data did not show these variables responsible for a total stand failure, as for high salinity or lack of moisture.

Apparently high sea oats survival after planting is partially dependent on high soil moisture and low salinity at the surface and subsurface, and sufficient rainfall to keep the soil moisture at a high level. Soil moisture less than 10 percent at a depth of 6 inches with no more than 1 inch of rainfall during the month resulted in low plant survival, especially during the more arid 1970-72 planting seasons. However, the 1972-74 planting conditions were not as dry except on the south Padre sites where transplant survival also was influenced by low moisture, but the relationship was less consistent.

Salinity was a problem only if seawater covered the new transplants for extended periods. Such occasions also left the soil high in salt content until sufficient rain reduced the salt content to tolerable levels. Salinity levels increased during extended periods of low rainfall, probably from salt spray, and this aggravated the drought stress on new transplants since only the soil moisture and salinity factors often accounted for 100 percent of the variation in sea oats survival (Table 27).

Air and soil temperatures and carbohydrate storage were often important to sea oats survival, but the time interval and location on the island indicated that these factors had no consistent influence on survival. Correlation coefficients relating temperature to transplant survival were mostly negative indicating that cooler temperatures were more optimum. Surprisingly, high carbohydrate storage did not improve transplant survival and correlation coefficients were mostly negative.

Table 26. Environmental and plant parameters measured in conjunction with monthly plantings of test species on Padre Island.

Date	Soil salinity (µmhos/cm)		Soil moisture (percent)		Precipitation (inches)	Total available carbohydrates (percent)			Soil temperature (Farenheit)	Air temperature (Farenheit)		Plant survival (percent)		
	Surface	Depth (6 in.)	Surface	Depth (6 in.)	Total	Sea oats	Bitter panicum	Shoredune panicum	Depth (4 in.)	Date[1]	Month[2]	Sea oats	Bitter panicum	Shoredune panicum
	(x2)	(x3)	(x4)	(x5)	(x6)	(x7)	(x8)	(x9)	(x10)	(x11)	(x12)	(y1)	(y2)	(y3)
North Padre														
1970														
Nov.	455	671	7.6	11.9	1.32	13.3	27.6	15.8	*64*[3]	66.0	63.5	12	8	
Dec.	310	58	3.0	7.5	0.27	10.4	23.0	11.5	*57*	59.5	65.5	28	37	
1971														
Jan.	583	68	4.3	8.4	0.26	10.0	14.5	14.9	*59*	56.0	59.0	8	10	
Feb.					0.14	10.8	13.4	11.6	*70*	65.0	55.0	2	0	
Mar.	2,108	408	1.8	7.0	0.00	9.4	15.4	12.4	*72*	66.5	66.0	0	2	
Apr.	1,358	558	2.1	8.4	1.35	7.1	11.0	9.2	*79*	73.5	69.5	4	10	
Oct.	233	108	19.4	21.9	2.89	10.5	28.4	26.2	*72*	70.5	68.0	7	34	48
Nov.	2,275	725	5.5	12.0	2.63	14.5	19.9	14.2	72	77.0	66.5	46	22	20
Dec.	208	166	21.6	22.3	5.25	11.0	25.7	23.7	64	59.5	62.0	—[4]	—[4]	—[4]
1972														
Jan.	3,283	1,613	16.6	20.6	0.08	4.7	21.5	22.5	60	46.5	59.0	64	37	60
Feb.	83	640	17.8	19.8	3.33	8.4	15.6	16.5	54	50.5	57.5	—[5]	84	76
Mar.	1,150	250	20.5	22.5	3.99	7.0	17.2	15.7	*69*	69.0	67.5	76	88	78
Apr.	3,920	810	4.4	13.0	2.45	6.6	14.0	15.1	*84*	70.5	73.0	27	58	37
May	1,290	1,940	17.4	21.4	3.75	3.7	5.7	4.0	84	73.0	75.5	75	80	37
Sept.	7,900	1,070	4.6	13.4	7.75	11.4	14.8		*82*	81.0	82.2	6	4	
Oct.	750	400	14.2	18.8	1.33	11.4	19.0		*81*	80.0	77.1	0	0	
Nov.	128	520	13.6	18.0	4.95	10.1	20.5		*65*	65.0	61.4	6	30	
Dec.	380	370	0.7	12.2	0.29	13.4	16.2		*63*	62.0	55.3	2	24	
1973														
Jan.	46	500	12.2	21.3	3.55	13.1	22.8		40	38.0	51.0	26	10	
Feb.	150	5,500	6.5	22.4	1.16	18.3	17.1		54	46.0	54.3	60	34	
Mar.	758	1,150	0.2	17.8	0.23	6.3	16.6		66	69.0	67.0	0	62	
Apr.	1,790	1,690	0.5	14.2	0.90	3.0	13.3		75	69.0	68.2	34	68	
May	1,263	1,120	0.2	18.4	1.65	6.9	18.1		73	73.0	75.4	8	70	
June	123	174	1.8	20.5	10.67	6.4	15.8		82	77.0	80.1	18	78	
July	2,760	67	0.2	5.8	0.97	6.6	19.6		*82*	81.0	83.0	37	93	
Aug.	105	225	1.0	13.2	2.27	6.6	11.7		84	80.0	82.0	5	89	
Sept.	83	58	8.1	20.5	12.40	5.7	25.2		77	81.0	81.0	22	81	
Oct.	133	880	10.0	22.6	9.91	11.1	25.4		75	70.0	77.0	21	40	
Nov.	546	1,020	0.3	20.1	1.52	10.4	17.7		74	78.0	73.0	14	58	
Dec.	2,110	1,025	0.2	17.5	0.16	16.3	24.2		53	53.0	61.9	4	82	
1974														
Jan.	2,480	956	1.7	16.5	1.88	14.9	19.3		60	57.0	54.7	23	80	
Feb.	151	508	0.3	14.4	0.10	8.1	13.5		57	60.0	60.6	25	64	

1. Average temperature at date of planting (Ranger Station, north Padre; Lorraine Station, south Padre).
2. Average temperature at month of planting (Ranger Station, north Padre; Brownsville, south Padre).
3. Values in underlined italics computed from air temperatures.
4. Destroyed by vehicles.
5. Rabbits pulled up all sea oats on this date.

Table 26. Environmental and plant parameters measured in conjunction with monthly plantings of test species on Padre Island.—Continued

Date	Soil salinity (µmhos/cm)		Soil moisture (percent)		Precipitation (inches)	Total available carbohydrates (percent)			Soil temperature (Farenheit)	Air temperature (Farenheit)		Plant survival (percent)		
	Surface (x2)	Depth (6 in.) (x3)	Surface (x4)	Depth (6 in.) (x5)	Total (x6)	Sea oats (x7)	Bitter panicum (x8)	Shoredune panicum (x9)	Depth (4 in.) (x10)	Date[1] (x11)	Month[2] (x12)	Sea oats (y1)	Bitter panicum (y2)	Shoredune panicum (y3)
South Padre														
1970														
Nov.	2,264	798	2.0	6.4	0.37	14.1	13.8	17.1	65	*65.0*	66.2	0	32	
Dec.	69	305	4.7	7.2	0.99	14.9	17.0	23.0	64	*56.0*	69.8	0	7	
1971														
Jan.	476	475	5.1	9.9	0.51	12.4	13.2	19.2	68	*65.0*	66.5	9	32	
Feb.	5,428	1,204	4.9	9.1	1.15	12.1	14.6	19.1	68	*68.0*	67.2	2	22	
Mar.	2,458	912	2.5	8.6	0.00	8.1	9.8	16.6	69	*69.0*	72.1	0	34	
Oct.	478	400	16.1	18.2	5.57	6.3	6.7	7.4	80	80.0	76.9	29	28	44
Nov.	686	482	12.0	8.6	3.29	19.6	31.7	17.6	79	67.0	69.3	—[4]	—[4]	—[4]
Dec.	1,265	437	7.7	8.7	2.28	15.4	22.0	18.8	71	73.0	67.3	76	39	35
1972														
Jan.	1,600	1,540	6.6	12.8	1.30	8.1	19.7	10.2	66	71.5	66.0	73	21	39
Feb.	1,000	2,160	1.6	7.0	1.46	7.2	14.4	8.9	82	55.5	64.7	61	26	87
Mar.	50	190	10.2	10.4	1.14	4.4	9.2	7.4	72	68.0	72.4	59	35	49
Apr.	4,190	5,295	0.4	5.4	1.54	9.0	16.2	7.9	83	76.5	77.4	0	0	0
May	2,683	2,216	8.3	16.3	2.02	8.1	9.2	6.4	80	80.0	77.6	22	51	56
Nov.	102	174	6.9	10.1	2.83	11.4	22.4		59	65.0	68.9	5	0	
Dec.	480	112	1.3	3.4	0.25	12.4	20.5		62	65.0	62.4	26	12	
1973														
Jan.	122	60	2.7	4.0	4.39	11.1	16.0		58	48.0	57.8	43	40	
Feb.	61	300	11.7	15.2	3.20	17.3	12.0		58	60.0	62.1	81	33	
Mar.	1,110	72	0.1	2.3	0.16	9.1	8.8		74	74.0	71.4	0	38	
Apr.	1,540	482	0.2	2.8	0.72	5.9	10.8		73	75.0	71.9	4	46	
May	1,580	400	0.2	2.0	1.32	13.1	13.5		86	83.0	79.1	15	40	
June	51	40	8.3	9.6	6.21	9.0	17.1		74	78.0	82.9	41	97	
July	306	63	0.1	2.0	0.60				90	88.0	86.3	46	83	
Sept.	2,994	182	0.2	3.0	3.44	9.2	19.2		86	86.0	85.7	32	12	
Oct.	4,820	720	1.6	15.7	3.27	8.2	19.9		75	83.0	82.0	39	35	
Nov.	1,098	343	0.4	14.6	0.87	10.7	20.7		71	81.0	80.0	22	28	
Dec.	1,525	125	0.2	6.7	0.31	20.4	19.5		73	74.0	68.5	16	22	
1974														
Jan.	68	300	5.8	6.9	1.04	7.9	16.7		55	52.0	62.1	66	57	
Feb.	915	127	1.1	3.2	0.08	8.6	12.3		68	74.0	67.6	33		

1. Average temperature at date of planting (Ranger Station, north Padre; Lorraine Station, south Padre).
2. Average temperature at month of planting (Ranger Station, north Padre; Brownsville, south Padre).
3. Values in underlined italics computed from air temperatures.
4. Destroyed by vehicles.
5. Rabbits pulled up all sea oats on this date.

Table 27. Multiple correlation coefficients (R) and coefficients of determination (R^2) relating environmental and plant parameters to survival of test species on Padre Island.

Sea oats		North Padre			South Padre		
Season	Variables included	Variables used[1]	R	R^2	Variables used[1]	R	R^2
1970, 71	Soil moisture and salinity	(x) 2	–0.79	0.62	(x) 2	0.87	0.75
		3	0.87	0.76	4	0.99	0.98
		5	0.92	0.84	5	1.00	1.00
	All variables	2	–0.79	0.62	2	0.87	0.75
		5	0.87	0.76	4	0.99	0.98
		12	0.93	0.86	6	1.00	1.00
1971, 72	Soil moisture and salinity	(x) 3	0.55	0.30	(x) 3	–0.68	0.47
		4	0.64	0.41	4	0.95	0.90
		5	0.71	0.50	2	0.95	0.91
		2	0.76	0.57	5	0.95	0.91
	All variables	3	0.55	0.30	12	–0.88	0.78
		4	0.64	0.41	3	0.98	0.96
		5	0.71	0.50	10	1.00	0.99
		7	0.98	0.96	4	1.00	1.00
1972, 73	Soil moisture and salinity	(x) 3	0.67	0.46	(x) 4	0.74	0.55
		5	0.70	0.49	5	0.77	0.59
		2	0.74	0.54	3	0.79	0.62
		4	0.75	0.57	2	0.81	0.65
	All variables	3	0.67	0.45	4	0.74	0.55
		5	0.70	0.49	7	0.82	0.67
		11	0.74	0.54	5	0.87	0.76
		10	0.89	0.79	12	0.90	0.82
1973, 74	Soil moisture and salinity	(x) 5	0.42	0.18	(x) 4	0.95	0.90
		4	0.46	0.21	2	0.97	0.94
		2	0.54	0.29	5	0.98	0.96
		----	---------	-------	3	0.99	0.98
	All variables	5	0.42	0.18	4	0.95	0.90
		11	0.51	0.26	7	0.99	0.97
		7	0.78	0.61	10	1.00	0.99
		6	0.91	0.83	12	1.00	1.00

1. Variable numbers correspond to those in Table 26.

Table 27. Multiple correlation coefficients (R) and coefficients of determination (R^2) relating environmental and plant parameters to survival of test species on Padre Island.—Continued

Sea oats		North Padre			South Padre		
Season	Variables included	Variables used[1]	R	R^2	Variables used[1]	R	R^2
1970, 72	Soil moisture and salinity	(x) 5	0.69	0.48	(x) 2	–0.39	0.15
		3	0.77	0.59	4	0.45	0.19
		2	0.77	0.59	3	0.48	0.23
		4	0.78	0.61	5	0.49	0.24
	All variables	5	0.69	0.48	2	–0.39	0.15
		3	0.77	0.59	7	0.47	0.22
		10	0.79	0.62	12	0.60	0.36
		6	0.88	0.78	11	0.75	0.57
1972, 74	Soil moisture and salinity	(x) 3	0.61	0.37	(x) 4	0.66	0.44
		2	0.62	0.39	2	0.69	0.47
		5	0.64	0.41	3	0.69	0.48
		4	0.65	0.43	----	---------	-------
	All variables	3	0.61	0.37	4	0.66	0.44
		2	0.62	0.39	2	0.69	0.47
		12	0.65	0.42	11	0.77	0.58
		11	0.68	0.46	10	0.77	0.60
1970, 74	Soil moisture and salinity	(x) 4	0.52	0.27	(x) 4	0.44	0.19
		3	0.66	0.43	2	0.48	0.23
		5	0.66	0.44	5	0.49	0.24
		2	0.66	0.44	3	0.49	0.24
	All variables	4	0.52	0.27	4	0.44	0.19
		3	0.66	0.43	12	0.50	0.25
		7	0.70	0.49	6	0.55	0.30
		11	0.71	0.50	11	0.56	0.32
Bitter panicum		**North Padre**			**South Padre**		
1970, 71	Soil moisture and salinity	(x) 2	–0.63	0.39	(x) 4	–0.52	0.27
		4	0.90	0.81	5	0.91	0.83
		3	0.90	0.82	3	0.91	0.83
	All variables	2	–0.63	0.39	8	–0.85	0.72
		4	0.90	0.81	12	0.99	0.99
		8	1.00	0.99	6	1.00	1.00

1. Variable numbers correspond to those in Table 26.

Table 27. Multiple correlation coefficients (R) and coefficients of determination (R^2) relating environmental and plant parameters to survival of test species on Padre Island.—Continued

Bitter panicum		North Padre			South Padre		
Season	Variables included	Variables used[1]	R	R^2	Variables used[1]	R	R^2
1971, 72	Soil moisture and salinity	(x) 5	0.46	0.21	(x) 3	–0.66	0.44
		2	0.47	0.22	2	0.77	0.59
		4	0.49	0.24	4	0.78	0.61
		3	0.50	0.25	5	0.84	0.71
	All variables	8	–0.66	0.44	3	–0.66	0.44
		4	0.85	0.72	2	0.77	0.59
		3	0.96	0.92	10	0.84	0.70
		6	1.00	1.00	6	0.97	0.94
1972, 73	Soil moisture and salinity	(x) 4	–0.64	0.41	(x) 4	0.15	0.02
		2	0.73	0.53	5	0.72	0.53
		5	0.75	0.56	2	0.91	0.82
		3	0.75	0.56	3	0.92	0.84
	All variables	4	–0.64	0.41	12	0.61	0.38
		2	0.73	0.53	6	0.78	0.61
		12	0.93	0.87	8	0.90	0.80
		6	0.97	0.95	5	0.92	0.85
1973, 74	Soil moisture and salinity	(x) 5	–0.73	0.53	(x) 4	0.94	0.88
		3	0.79	0.63	5	0.99	0.98
		2	0.98	0.96	3	1.00	0.99
		4	0.98	0.97	----	---------	-------
	All variables	5	–0.73	0.53	4	0.94	0.88
		8	0.91	0.82	5	0.99	0.98
		3	0.96	0.93	12	1.00	1.00
		2	0.99	0.98	----	---------	-------
1970, 72	Soil moisture	(x) 5	0.75	0.56	(x) 5	0.49	0.24
		4	0.75	0.56	3	0.59	0.35
		2	0.76	0.57	4	0.66	0.43
		----	---------	-------	2	0.66	0.43
	All variables	6	0.77	0.59	5	0.49	0.24
		11	0.90	0.80	6	0.62	0.38
		12	0.96	0.93	3	0.67	0.45
		10	0.97	0.94	10	0.82	0.67

1. Variable numbers correspond to those in Table 26.

Table 27. Multiple correlation coefficients (R) and coefficients of determination (R^2) relating environmental and plant parameters to survival of test species on Padre Island.—Continued

Bitter panicum		North Padre			South Padre		
Season	Variables included	Variables used[1]	R	R^2	Variables used[1]	R	R^2
1972, 74	Soil moisture and salinity	(x) 4	–0.56	0.32	(x) 4	0.30	0.09
		2	0.65	0.42	5	0.33	0.11
		3	0.68	0.47	3	0.35	0.12
		5	0.68	0.47	2	0.36	0.13
	All variables	4	–0.56	0.32	6	0.43	0.18
		2	0.65	0.42	8	0.63	0.40
		11	0.75	0.57	12	0.64	0.41
		8	0.82	0.66	11	0.71	0.51
1970, 74	Soil moisture and salinity	(x) 5	0.30	0.09	(x) 3	0.29	0.08
		4	0.38	0.14	4	0.34	0.12
		3	0.44	0.19	5	0.34	0.12
		2	0.44	0.19	----	-------	-------
	All variables	5	0.30	0.09	6	0.35	0.12
		12	0.43	0.09	8	0.45	0.20
		8	0.48	0.23	3	0.52	0.27
		2	0.51	0.26	4	0.53	0.29
Shoredune panicum		North Padre			South Padre		
1971, 72	Soil moisture and salinity	(x) 5	0.82	0.67	(x) 2	0.60	0.35
		3	0.86	0.75	4	0.69	0.47
		2	0.88	0.77	5	0.91	0.83
	All variables	5	0.82	0.67	11	0.63	0.40
		9	0.94	0.89	5	0.93	0.86
		11	0.98	0.96	10	0.95	0.90
		3	0.99	0.99	9	0.96	0.92

1. Variable numbers correspond to those in Table 26.

Table 28. Correlation coefficients (r) showing relationship of environmental and plant parameters measured in conjunction with survival of test species on Padre Island.

Island	Soil salinity		Soil moisture		Precipitation	TAC[1]	Temperature		
	Surface	6 inches	Surface	6 inches			Soil 6 inches	Air at planting date	$\bar{x}$ Air for month
Sea oats									
1970 to 1971									
North	–0.79	–0.48	0.22	0.05	–0.09	0.39	–0.73	–0.49	–0.11
South	0.87	0.73	0.40	0.34	0.65	–0.05	0.31	0.37	–0.26
1971 to 1972									
North	0.05	0.55	0.32	0.32	0.11	–0.50	–0.17	–0.23	–0.07
South	–0.67	–0.68	0.10	–0.10	–0.26	0.25	–0.76	–0.55	–0.88
1972 to 1973									
North	–0.16	0.67	0.09	0.11	–0.20	0.29	–0.21	–0.38	–0.17
South	–0.62	–0.12	0.74	0.70	0.56	0.69	–0.46	–0.48	–0.36
1973 to 1974									
North	–0.21	0.16	0.18	0.42	0.19	–0.18	0.07	–0.31	0.12
South	–0.20	0.27	0.95	–0.07	0.14	–0.65	–0.65	–0.73	–0.43
1970 to 1972									
North	–0.26	0.60	0.65	0.69	0.53	–0.49	0.10	–0.05	0.20
South	–0.39	–0.15	0.36	0.23	0.28	–0.30	0.16	0.06	–0.26
1972 to 1974									
North	–0.16	0.61	0.11	0.16	–0.07	0.17	–0.14	–0.35	–0.09
South	–0.19	0.07	0.66	0.44	0.40	0.14	–0.46	–0.47	–0.30
1970 to 1974									
North	0.04	0.43	0.52	0.38	0.01	–0.16	–0.01	–0.18	–0.03
South	–0.33	–0.13	0.44	0.30	0.33	–0.07	–0.19	–0.22	–0.26
Bitter panicum									
1970 to 1971									
North	–0.63	–0.59	–0.10	–0.23	–0.18	0.36	–0.58	–0.41	0.06
South	0.20	0.41	–0.59	0.28	–0.77	–0.85	0.64	0.82	–0.15
1971 to 1972									
North	–0.36	0.06	0.46	0.46	0.62	–0.66	–0.02	–0.13	0.11
South	–0.45	–0.66	0.51	0.53	0.11	–0.28	–0.21	0.09	–0.02
1972 to 1973									
North	–0.23	–0.16	–0.64	–0.29	–0.15	–0.18	0.55	0.52	0.55
South	0.01	–0.12	0.15	0.04	0.57	–0.34	0.47	0.38	0.62
1973 to 1974									
North	0.29	–0.51	–0.38	–0.73	–0.24	–0.29	–0.24	0.34	–0.39
South	–0.41	0.34	0.94	0.24	–0.29	–0.68	–0.93	–0.84	–0.71
1970 to 1972									
North	–0.02	0.32	0.72	0.75	0.77	–0.32	0.07	–0.08	0.20
South	–0.18	–0.45	0.38	0.49	0.06	–0.37	0.02	0.28	0.00
1972 to 1974									
North	–0.21	–0.26	–0.56	–0.28	–0.11	–0.07	0.32	0.39	0.31
South	–0.21	–0.03	0.30	0.04	0.43	–0.39	0.06	–0.02	0.16
1970 to 1974									
North	–0.15	–0.04	–0.02	0.30	0.14	–0.18	0.21	0.21	0.30
South	–0.22	–0.29	0.22	0.10	0.35	–0.27	0.01	0.07	0.15
Shoredune panicum									
1971 to 1972									
North	–0.48	0.31	0.79	0.82	0.36	–0.34	–0.19	–0.36	–0.05
South	–0.60	–0.46	0.10	0.20	–0.03	–0.14	0.07	–0.63	–0.46

1. Total available carbohydrates.

Table 29. Correlation coefficients showing relationship of environmental and plant parameters to survival of test species.

Seasonal variables	Soil salinity						Soil moisture						Precipitation			Available carbohydrates	Temperature								
Year	Surface			6 inch			Surface			6 inch						Total	Soil (6 in.)			Date[1]			Month[2]		
	r	R	R^2	r	R	R^2	r	R	R^2	r	R	R^2	r	R	R^2	r	r	R	R^2	r	R	R^2	r	R	R^2
Sea oats survival																									
Summer 1973	–0.56			–0.17	0.79	0.63	0.52			0.50			0.32			0.22	–0.67	–0.67	0.44	–0.62	0.91	0.83	–0.21		
Fall 1970–1973	–0.36			–0.16	0.75	0.56	0.11	0.66	0.44	0.60	+0.60	0.37	0.49	0.78	0.60	0.16	0.21			–0.04			0.25		
Winter 1970–1974	0.11	0.56	0.32	0.07			–0.26	0.50	0.25	0.27	+0.27	0.07	–0.09			–0.05	–0.19	0.54	0.29	–0.21			–0.08		
Spring 1971–1973	–0.32			–0.22	0.79	0.63	0.52			0.74	+0.74	0.55	0.58			0.02	–0.14			–0.13	0.83	0.69	–0.01	0.83	0.69
Bitter panicum survival																									
Summer 1973	0.19			–0.75			0.37			–0.44	0.94	0.89	–0.02			–0.04	0.05	0.92	0.84	0.40			0.84	+0.84	0.71
Fall 1970–1973	0.08	0.62	0.39	0.08			–0.30	0.56	0.31	0.06			0.01			–0.24	0.51	+0.51	0.26	0.31	0.65	0.42	0.48		
Winter 1970–1974	–0.10	0.53	0.28	0.32	0.47	0.22	0.38	+0.38	0.14	0.12	0.50	0.25	0.24			–0.18	0.03			–0.10			–0.07		
Spring 1971–1973	–0.30			–0.11			0.91	+0.91	0.82	0.63			0.79			–0.51	0.10			–0.22			0.03		

1. Air temperature on planting date.
2. Air temperature month of planting.

Notes: r = correlation coefficient
R = multiple correlation coefficient
R^2 = coefficient of determination

Generally, the response of bitter panicum transplants to the environment was similar to sea oats. High salinity and low moisture resulted in low survival, but the transplants appeared to do better when the carbohydrate content was low. In combination with other variables, temperature was occasionally important to bitter panicum survival but significant patterns were harder to define.

Shoredune panicum was planted only in 1971-72, and the influence of environmental factors on survival was similar to the other two species. Multiple correlation analyses are included in Table 27.

Brown and Hafenrichter (1948a) also found environmental parameters important to transplant survival for species on Pacific coastal sand dunes. Over 50 percent survival for European beachgrass was always obtained when maximum air temperatures did not exceed 55° Fahrenheit for 3 days after planting; survival was always less than 50 percent when maximum temperatures exceeded 60° Fahrenheit. Dormancy of American dunegrass transplants was more important to survival than environmental variables. American beachgrass was less sensitive to either climate or dormancy, and hence was the best choice for transplanting on Pacific coastal dunes.

To further assess the influence of periodically high salinities on plant survival, monthly plantings of sea oats and bitter panicum were made at open and protected beach sites on north and south Padre in 1973-74. Open beach sites were similar to those of previous monthly and major plantings. Soil moisture was usually high, but salinity varied from low to high as a result of periodic saltwater inundations and heavy salt spray; plantings were also subject to burial by drifting sand. Protected beach plantings leeward of an artificial dune line were protected from saltwater inundation, drifting sand, and some salt spray. Culms for each paired planting were obtained from the same location, thoroughly mixed, and transplanted the same day. Survival comparisons are given in Table 30.

Protected beach transplant survival for both species was consistently higher in all months. Multiple and single correlation analyses (Table 31) showed that no single factor including salinity was responsible for this difference.

On north Padre, soil salinity of the open beach was greater than the protected site. However, soil salinities of the two south Padre sites were more comparable. Soil moisture, rainfall, TAC, soil, and air temperatures were similar or equal for each pair of open and protected sites for a given planting. This suggests that some unmeasured variables (probably salt spray and drifting sand) were adversely affecting the open beach transplants. The survival potential, as exhibited by the protected plantings, was considerably higher and with less variation than was realized on the open beach.

Inundation by saltwater soon after planting, particularly in conjunction with drought, caused complete or nearly complete failures of some monthly test plantings and of several major plantings on south Padre (Table 11). Minor surges are common in winter and spring, and any winter beach planting of less than 5 feet MSL is vulnerable to inundation. Minor

Table 30. Comparison of survival of sea oats and bitter panicum plantings on open and protected beach sites, Padre Island.[1]

Month	Planting site	Percent survival		Percent soil moisture at 6 inches	Soil salinity at 6 inches (μmho/cm)	Precipitation (month)
		Bitter panicum	Sea oats			
			North Padre			
Nov. 73	open[2]	53	12	20.1	1,020	1.52
	protected[3]	100	72	23.0	94	-------
Dec.	open	78	3	17.5	1,025	0.16
	protected	96	37	19.9	75	-------
Jan. 74	open	77	19	16.5	956	1.88
	protected	98	43	13.7	90	-------
Feb.	open	78	21	14.4	508	0.10
	protected	92	36	18.1	380	-------
Mar.	open	72	6	16.9	642	3.92
	protected	92	56	16.3	212	-------
Apr.	open	50	29	17.4	3,900	0.03
	protected	98	61	19.7	225	-------
Total (x)	open	68	15	17.1	1,342	7.61
	protected	96	51	18.5	179	-------
			South Padre			
Oct. 73	open	36	38	15.7	720	3.27
	protected	92	90	20.6	130	-------
Nov.	open	32	22	14.6	343	0.87
	protected	94	79	17.3	150	-------
Dec.	open	19	17	6.7	125	0.31
	protected	93	55	17.3	165	-------
Jan. 74	open	59	62	6.9	300	1.04
	protected	84	82	10.3	155	-------
Feb.	open	39	24	3.2	127	0.08
	protected	79	64	8.8	202	-------
Total (x)	open	37	33	9.4	323	5.57
	protected	88	74	14.9	160	-------

1. N = 100 plants.
2. Bare backshore, 350 to 450 feet inland from shoreline.
3. Similar to above, but located immediately behind the protection of an artifical dune line (1,100-foot bitter panicum on north Padre, and mid-panicum, North Section Fence on south Padre), about 100 feet farther inland than open beach sites. Elevations of the two sites are 4.5 to 5.0 feet MSL.

Table 31. Correlation coefficients showing relationships of environmental and plant parameters.[1]

Variables	Sea oats survival			Bitter panicum survival		
	Beaches			Beaches		
	Open	Protected	Open-Protected	Open	Protected	Open-Protected
	Correlation coefficients (r)					
Soil salinity at 6 inches	–0.41	–0.31	–0.64	0.69	–0.36	–0.40
Total available carbohydrates	–0.59	–0.46	–0.35	–0.09	0.42	–0.57
Precipitation	0.30	0.57	0.29	–0.17	0.03	–0.55
Air temperature, $\bar{x}$ minimum	0.04	0.78	0.28	–0.79	0.10	–0.31
Air temperature, $\bar{x}$ maximum	–0.14	0.63	0.17	–0.72	0.22	–0.35
Air temperature, $\bar{x}$	-------	-------	0.24	-------	-------	–0.39
Soil temperature at 6 inches	–0.16	0.59	0.15	–0.76	0.31	–0.39
Soil moisture at 6 inches	–0.49	–0.09	0.07	0.46	0.66	0.07
	Multiple correlation coefficients (R)					
Total available carbohydrates	0.59					
Soil moisture at 6 inches	0.76					
Precipitation	0.86					
Soil temperature at 6 inches	0.95					
Air temperature, $\bar{x}$ minimum		0.78				
Air temperature, $\bar{x}$ maximum		0.95				
Total available carbohydrates		0.98				
Soil salinity at 6 inches		0.98				
Soil salinity at 6 inches			0.64			
Precipitation			0.72			
Air temperature, $\bar{x}$ minimum				0.79		
Soil salinity at 6 inches				0.95		
Soil temperature at 6 inches				0.98		
Total available carbohydrates				1.00		
Soil moisture at 6 inches					0.67	
Soil salinity at 6 inches					0.73	
Air temperature, $\bar{x}$ minimum					0.79	
Air temperature, $\bar{x}$ maximum					0.84	
Total available carbohydrates						0.57
Soil moisture at 6 inches						0.74
Air temperature, $\bar{x}$ maximum						0.83
Soil salinity at 6 inches						0.91

1. Measured in conjunction with survival of test species on open versus protected beach plantings on Padre Island during 1973 and 1974 seasons.

surges may inundate backshore plantings, but usually do not erode or deposit much sediment, since most wave energy is dissipated near the berm. Often, the result is a gradual flooding of the planting rather than wave attack. However, lower elevation hurricane washover channels may suffer erosion or sediment deposition.

Survival and growth, expressed as the relative number of plants with visible nonchlorotic green leaves or new shoots, was determined at approximately weekly intervals for both open and protected beach monthly plantings on north Padre in 1973-74. Data were collected until no further changes occurred or individual plants could no longer be distinguished. Survival data for representative months, and periods of saltwater inundation, are shown in Figures 28 and 29; comparisons include open versus protected beach, two categories of panicum culms, and season of planting. The latter two comparisons will be discussed later.

In these figures, the effect of inundations is unclear. October sea oats (Fig. 28) had a gradual decline in survival after an early inundation. The same surge on the November planting may account for much of the difference between this and the protected planting survival. Inundation several months after planting appears to have had little influence. Bitter panicum tillers planted in October and November (Fig. 29) exhibited a gradual decline in survival after inundations, but a similar decline in the December planting occurred a month before the surge. The three panicum primary culm plantings did not respond negatively to the inundations. These inundations were not accompanied nor followed by rain for over 2 weeks.

The effects of inundations have been variable, ranging from total failure of some past plantings to little response. One major plot in the north (1,200-foot dune-width panicum), inundated by a surge soon after planting, had over 70 percent survival and is one of the most successful dunes for rapid growth and maximum accumulation of sand.

In summary, inundation of a planting by a minor surge, lasting 1 to 2 days, is not always detrimental, but can affect survival if it occurs during a drought, especially if the water remains ponded on the planting for several days.

f. Season of Planting. Transplant survival, as determined from monthly test plantings, is influenced more by soil salinity, soil moisture and TAC, than by seasonality. Tests to determine the best time of planting were conducted monthly from 1970 to 1972, fall through spring. Data from Table 16 show that sea oats had an optimum planting season from December through March. December was the best month on south Padre, while January was best in the north part. Unlike sea oats, the best planting time for bitter panicum was not limited to a short season, but could be transplanted from November through May with good results if soil moisture was high.

In 1973, test plantings were continued year round on both north and south Padre. Atypically high precipitation from June through October on north Padre may have been unusually advantageous to the plants, but in the south, rainfall was near normal. Data (Table 16) show that either species can be planted year round; but bitter panicum survival

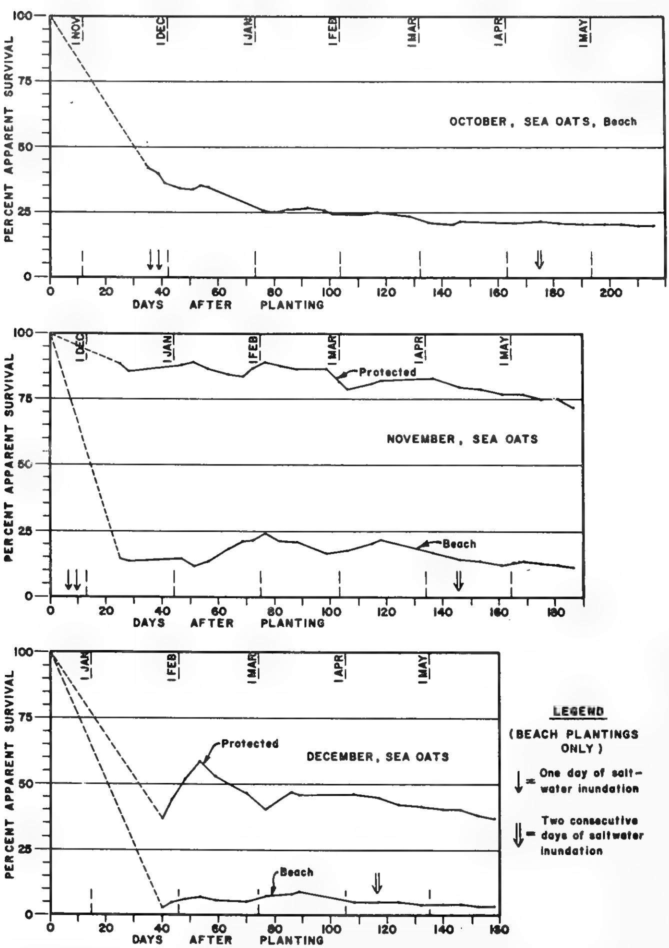


Figure 28. Survival and growth of selected north Padre sea oats plantings, comparing open beach versus protected beach sites. Data are relative number of plants with exposed green leaves or new shoots, on successive days after planting. Vertical arrows denote dates or surge inundation of beach plantings only.

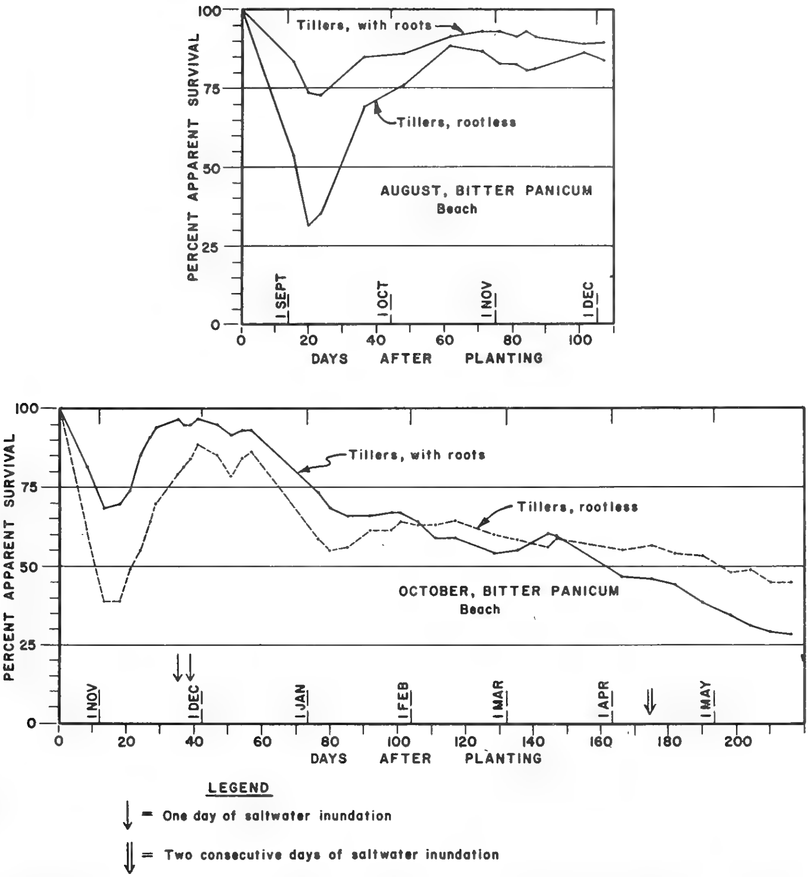


Figure 29. Survival and growth of selected north Padre bitter panicum plantings, comparing tillers versus primary culms and open beach versus protected beach. Data are relative number of plants with exposed green leaves or new shoots on successive days after planting. Vertical arrows denote dates of surge inundation of beach plantings only.

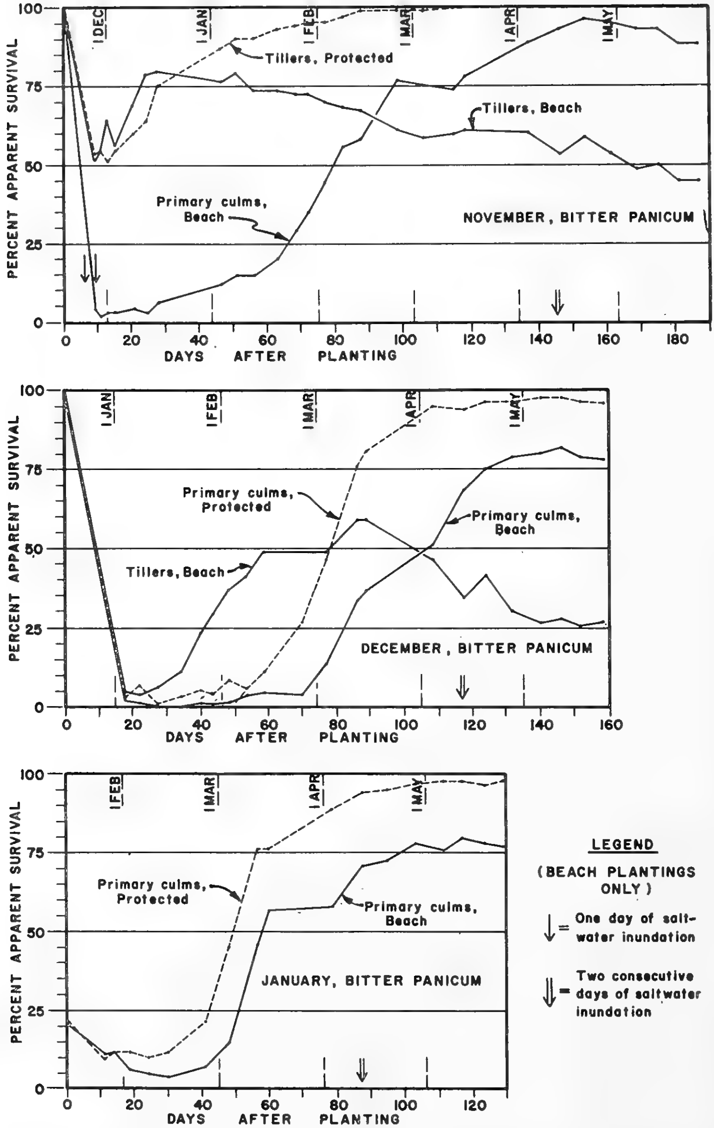


Figure 29. Survival and growth of selected north Padre bitter panicum plantings, comparing tillers versus primary culms and open beach versus protected beach.—continued

was higher in summer than winter, with only a short period of transplant shock. The plants began growth quickly and were trapping sand within 2 to 3 months. In contrast, winter transplants became dormant, most or all leaves died, and growth did not begin until late spring. Fall and early winter plantings in 1972-73 and 1973-74 exhibited high initial survival, as evidenced by new shoots emerging during late winter, but early spring mortality was pronounced. Survival curves, comparing summer (August) and winter (November to January) bitter panicum growth are shown in Figure 29.

Probably the least desirable time to plant bitter panicum is in fall. Plants will remain mostly dormant until the following spring, and vigorous growth will not begin until nearly 6 months later. During this 6-month period, the chances for inundations, drought, and sand burial to occur are increased over a spring or early summer transplant, which will start growth quickly. By mid-summer, culms planted in spring were nearly equal in size to those planted the previous fall (Table 32). If environmental conditions are favorable, the best time

Table 32. Growth of bitter panicum transplants on 1 July 1974.[1]

Planting date	Days after planting	Tillers per plant[2]	Mean weight per plant (grams)[3]
17 Nov. 1973	226	7.0 a	15.4
14 Dec. 1973	199	6.5 a, b	12.5
15 Jan. 1974	167	5.5 c	14.7
11 Feb. 1974	140	5.8 b, c	15.8
16 Apr. 1974	76	6.1 b, c	12.8

1. Culms were transplanted at a north Padre protected site on dates indicated but not fertilized.
2. All exposed tillers, including those recently emerged; N = 90 plants per month. Figures sharing common letter are not significantly different ($P_{0.05}$).
3. Oven-dried weight of exposed (aerial) growth only; N = 24 plants per month. No significant difference ($P_{0.05}$).

to plant is from late winter to early summer. There are no concrete guidelines on when to plant bitter panicum; problems are encountered in summer or winter (Table 33). All major plots were planted in winter and spring (through April); none has been tried in summer. The hot climate for physical labor and rapid drying of the substrate make summer planting undesirable.

Similarly, sea oats was successfully planted in the summer of 1973. However, January and February seems the best time to plant sea oats on either end of the island, but any time that soil moisture is high and soil salinity low, good results are possible. Again, the season is not a strict influencing factor.

Results of 70 experimental beach plantings of sea oats indicate a survival rate of 50 percent or better and should be considered excellent; 25 to 50 percent survival is very good. Only 3 of 70 plantings had a survival rate greater than 75 percent; 12 had a survival rate of over 50 percent; and 30 had greater than 25 percent survival. The remainder were all 25 percent or less.

Table 33. Early summer versus winter planting of bitter panicum.

Summer	Winter
Higher, more consistent transplant survival.	Survival generally poorer, more erratic.
Transplants begin growth within 1 month after planting and are trapping sand within 2 to 3 months.	Transplants remain semidormant 3 to 6 months; active growth does not begin until the following spring.
Inundation of plantings by seawater is less likely.	Inundation of plantings may be regular in winter and spring.
Evaporation severe; beach usually has several inches of dry surface sand except soon after heavy rain, although subsurface moisture is usually greater than field capacity.	Evaporation much reduced; beach surface is usually moist.
Beach plantings require irrigation to prepare planting surface or planting soon after a heavy rain.	Beach plantings do not require irrigation to prepare planting surface except after prolonged drought.
Climate is unsuitable for prolonged physical labor during much of the day.	Climate is usually more suitable for physical labor.
Winds are typically southeast. Sand movement is predictable; elevated, barren dune plantings are less likely to be eroded or buried.	Winds are variable; sand movement unpredictable. Elevated plantings often buried or eroded.
Transplants require extra care (storage in freshwater or partial burial in wet sand) to prevent dessication between digging and planting.	Usually no extra care is required.

Bitter panicum survival was generally higher than sea oats. Of 70 plantings, 11 were over 75 percent; 24 over 50 percent; and 46 over 25 percent survival. In only 21 of 70 paired plantings did the survival of sea oats exceed that of bitter panicum. This is one reason bitter panicum is the better choice of the two species for transplanting.

g. Selection of Transplants. Bitter panicum and sea oats were tested to determine if variations in transplant material affected survival rates. These transplant variations included: number of culms per clump, size of culm, and presence or absence of a root system for sea oats; and size of culm, age of culm (tillers versus primary culms), and root system for bitter panicum.

(1) Sea Oats. During 1969-70, comparisons were made of the survival of sea oats clumps, consisting of one, three, and six culms per clump, at 7-month intervals (Table 34). Clump size had little influence on sea oats survival for the optimum January 1970 period.

Table 34. Clump size versus survival of sea oats on Padre Island.[1]

Culms per clump	Percent survival of clumps							Total
	1969			1970				
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	
North Padre								
1	0	5	5	79	31	12	6	20 a, b[2]
3	10	1	13	53	32	20	5	19 a, b
6	8	4	31	77	57	27	4	30 a
South Padre								
1	0	0	2	14	0	1	18	5 b
3	0	0	5	29	3	1	19	8 b
6	0	0	7	29	31	1	33	14 a, b

1. N = 150 clumps.
2. Means sharing a common letter are not significantly different ($P_{0.05}$).

The larger clumps did enhance survival for plantings made during less than optimum conditions. When transplanting conditions were poor, plants survived poorly regardless of clump size. The additional time and planting material required for multiculm clumps make this an unattractive alternative, particularly since no advantage was obtained during the best season and with the best planting conditions.

In 1973-74, single-culm sea oats transplants were segregated into four discrete sizes and planted over 7 months (Table 35). Size variation is attributable to culm age, although exact figures are unknown. Three sizes, from very small to large, are in the same clump: the small sizes are generally young tillers and the very small culms are usually very young (seedling)

Table 35. Survival of culm-size classes of sea oats transplants on north Padre Island.[1]

Culm class	Total length (feet)	Mean net weight per culm (grams)	Percent survival							
			1973					1974		Total
			Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	
Large	4 to 5	74	10	32	26	18	4	36	12	20 a[2]
Medium	2.5 to 3.5	27	4	12	26	22	6	30	8	15 a, b
Small	1.5 to 2.5	10	2	24	6	8	2	8	40	13 b
Very small	<1.5	4.5	2	20	22	0	0	2	26	10 b

1. N = 50 plants.
2. Means sharing common letters are not significantly different ($P_{0.05}$).

clumps. Most large culms are found in the center of a fairly large hummock dune and are buried deeply, indicating they are several years old. Large culms had the highest average survival rate, while very small culms had the lowest. Differences within months were variable and no clear pattern was evident except for January. Small and very small culms were probably adversely affected by sand deposition before growth had begun. The difficulty of obtaining large culms, which are comparatively rare and deeply buried, negates any survival benefit. Five or more small culms can easily be procured in the same time as one large culm. However, large culms attained sand-trapping size faster than the smallest.

Limited testing (2 months, 100 plants each per month) of sea oats culms with roots versus without roots gave variable results. In January 1974, rooted culms of small and very small sizes had 5 percent survival, while nonrooted culms of the same size had 7 percent survival. In February, rooted culms had 33 percent survival compared with only 2 percent for nonrooted culms. Woodhouse, Seneca, and Cooper (1968) found that nonrooted sea oats culms had only slightly lower survival (87 percent versus 97 percent), and made satisfactory transplants.

(2) Bitter Panicum. In 1973, bitter panicum culms with a well developed root system and without roots were compared for relative survival. In contrast to sea oats, many bitter panicum culms have no roots, especially during winter when culms are brittle and easily broken near the surface. Results (Table 36) showed no mean difference between the two

Table 36. Percent survival of bitter panicum transplants on north Padre Island, 1973.[1]

Transplants	Mar.	Aug.	Sept.	Oct.	Nov.	Total[2]
With roots	79	89	79	28	45	64
Without roots	57	84	81	46	62	66

1. N = 100 plants.
2. No significant difference ($P_{0.05}$) between totals.

categories, although in October and November, nonrooted culms had higher survival than rooted culms. No explanation for this is known. Comparative growth rates (Fig. 29) showed that rooted transplants exhibited less transplant shock and began regrowth more quickly in summer. However, after a short period, this difference was no longer evident. The conclusion was that there is no advantage to selecting rooted over nonrooted stock.

Bitter panicum culm size had a decided effect on survival (Table 37). The small size included the smallest available primary culms, generally too slight for mechanical transplanting. Small-culm survival was significantly less than for larger, more robust primary culms, which were the typical size of fertilized nursery stock or young expanding wild stands. Small culms are typically found in old, stabilized stands. Fertilization will increase the size considerably. The reason for the differential survival is unclear but may be related to relative amount of food storage. In selecting transplant material during winter, larger primary culms should be selected over smaller primary culms.

Table 37. Survival of bitter panicum primary culms on north Padre Island.[1]

Size	Total length (feet)	Average culm weight[2] (grams)	Percent survival[3]		
			1973	1974	
			Mar.	Jan.	Feb.
Large	> 2.0	25 to 30	79 a[4]	77 a	78 a
Small	< 1.0	5	5 c	10 c	26 b

1. Previous year's growth.
2. All but terminal leaves dry; culm brittle.
3. N = 150 plants, March; N = 100, January and February.
4. Figures sharing common letters are not significantly different ($P_{0.05}$).

During fall and spring, two basic bitter panicum culms are available: primary culms and tillers (Fig. 30). Primary culms consist of the previous year's growth, and are mature, have flowered, and are generally dry and brittle. Most lower leaves are dead, although terminal leaves may remain green. In areas of light sand deposition, the culms are often a yard or more long. In contrast, tillers during the same period are actively growing; the leaves are green and the culm is succulent, but the size is usually smaller. During spring through fall, tillers are abundant. By fall, many have matured, flowered, and become primary culms. Comparison of survival and growth of tillers versus primary culms (Table 38 and Fig. 29) shows that tillers with new growth were a superior choice over primary culms from late spring through summer. When transplanted to the beach during this period, tillers responded with rapid establishment and growth. However, from fall through spring primary culms were the best choice. During this period, tillers began growth quickly after transplanting, especially during warm weather, but soon became semidormant and many did not survive through spring.

Figure 30. Selection of transplant material. Upper photo shows sea oats in sizes large through very small. Largest culms had best transplant survival and grew more rapidly, but are the most difficult to procure. Any size is satisfactory for planting. Lower photo shows bitter panicum with young, actively growing tillers (right of ruler) and larger, mature primary culms (left of ruler). Primary culms were best for fall through early spring planting; in late spring and summer, tillers had high survival combined with rapid establishment.

Table 38. Survival of tillers versus primary culms of bitter panicum transplants, Padre Island.[1]

Transplants	Percent survival								
	1973				1974				
	June	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May
North Padre									
Tillers[2]	91	37	54	27	----	40	16	52	72
Primary culms[3]	62	75	89	78	----	80	78	48	26
South Padre									
Tillers	----	----	----	----	57	6	----	----	----
Primary culms	----	----	----	----	59	39	----	----	----

1. Monthly plantings, 1973 and 1974. N = 100 plants.
2. Actively growing, young tillers selected from perimeter of panicum clump (leaves green, stems and leaves succulent).
3. Previous year's growth, selected from center of panicum clump. Comparatively inactive; in winter few leaves are green, while in spring and summer some lateral and apical leaves are green, but main culm is dry and brittle (Fig. 30).

Bitter panicum culms must be trimmed to a length of 12 to 15 inches for mechanical transplanting. Primary culms are often twice as long, and can be segmented into two or more equal-sized transplants. An experiment in 1974 determined the effect of segmentation on survival rates (Table 39). Comparisons were between 1-yard-long primary culms, and similar 1-yard culms broken in two segments (top and bottom half). None had a root system, since the original culms were harvested at ground level.

In the January planting, the entire and bottom-half segments had higher survival than the top half, while in February the reverse was true. The conclusion from this experiment is that

Table 39. Comparison of survival of segmented and entire bitter panicum culms.[1]

Culm description[2]	Percent survival		
	Jan.	Feb.	Total
Entire	82 a[3]	52 d	67
Bottom half	87 a	65 b, c	76
Top half	58 c, d	76 a, b	67

1. From two 1974 plantings. N = 100 plants.
2. Each planting, 200 large (1 yard, 50 gram) culms were procured and mixed; 100 were separated and planted intact (entire); the remaining 100 were broken in half and planted (bottom half, top half).
3. Figures sharing a common letter are not significantly different ($P_{0.05}$).

the number of bitter panicum transplants can be increased by segmenting large primary culms. Survival potential is not reduced, and the segmented culms are more easily handled than entire ones.

4. **Planting Procedures.**

a. Selecting the Appropriate Procedures. Foredunes were established in two general locations: (a) broad overwash areas (4 to 6 feet MSL), where foredunes have been eroded by hurricanes or destroyed by blowouts; and (b) across hurricane washover channels, of lower elevation behind the berm and more susceptible to surges. Two general techniques of foredune construction were tested: (a) planting directly on the open beach at the original elevation; and (b) constructing barren foredunes with sand fencing, and planting after the dune line formed. Additionally, the same techniques were applied to stabilize a wind-eroding (blowout) natural foredune, and to stabilize several extensive barren areas behind the foredunes (oil well drilling pad; and an active dune field encroaching upon a road).

b. Planting on Level Sites. The least costly, easiest, and generally most successful method of establishing a vegetated dune was by transplanting directly onto the level backshore, in areas where the original dune was eroded by broad overwash or denuded and then wind-eroded. No special preparations were required since subsurface moisture was usually high enough for survival and wind erosion of the planting surface did not normally occur. The plantings approximated the original location of the dune line, and were between 350 and 500 feet inland from the shoreline.

All the north Padre plots and several in the south were established on this type of site. Photo sequences of three major beach plantings are shown in Figure 31 (1,200-foot sea oats dune, north Padre); Figure 32 (1,000-foot bitter pancium dune, north Padre); and Figure 33 (south 400-foot sea oats dune on south Padre).

c. Planting Across Overwash Channels. In hurricane overwash channels, periodic storm surges leave soils with salinity levels more toxic to transplants than on nonchanneled barren backshore areas of higher elevation. From 1969 to 1971, plantings made in several south Padre passes were unsuccessful.

To close the passes with vegetated dunes, soil salinity must be lowered to allow transplant survival by elevating the planting surface high enough to prevent frequent saltwater inundation. Parallel 2-foot-high sand fences placed 8 to 12 feet apart at a width of 50 feet will create a flat-topped, broad, low dune relatively free of salt. Fences across two south Padre passes were filled with sand and ready for planting within a year after erection. Subsurface soil salinity of an unaltered washover pass during winter 1971-72 averaged 2,800 micromhos per centimeter, while during the same period, the elevated 2-foot dune averaged only 500 micromhos per centimeter. Parallel 2-foot sand fencing was used with excellent success to establish young dunes (1.5 years after planting) across two overwash channels where normal planting methods resulted in total failure. A photo sequence of a 2-foot fence planting is shown in Figure 34. On these dunes, mulching is not required, but irrigation may be necessary during drought.

After 4 months, July 1969

After 18 months, September 1970

After 28 months, July 1971

After 64 months, July 1974

Figure 31. Twin Batteries 1,200-foot section planted March 1969, with sea oats and saltmeadow cordgrass.

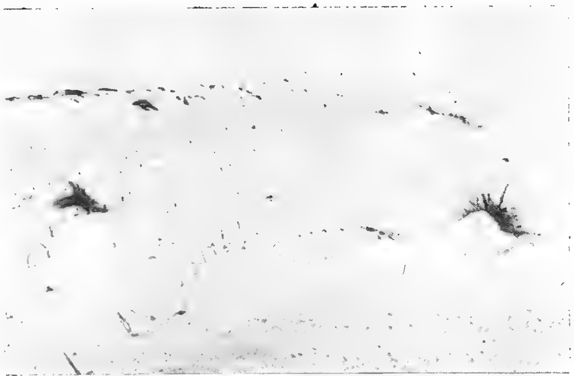
After 5 months, July 1970

After 7 months, September 1970

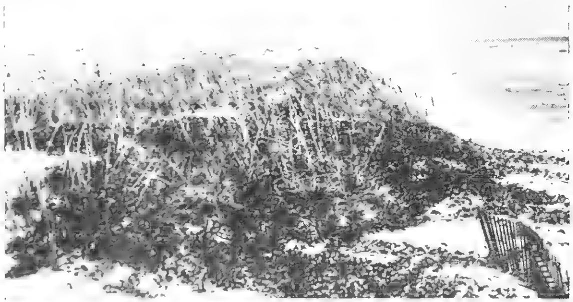
After 18 months, August 1971

After 53 months, July 1974

Figure 32. Bitter panicum (1,100-foot plot) planted on north Padre Island, February 1970.


Initial planting, February 1969


After 17 months, July 1970


After 29 months, July 1971


After 53 months, July 1973

Figure 33. South 400-foot sea oats planting on south Padre Island. Dark, prostrate plant in lower right photo is railroad vine, a natural invader.

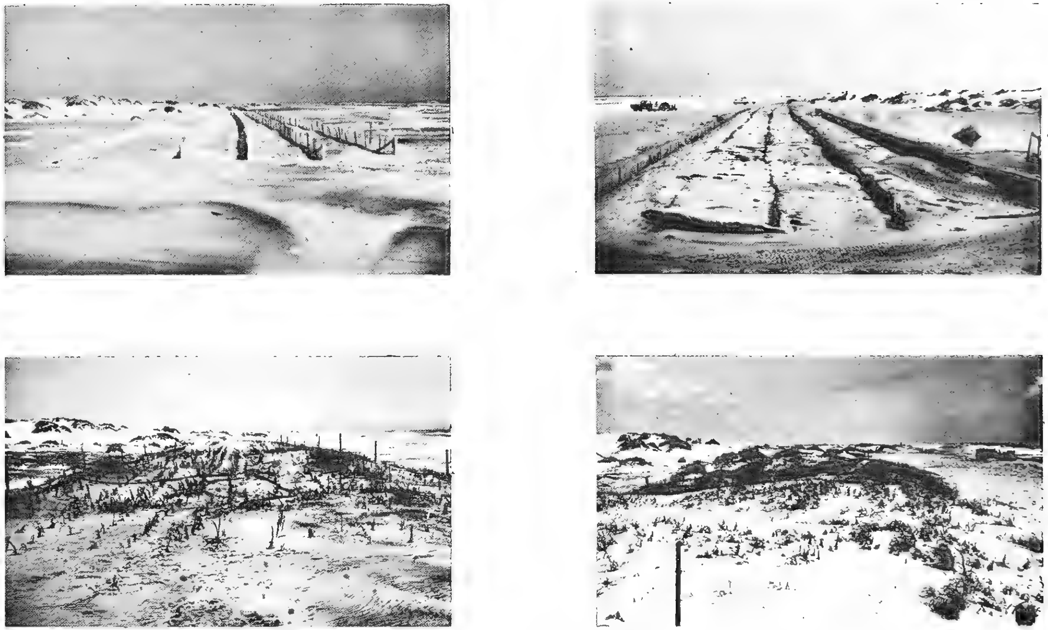


Figure 34. Two-foot-high pocket fences used for elevating the planting surface across a hurricane washover channel (Pass No.4, south Padre). Newly installed fence (upper left), November 1971; fence partially filled with sand, immediately after saltwater inundation (upper right), April 1972 (panicum planted here in December 1971 had poor survival); fences filled with sand (lower left, March 1973) were planted in bitter panicum and sea oats 1 month earlier and irrigated; photo in lower right shows planting 14 months later (April 1974).

d. Planting on Fence-Constructed Dunes. Fabric and wooden picket sand fencing has been used to build foredune barriers and temporarily halt free-drifting sand (Savage and Woodhouse, 1968; Gage, 1970). Sand blown inland from the beach is trapped by one or several parallel rows of 4-foot-high fencing, until a dune has built to nearly the fence top, at which point the dune grows no higher. Using different configurations of sand fencing, the U.S. Army Engineer District, Galveston, conducted experiments concurrently with the vegetation-grown dunes on south Padre.

Practical problems of fence-constructed dunes are: (a) there is a limit to the dune height a single tier of fence can build, and more height is achieved only by adding tiers; (b) fence material deteriorates in time and the barren dune is only temporary unless periodically maintained; and (c) the sand surface is unstable and shifting winds may change the dune configuration.

These problems would be greatly reduced if dune-building grasses were planted after the sand fences fill with sand and before the dunes begin to deteriorate. The sand would then stabilize and allow the dune to continue growth without maintenance.

Methods of establishing vegetation were tested on about 2,000 linear feet of barren fence-built dunes, from 50 to 90 feet wide, in 1972-73 on south Padre. Problems of dune stabilization were different from the establishment of plants on the original backshore elevation because: (a) soil salinity on the dunes was low and probably had little effect on survival; (b) moisture was also low, and the addition of beach-blown dry sand plus rapid drying of the surface made supplemental irrigation necessary; and (c) instability of the substrate and rapid drying and shifting of sands, even during periods of wet weather, made a sand-stabilizing mulch essential. A major source of transplant mortality in 1973 was burial by drifting sand after spring planting, when strong, predominantly onshore winds transported a large volume of sand across the foreslope and deposited several feet of sand on the backslope. Plants survived better and more uniformly on the foreslope. In 1972, however, burial was not a problem.

With irrigation and mulch-netting, a uniform vegetative cover on fence-built dunes within 1 year after planting is possible (Fig. 35). However, the cost of fencing, irrigation, mulching, and the irregular survival from sand burial, make dune establishment by planting on the original beach a more attractive alternative. A benefit of establishing a dune by fencing is that sand accumulation and dune growth begin as soon as fences are erected, and some protection is achieved quickly.

e. Planting on Deteriorating Foredunes. In March 1974, with the cooperation of personnel from the national seashore, an effort was made to halt the wind erosion of a large and scenic foredune on north Padre. A foot trail to the crest allowed prevailing winds to scour out a large part of the dune face; without intervention the dune would be destroyed. After transplanting bitter panicum on 18-inch centers and stabilizing with mulch-netting, an excellent vegetative cover was reestablished, and erosion was halted (Fig. 36). Irrigation was

February planting without mulch-netting

February planting without mulch-netting after 3 months

February planting with mulch-netting after 3 months

February planting with mulch-netting after 7 months.

Figure 35. Transplanting bitter panicum on fence-built dunes with and without mulch-netting, 1972.

Large blowout on actively eroding north Padre foredune

Placing mulch-netting after hand planting bitter panicum, March 1974

Blowout 4 months after planting, July 1974

Figure 36. Techniques used to stabilize an active blowout on natural foredune.

not needed, but may be necessary for other dunes during a drought. This technique could be used in similar foredune blowouts, especially in areas with heavy visitor usage where trampling of dune faces and foot trails initiates active blowouts.

f. Hand-Machine Method of Planting. For major backshore plantings, a two-row tobacco transplanter pulled by a rubber-tire tractor was used. The transplanter seats four men, who feed plants into trays where they are picked up by rotating arms and placed in a vertical position in 8-inch-deep furrows. Sand is packed tightly against the plants by packing wheels. On reasonably flat surfaces, the transplanter functions well, and is recommended for any extensive beach plantings. The only drawback is the lack of precise depth control on undulatory surfaces, e.g., small dunes of barren sand or sea purslane on the backshore. Transplants must be trimmed to about 12 to 15 inches in length to pass through the machine without binding.

The mechanical transplanter was unsatisfactory for planting on slopes of fence-built dunes and on uneven surfaces of the 2-foot-high sand-fence dunes used in hurricane washover passes. The tractor could not be held steady on the slopes and on the uneven terrain, and many plants were seated too shallowly (less than 6 inches). Thus, for any planting other than on the flat backshore, hand labor is required. The hand-planting operation was most efficient by the use of several two-man crews. One man with a sharpshooter shovel opens a 12-inch-deep hole; the other follows with a supply of plants, positions the culms, and closes the hole with the heel of his foot. Hand planting on elevated surfaces allows deeper culm placement, which helps reduce wind excavation where mulching is not used, and also reduces the possibility of the soil becoming dry at the root zone after planting.

Beach sites can be planted by hand but the higher soil moisture and more densely packed sand relative to elevated sites make this more laborious. Even if the top 1 or 2 inches of surface sand are dry, hand planting is slowed considerably since the dry sand must first be shoveled away. Otherwise, the hole fills with sand as it is dug. In contrast, the transplanter penetrates dry surface sand, positions, and packs the culm in moist subsurface sand.

g. Erect-Horizontal Method of Planting. Mechanically transplanted and hand-transplanted culms were placed vertically, usually with one-half or more of the culm protruding above the surface. Due to the horizontal rhizomatic growth of both bitter panicum and sea oats, it was thought that horizontal positioning of the culms would be a more satisfactory planting method, especially with bitter panicum which can produce roots or tillers at any of the separated nodes. A series of monthly plantings comparing vertical with horizontal planting for both species was made during 1972-73. Horizontal plantings were made by digging a 6-inch-deep trench with a shovel, and placing the transplant lengthwise in the trench with only the terminal leaves exposed after the trench was refilled with sand. This method resulted in poorer survival for both species than erect planting (Table 40). Apparently 6-inch-deep horizontal transplants are more vulnerable to total burial by sand drifts. In addition to poorer survival, horizontal hand planting required a greater expenditure of energy and time.

Table 40. Comparison of percent survival of vertical and horizontal plantings of sea oats and bitter panicum.[1]

Planting	Bitter panicum				Sea oats			
	North Padre		South Padre		North Padre		South Padre	
	H[2]	V[3]	H	V	H	V	H	V
Sept. 1972	6	4	----	----	0	6	----	----
Oct.	12	0	----	----	0	16	----	----
Nov.	30	30	3	0	2	6	0	5
Dec.	6	24	0	12	0	2	14	26
Jan. 1973	12	10	40	40	26	26	33[4]	43[4]
Feb.	20	34	21[4]	33[4]	20	60	17[4]	81[4]
Mar.	30	62	20	38	0	0	0	0
Apr.	48	68	18	46	0	34	0	4
May	58	70	----	----	0	8	----	----
Total	25[5]	34	17[5]	28	5[5]	18	11[5]	27

1. Nonirrigated only; N = 50 plants.
2. Horizontal: culms laid horizontally in 6-inch-deep trench and covered with sand.
3. Vertical: culms planted 8 inches deep, erect.
4. N = 42 plants.
5. Mean totals of each pair (horizontal versus vertical) are significantly different ($P_{0.01}$).

When planting areas where drifting sand is not a problem, a combination of mechanical and hand planting can be used successfully. The transplanter is positioned so the packing wheels are off the ground, and an 8-inch-deep furrow is dug with the blade. The crew walks behind the tractor dropping untrimmed transplants horizontally into the furrows, which are then closed by heeling. This method was used successfully on two 400-foot-long beach plantings in 1973. The only limitations are that drifting sand should be minimal, and the soil, including the surface, must be moist so that the furrows remain open.

h. Time-Cost Analysis of Method of Planting. Time-cost analysis in man-hours for the mechanical and hand-planting methods is given in Tables 41 and 42. This information should be considered as a guideline only, since variables such as labor crew experience, planting conditions, and distance to planting site from nursery or harvest locations, affect the planting time. All data for hand planting assume ideal soil conditions.

i. Density of Planting. Optimum transplant spacing is dependent on the resulting survival. Most plantings for Padre Island were on 2-foot centers, i.e., 2 feet between rows and 2 feet between plants within rows. This seems the best spacing for transplant survival of 25 to 50 percent. Survival approaching 100 percent would permit 3-foot-center spacing without reducing sand-trapping efficiency. Since survival this high is rare except in protected plantings, e.g., a nursery, a planting on 2-foot centers is recommended.

Table 41. Time-cost analysis for three methods of planting at two sites on Padre Island.[1]

Methods	Beach			Elevated sand-fence dune
	Mechanical planting		Hand shovel[2]	Hand shovel[2]
	Vertical[3]	Horizontal in furrows[4]		
Bitter panicum				
Harvesting		1.5	1.5	1.5
Processing		none	none	none
Planting		1.7	4.0	2.3
Total	4.3[5]	3.2	5.5	3.8
Sea oats				
Harvesting		3.8	3.8	3.8
Processing		none	none	none
Planting		1.7	4.0	2.3
Total	7.6[5]	5.5	7.8	6.1

1. Expressed as man-hours per 1,000 culms.
2. Subcrews of one man digging, one man planting. Figures are for thoroughly moist planting surface only; dry surface sand increases planting time.
3. Crew seated on transplanter.
4. Crew walking behind transplanter; method limited to level site with moist sand.
5. Total figure available only. Includes processing (trimming leaves from culm).

Table 42. Time-cost in man-hours for a 50-foot-wide planting, using three planting methods and two sites.[1]

Size of planting (feet)	Beach			Elevated sand-fence dune
	Mechanical planting		Hand shovel[2]	Hand shovel[2]
	Vertical[3]	Horizontal in furrows[4]		
Bitter panicum				
50 by 400	22	16	28	19
50 by 5,280	287	211	363	251
Sea oats				
50 by 400	38	28	39	31
50 by 5,280	500	363	514	403

1. Plants are spaced on 2-foot centers (2 feet between rows and between plants within rows).
2. Figures are for thoroughly moist planting surface.
3. Crew seated on transplanter.
4. Crew walking behind transplanter; method limited to level site with moist sand.

The benefit of high survival to sand-trapping efficiency is most noticeable during the first year of dune growth. After the first year, plantings with low density survival have filled in sufficiently to trap sand at a maximum rate, as illustrated by the 1,200-foot dune-width panicum planting on north Padre. The north half of this planting (Fig. 37) was made in February 1972, on 2-foot centers; survival was 76 percent. The south half (Fig. 38) was planted in April 1972, with 4-foot rows, and 2-foot centers within rows. Survival was 36 percent, but the density of surviving plants compared with a 2-foot-center planting was only 18 percent. Thus, the surviving plant density of the north half was over 4 times that of the south half. First-year sand accumulation was much greater for the north half when comparing May 1973 profiles between Figures 37 and 38, but subsequent growth was nearly equal. The south half is now a uniform dune, trapping all available sand, and is only slightly smaller than the north half.

Generally, a 2-foot center planting with 20 percent or greater survival is sufficient to yield maximum dune growth after the first year, although higher survival density results in more rapid early dune growth. There also was good success on a sea oats planting with only 8 percent survival (south 400-foot sea oats, south Padre), although it normally would be advisable to replant areas with survival this low.

j. Width of Planting. To build a foredune quickly, all available blowing sand should be trapped. Foredune construction costs are closely related to the number of culms planted; therefore, it is important to determine the minimum planting width which will trap all available sand. The 1,200-foot dune-width panicum plot, discussed previously, was planted for this purpose. Four alternating blocks of two different widths (50 by 300 feet, and 100 by 300 feet) were planted with bitter panicum in February and April 1972. Dune profiles up to 2 years after planting (Figs. 37 and 38) showed that only the shoreward 50 feet of either planting (high or low transplant survival) trapped sand for dune growth. No sand reached the west half of the 100-foot-wide blocks, except for a small ridge at the extreme west edge, which represented sand blown from behind the beach during "northers". A photo sequence of the north half of this dune is shown in Figure 39.

Conclusions from this experiment are: (a) initial plantings of greater than 50-foot width did not result in improved dune growth, and culms planted in excess of 50 feet were not used in trapping sand; and (b) the source of sand available for dune growth was almost exclusively from the beach east of the planting, and only about 10 percent originated from the west.

k. Preparing the Field for Planting: Preplanting Irrigation. On elevated surfaces, such as fence-built dunes, soil moisture was typically low (around 4 percent), and evaporation from the surface layer was rapid. Leeward drifts up to several feet deep of wind-dried sand were regular. Irrigation proved an essential preplanting procedure on all elevated surfaces except during and soon after heavy rains. Also preplanting irrigation may be useful for winter beach plantings during prolonged droughts, or any time in summer except the first week after a

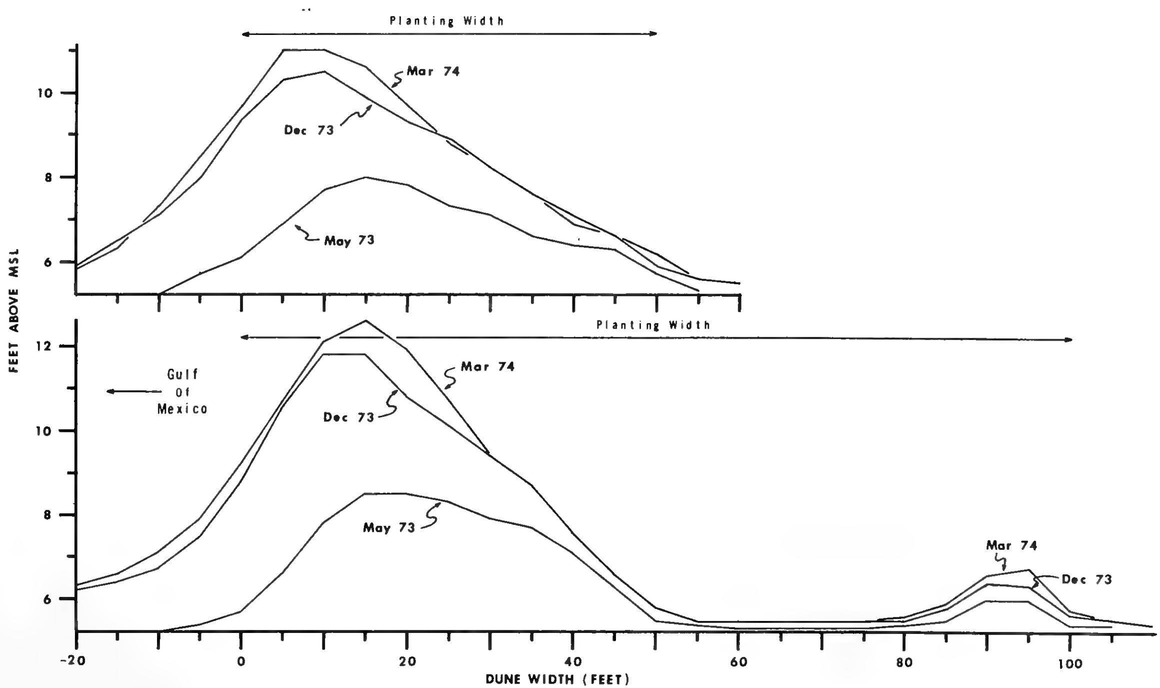


Figure 37. Mean cross-sectional profiles for north half of 1,200-foot bitter panicum dune-width plot, north Padre; 0- to 300-foot section at top, and 300- to 600-foot section at bottom. Initial planting was in February 1972; planting surface was 5.2 feet MSL. Each is the mean of 12 (May) or 6 (December, March) profiles.

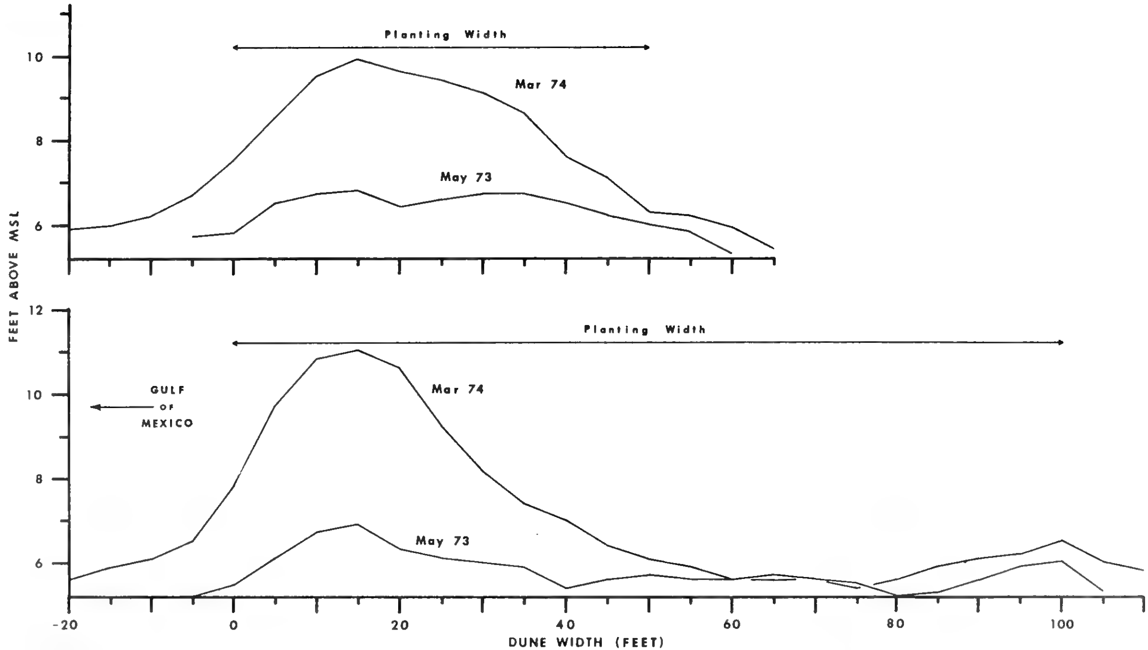


Figure 38. Mean cross-sectional profiles for south half of 1,200-foot bitter panicum dune-width plot, north Padre; 600- to 900-foot section at top, and 900- to 1,200-foot section at bottom. Initial planting was in April 1972; planting surface was 5.2 feet MSL. Each is the mean of three (May) or five (March) profiles.

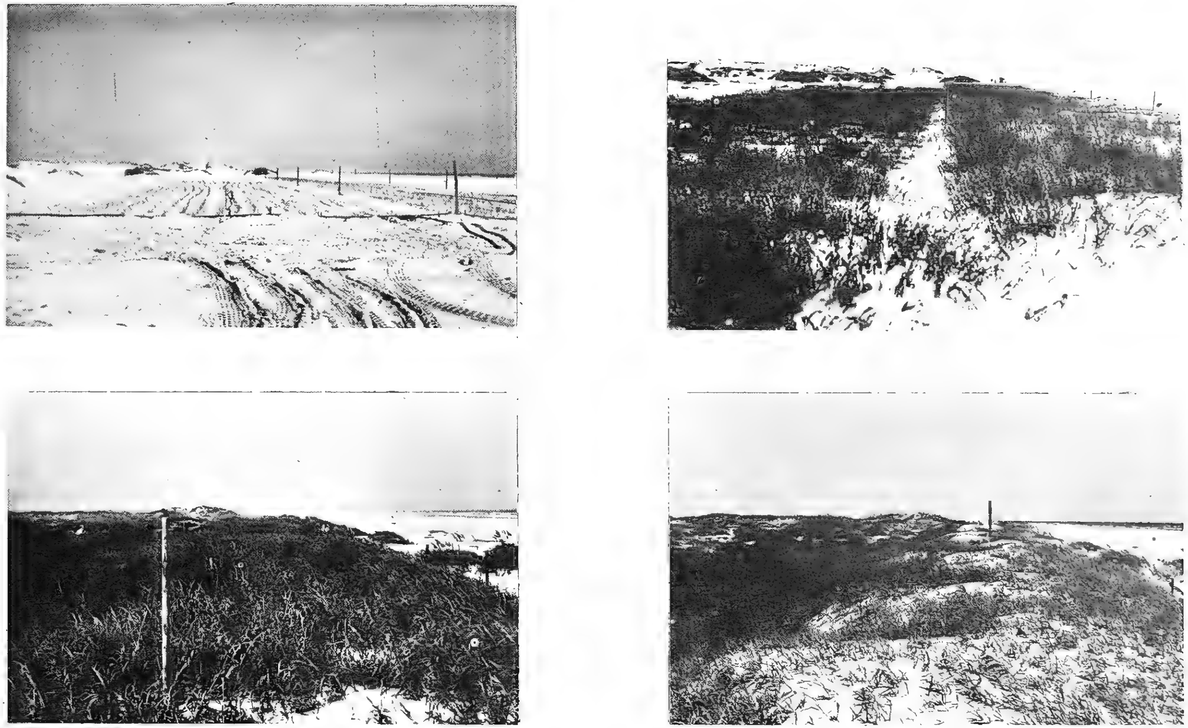


Figure 39. North half (0 to 600 feet) bitter panicum dune-width plot planted February 1972. Upper left photo taken immediately after planting 300- by 100-foot section in foreground and 300- by 50-foot sections in background. Upper right photo shows planting after 11 months (January 1973); lower left after 19 months (September 1973); and lower right after 29 months (July 1974). Note that east 50-foot width has trapped nearly all the sand.

soaking rain. The factor determining irrigation need is the amount of dry surface sand overlaying the moist sand. Except during droughts, moist sand on the backshore is less than 6 inches deep. Hand planting requires less than 2 inches of dry surface sand; otherwise, the dry sand fills each hole when dug. Therefore, hand planting is time consuming and costly. Machine transplanting can be successful with several inches of dry surface sand.

In hand planting 1,800 linear feet of a south Padre fence-built dune (North Section Fence) in 1973, all sites were irrigated before planting, with satisfactory results. Although the winter was wetter than normal, irrigation was essential except for a few sections planted soon after a soaking rain.

The irrigation system consisted of sprinklers spaced at 40-foot intervals along a line of 1.5-inch flexible plastic pipe. The freshwater source was a series of pits, each about 40 feet square and 5 feet deep, dug with a backhoe behind the artificial dune line, and protected from blowing sand with fencing around the perimeter of the pit. Average time of excavation was 3 to 5 hours; pit capacity was about 18,000 gallons, but this varied during periods of rainfall or drought. Pits excavated in 1973 had partially filled with sand but still contained water in 1974, even though drought conditions prevailed from November 1973, to the summer of 1974. In 1973, a pit pumped dry at the end of the first day was more than half full the second day, and completely full of water on the third day. Salinity of the irrigation water varied and was not predictable; therefore, it was essential to test a water sample from the site before excavating the pit. Ideal irrigation water salinity (undiluted) is less than 2,000 micromhos per centimeter (about 5 percent seawater); however, up to 5,000 micromhos per centimeter is tolerable. Irrigation water with a salinity of 15,000 micromhos per centimeter caused salt damage to leaves of both sea oats and bitter panicum, and most plants died, although soil salinity did not exceed 600 micromhos per centimeter (2:1 dilution).

A single irrigation line with 10 sprinklers effectively watered a strip 40 to 50 feet wide by 400 feet long at an equivalent precipitation rate of 0.22 inches per hour. Mean output per sprinkler was 3.5 gallons per minute, with a range of 3.2 to 3.8 depending on distance from the pump. For a five-sprinkler system, 200 feet long, the average output was 3.8 gallons per minute. Moistening a 6-inch layer of dry surface sand usually takes 1 day of irrigation.

l. Preparing the Field for Planting: Grading. The backshore often has irregular low drifts of shifting sand and low dunes temporarily stabilized by sea purslane, which cause undulations in the planting surface and form localized areas where dry sand is too deep for planting. The problem was eliminated on several plantings by grading the planting surface with a bulldozer before planting. However, this is unnecessary unless low dunes of dry sand are common.

m. Mulch-Netting. On south Padre, plantings were made in 1972-73 on the slopes of barren dunes built with sand fencing. Plantings not protected from wind were eroded and the transplants excavated (Fig. 35). Therefore, to stabilize the dunes with vegetation, mulching, or netting materials were needed to prevent sand movement for the first few months after planting.

Materials tested in 1972 as sand binders were a 7.5-ounce burlap and an open-weave, 0.5- by 2.5-inch netting (Fig. 40). Both materials were placed on the slopes of fence-built dunes over horizontally transplanted culms of bitter panicum and secured to the sand with 6-inch staples. The open-weave netting was easier for the leaf blades of the transplants to grow through without raising the netting off the ground. In the 1972 trials, the open-weave netting proved satisfactory, containing sand in winds of 30 miles per hour, except on the windward edge. Here, sand adjacent to the netting was excavated and the netting undermined.

In the 1973 plantings, about 60,000 square feet of the open-weave netting were used on slopes of the North Section Fence including the foreslope. All plantings, including bitter panicum and sea oats, were placed vertically and were untrimmed. The netting was placed over the vertical culms, stretched tight and secured to the sand with staples. Since most of the culms protruded from the ground and the netting was above the soil in many places, the netting was raised 6 to 8 inches. Nevertheless, the mulch net was 100 percent effective in preventing wind excavation of the transplants. None was lost on the critical foreslope whereas unmulched areas suffered sporadic and locally severe wind erosion. Since vertical placement of transplants by hand is less tedious and costly than horizontal hand planting on slopes, and since the netting is effective when not completely in contact with the ground, vertical transplanting followed by covering with the open-weave mulch net is recommended.

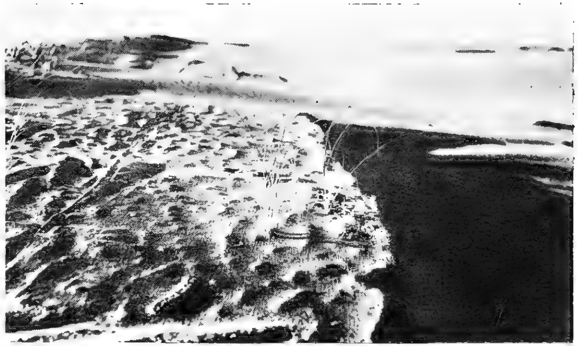
In 1972, burlap proved to be a better sand binder than the netting but was more expensive. Since the open weave is satisfactory, it is recommended over burlap. Both materials begin to decay after 2 or 3 months, but in some areas the open-weave netting was still intact and binding sand after 15 months.

The netting is most easily spread with a four-man crew; two spread the netting over the plants while the other two secure it to the sand with metal staples. The process requires about 1 man-hour per 2,500 square feet of netting, or a single strip 667 feet long. To completely cover a 400- by 50-foot dune with netting would require about 8 man-hours.

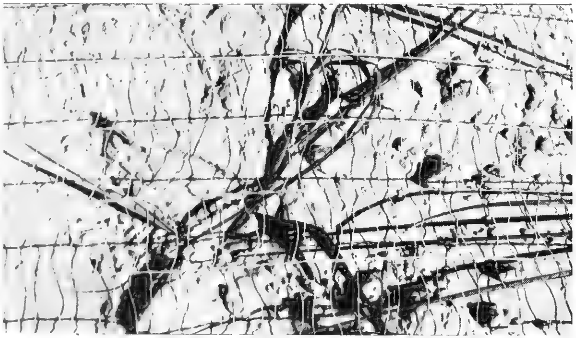
5. Postplanting Care.

a. Irrigation. Preplanting irrigation is necessary on elevated surfaces, except after a soaking rain. Since transplant survival of monthly plantings was positively correlated with high soil moisture, it was believed a program of regular irrigation for several months after planting would improve survival. Accordingly, all North Section Fence plantings were irrigated for 3 months after replanting. Comparisons between irrigated and nonirrigated plantings were made in 1973 at both north and south Padre monthly planting sites. Each planting was irrigated several times per month for 3 months. During March through May,

Burlap (7.5 ounces)



Burlap on a fence-built dune



Open-weave netting (0.5 by 2.5 inches)

Open-weave netting on fence-built dune

Figure 40. Mulch-netting for increased plant survival.

rainfall was low on both ends of the island, although it was high in winter. Table 43 shows the effect of postplanting irrigation on survival—there was little or no improvement in survival of either species. In July, plantings were irrigated heavily for 10 days after planting to test the possibility that the amount of irrigation of winter and spring plantings was too light. Results (Table 44) show no difference in survival of either species. These data agree with the conclusion from preliminary 1972 trials that postplanting irrigation does not improve plant survival sufficiently to warrant the time and expense. This conclusion may not be valid during extended drought, but with average or above average rainfall, natural precipitation is sufficient.

The reason irrigation had little effect on transplant survival is probably because it did not increase subsurface soil moisture (Table 45). On elevated surfaces (2-foot sand fence), soil moisture was usually near field capacity. Excess water drained through the soil pores and was not retained. Here, irrigation brought the surface layer of dry sand up to field capacity, but the subsurface layer was unaffected. On the backshore, the soil was not freely drained, and the soil moisture, usually in excess of field capacity, was partly dependent upon the water-table depth, normally about 2 feet beneath the surface. Water added by irrigation appeared to drain through the sand without affecting the water table. Only by raising the water table with heavy rainfall can backshore soil moisture be increased for longer than a few hours. However, irrigation partially leached heavy salt concentrations out of the backshore soil, which had occurred as a result of inundations not followed by rain (Table 45). On the elevated sand-fence dune, irrigation slightly increased soil salinity, since the irrigation water was moderately saline (3,000 micromhos per centimeter).

b. Nutrients. Several reports indicate windborne sand from the beach is higher in plant nutrients than stable sand or old dunes (Gorham, 1958; Wagner, 1964; Woodhouse, Seneca, and Cooper, 1968). Wagner found that sea oats grew more vigorously on foredune sites with accumulating sand than on interdunes and hind dunes. This could be attributed to higher nutrient content of the fresh sand and the additional area of sand from which nutrients may be drawn. A stabilized dune would presumably have lower nutrient content, and the root system of dune plants would be curtailed by increased competition.

Contrary to the above references, project analysis of Padre Island sands indicated a low level of many nutrients regardless of island location (Table 6). In June 1970, vegetative characteristics of sea oats were measured as an index of vigor to compare fertilized beach areas with nonfertilized plants growing on foredunes, interdunes, and hind dunes (Table 46). Vigor was evaluated by the weight of flowering culms per plant. This was chosen over number of leaves per shoot (Wagner, 1964) as Hyder and Sneva (1963) reported that the relative number of seed stalks is a better indicator for most species. Vigor measurements for this study were obtained by multiplying weight per flowering culm by number of flowering culms per plant.

Table 43. Percent survival of vertical plantings on Padre Island.

Planting date 1973	Sample size[1]	Sea oats		Bitter panicum	
		Irrigated	Nonirrigated	Irrigated	Nonirrigated
North Padre					
9 Jan.	50	38	26	28	10
19 Feb.	50	56	60	66	34
15 Mar.	50	0	0	60	62
15 Mar.	500	----	----	53	42
14 Apr.	50	42	34	68	68
13 May	50	26	8	56	70
14 June	100	9	18	75	78
15 July	100	38	37	94	93
Total[2]		28	26	60	53
South Padre					
7 Jan.	42	54	43	44	40
17 Feb.	42	54	81	32	33
1 Mar.	300	25	29	35	39
29 Mar.	50	10	0	44	38
29 Apr.	50	38	4	78	46
31 May	100	1	15	46	40
23 June	100	46	41	93	97
Total	684	28	29	49	48

1. Each column.
2. N (sea oats) = 450 each; N (panicum) = 950 each.

Table 44. Effect of heavy irrigation on survival of transplants on north Padre Island.[1]

Planting date	Irrigation, 15 to 24 July		July	Total[3]	Percent survival	
15 July 1973	Pump-hours	Artificial precipitation[2] (inches)	Rainfall (inches)	Precipitation[3] (inches)	Sea oats	Bitter panicum
Irrigated	31.5	8.8	1.0	9.8	38	94
Nonirrigated	-------	-----	1.0	1.0	37	93

1. N = 100 plants.
2. Irrigation system watered at equivalent precipitation rate of 0.28 inches per hour.
3. Irrigation plus rainfall.

Table 45. Comparison of soil moisture and soil salinity at 6-inch depth on Padre Island.

1973	Percent moisture		Salinity (μmho/cm)	
	Irrigated	Nonirrigated	Irrigated	Nonirrigated
		North Padre (beach)		
9 Feb.	16.2	8.2	250	80
13 Feb.	20.3	15.2	200	300
19 Feb.[1]	21.1	22.4	3,000	5,500
4 Mar.	19.8	16.0	280	1,850
17 Mar.	15.3	17.8	315	1,150
14 Apr.[2]	11.8	14.2	1,320	2,130
24 Apr.[3]	22.4	-------	2,125	---------
28 Apr.	-------	-------	450	2,025
14 May	17.3	18.4	883	1,116
15 June	19.1	20.5	64	174
		South Padre (2-foot sand fence elevated dune)		
13 Feb.	20.3	15.2	200	300
7 Mar.	8.0	3.0	125	50
31 Mar.	4.9	2.3	230	72
29 Apr.	9.0	2.8	516	482
12 May	3.6	2.2	334	65
31 May	2.8	2.0	225	400
24 June	7.6	9.6	43	40

1. Surge inundated site on 17 and 18 February.
2. Surge inundated site on 7 April.
3. Surge inundated site on 20, 21, and 22 April.

Table 46. Vigor measurements of sea oats for five sites in Nueces and Kleberg Counties, Texas.[1]

Area	Flowering culms (no.)	Leaves total (no.)	Culm width (mm)	Plant width (cm)	Basal leaves			Dry weight per culm (g)	Total weight culms (g)
					Leaf (no.)	Width (mm)	Length (mm)		
Nursery	4.2 a	36 a	27 b	17.8 a	5.6 b	12 b, c	106 d	21 f	99 a
Beach	2.4 b	21 b	26 b	5.9 b	4.9 c	13 a, b	101	36 b	87 a
Foredune									
Seashore	1.1 c	15 c, d, e	25 b	2.6 b	4.2 d, e	14 a	107 d	45 a	49 b
North Padre	1.0 c	9 f	20 c, d	1.9 b	4.1 d, e, f	12 b	107 d	35 b, c	35 b
Mustang	1.0 c	11 e, f	19 d	1.7 b	3.9 e, f	10 a, d	104	24 e, f	24 b
Interdune									
Seashore	1.1 c	19 b, c	25 b	3.7 b	3.8 f	12 b	119 b	29 c, d, e	32 b
North Padre	1.5 c	18 b, c, d	33 a	6.1 b	7.0 a	11 c, d	107 d	28 d, e, f	42 b
Mustang	1.5 c	21 b	22 c	7.6 b	3.9 e, f	10 d	118 b	23 f	34 b
Hind dune									
Seashore	1.4 c	24 b	26 b	4.9 b	4.3 d	11 c, d	120 a	31 b, c, d	43 b
North Padre	1.5 c	12 d, e, f	22 c, d	4.1 b	4.8 c	11 c, d	105	21 f	32 b
Mustang	1.4 c	20 b, c	22 c	3.4 b	4.4 d	10 d	110 c	24 e, f	34 b

1. Means not sharing a common letter are significantly ($P_{0.05}$) different from all others.

Sea oats from fertilized nursery and beach plantings were more vigorous than the natural unfertilized dune areas. Apparently, this resulted from the combined effect of fertilization and reduced competition by periodic weeding in the nursery and by the salt-spray environment on the beach. Boyce (1954) concluded that fertilized sea oats were less tolerant to salt spray than unfertilized sea oats in the dune habitat of the North Carolina Banks. No such evidence in fertilized plants was found on Padre Island. No differences in vigor were found among unfertilized foredunes, interdunes, and hind dune plants. If accumulating fresh sand provided extra nutrients to foredune plants, it was not sufficient to significantly increase sea oats vigor. However, compared to the beach planting, sea oats roots in all dune areas were prevented from exploiting their sites because of root competition from other plants growing in these more densely populated plant communities.

Padre Island data agree with the east coast researchers that sea oats grows most vigorously in sites of large sand accumulations. When stabilization approaches, sea oats' vigor declines and a community with a variety of plant species emerges. Probably the extra vigor is as much a result of reduced competition as from increased nutrients in the fresh sand.

c. *Plant Response to Fertilizer Application.*

(1) In Greenhouse. Most dune stabilization studies show fertilizer to be a valuable aid for increased plant growth which, in turn, allows for increased sand accumulation. To define basic responses of sea oats and bitter panicum to various kinds and levels of fertilization, a

greenhouse study was conducted at Texas Tech University in 1970. Sea oats plants were obtained from the Padre Island nursery and bitter panicum from wild harvest material on Mustang Island. Major objectives were to determine the best fertilizer levels for increasing shoot, root, and tiller production. Because plant response is different in pot versus field studies, results from pot studies should be viewed as an indication only of what can occur in the field.

Because potting mediums were different for sea oats and bitter panicum, and were grown in separate facilities, valid species comparisons are difficult. Yet, differences in response were large enough to conclude that their basic nutritional needs are different. This was also noted in the field, where bitter panicum from the Padre Island nursery grow as well without added nutrients as sea oats with fertilizer.

In the greenhouse, maximum sea oats root, shoot, and tiller production resulted from different fertilizer treatments (Table 47). High nitrogen rates boosted shoot weight while lower nitrogen rates were better for root and tiller production. Nitrogen applications

Table 47. Yield of shoots and roots, and tiller production of sea oats for various fertilizer treatments in greenhouse.

Fertilizer treatment			Yield		Tiller production (per 10 culms)
Nitrogen	Phosphorus (pounds per acre)	Potassium	Shoot (grams per 10 plants)	Root	
0	0	0	20.8	9.5	15.0
60	0	0	20.7	9.9	20.0
120	0	0	27.2	13.0	16.0
180	0	0	35.7	19.0	28.9
60	60	60	32.8	19.3	36.7
60	120	60	36.2	36.0	28.0
60	60	120	40.6	17.0	29.0
60	120	120	39.8	21.7	47.5
120	60	60	46.2	22.9	43.3
120	120	60	43.2	17.0	35.6
120	60	120	32.8	14.8	33.8
120	120	120	49.4	18.8	38.8
180	60	60	35.6	15.1	23.0
180	120	60	44.6	17.4	36.0
180	60	120	37.7	14.5	39.1
180	120	120	49.2	18.1	35.0

increased yields over the control in every treatment, and addition of phosphorus and potassium usually increased yields of roots, shoots, and tillers. Roots responded even more than shoots to a complete fertilizer. Treatments 180-120-120 (Nitrogen-phosphorus-potassium) and the more economical 120-120-120 resulted in maximum shoot growth. Maximum root growth, desirable in newly transplanted stands, resulted from the 60-120-60 treatment. A compromise level of 120-60-60 combined high yields of roots, shoots, and tillers.

In contrast to sea oats, some fertilizer treatments did not increase bitter panicum yields (Table 48). Also, the response to relative levels of phosphorus and potassium at high nitrogen levels was the reverse of that for sea oats. The most important nutrients for bitter panicum were nitrogen and potassium, whereas nitrogen and phosphorus were most important for sea oats. The root system of bitter panicum made up a very small part of the total plant weight. Best root weight came from the 180-60-60 treatment, producing a root system comprising only 13 percent of the total dry weight. However, sea oats roots in some

Table 48. Yield of shoots and roots, and tiller production of bitter panicum for various fertilizer treatments in greenhouse.

Fertilizer Treatment			Yield		Tiller production (per 10 culms)
Nitrogen	Phosphorus (pounds per acre)	Potassium	Shoot	Root (grams per 10 plants)	
0	0	0	22.0	2.8	19.4
60	0	0	27.4	4.2	32.5
120	0	0	23.6	3.8	21.8
180	0	0	21.2	3.7	20.6
60	60	60	22.8	3.4	35.0
60	120	60	21.1	3.0	21.8
60	60	120	23.2	4.1	23.3
60	120	120	23.8	3.4	20.0
120	60	60	21.8	3.9	27.1
120	120	60	31.4	4.2	21.9
120	60	120	40.0	4.6	25.8
120	120	120	27.6	4.3	22.5
180	60	60	37.8	5.6	20.0
180	120	60	21.6	2.5	18.4
180	60	120	26.2	3.9	19.5
180	120	120	21.1	3.2	17.8

treatments were half the plant weight. Sea oats were potted 1 to 2 months earlier, which probably contributed to the difference. The 120-60-120 treatment produced the highest bitter panicum shoot weight and second highest root weight, while highest tillering occurred at 60-60-60. The least productive treatments were the control and 180-120-120, the treatments with the least and the most nutrients added.

Both sea oats and bitter panicum responded to fertilizer but yields were increased no more than 2.5 times. Similar pot studies by Barr (1971) in Australia revealed that *Spinifex hirsutus* and *Ammophila arenaria* increased 23 to 40 times, respectively, with fertilizer.

(2) In Field. Field fertilizer trials were conducted in summer 1973, on established north Padre dunes. A randomized block design was used, with three blocks and seven treatments for sea oats and three blocks with six treatments for bitter panicum. The sea oats treatments were applied on the foreslope of the 1,200-foot sea oats dune, which was over 4 years old when fertilized. Bitter panicum treatments were on the foreslope of the 1,200-foot dune-width panicum plot (two blocks), which was 15 months old when fertilized, and the hind part of the Pan Am panicum site (one block), 38 months old at fertilization. Plot size in all blocks was 50 by 50 feet, but was reduced to 50 by 25 feet before the growth was randomly clipped. Fertilizer was applied in May, June, and July, with one-third total application each month. Aerial growth was clipped in October for bitter panicum and early November for sea oats.

Results of the field trials (Table 49) were different than the greenhouse results. Bitter panicum increased aerial growth in direct response to increased nitrogen. The heaviest application of nitrogen (180 pounds per acre) yielded nearly 4 times that of the control;

Table 49. Dry yield of bitter panicum and sea oats in response to fertilizer in field trials.[1]

Fertilizer treatment			Sea oats[2]				Bitter panicum[3]			
Pounds per acre			Block			Total	Block			Total
Nitrogen	Phosphorus	Potassium	1	2	3		1	2	3	
0	0	0	1,861	588	1,041	1,162	2,278	1,626	984	1,629 a
60	120	60	695	1,458	1,373	1,177	3,797	2,253	3,049	3,033 a, b
120	60	60	1,818	1,020	934	1,259	2,824	4,635	4,500	3,986 a, b, c
120	60	120	1,615	1,020	1,095	1,244	----------	--------	--------	---------
120	120	120	1,184	1,002	1,333	1,173	5,534	4,485	5,345	5,121 b, c
180	60	60	938	1,052	1,323	1,104	6,436	5,826	6,068	6,111 c
180	120	60	1,401	724	948	1,024	10,201	3,794	4,364	6,118 c

1. Treatment plots 50 by 25 feet; 10 random 0.25 square meter samples clipped per plot.
2. Three blocks, seven random treatments per block; 1,200-foot sea oats dune. All data from foreslope (0- to 24-foot basal). Treatment means are not significantly different ($P_{0.05}$).
3. Three blocks, six random treatments per block: 0- to 600-foot dune-width panicum blocks 1 and 2); data from foreslope (0- to 25-foot basal); Pan Am panicum (block 3) data from backslope (no sand accumulation). Treatment means sharing a common letter are not significantly different ($P_{0.05}$).

even the lowest application (60 pounds per acre of nitrogen) resulted in nearly twice the yield. The difference in growth was even greater on the backslope of the dune-width panicum, where sand accumulation was minimal (Fig. 41). Effects of phosphorus and potassium were unclear from these data, but as a result of greenhouse trials, application of a complete fertilizer with 120 to 180 pounds per acre of nitrogen is recommended.

Sea oats showed no response to any of the treatments, in direct contrast to greenhouse results, and to general observations from the fertilized nurseries and beach plantings. The reason may be the age of the dune, in comparison with the recently planted greenhouse and nursery transplants, which responded with a 2.5 times increased yield.

Woodhouse and Hanes (1967) tested field fertilizer response of deteriorating stands of both sea oats and bitter panicum in North Carolina. Unfertilized plots yielded 1,899 pounds per acre for sea oats, and 1,136 pounds per acre for bitter panicum, a higher yield than sea oats control but lower than bitter panicum control for this study. Response to 90-30-0 pounds per acre of nitrogen-phosphorus-potassium fertilizer was 9,854 pounds per acre for sea oats (5 times the control) and 9,411 pounds per acre for bitter panicum (8 times the control).

d. Effect of Fertilizer Application on Dune Growth. The purpose of fertilizing a dune planting is to improve its sand-trapping ability by increasing the mass of plant material per unit area. The effect of different rates of fertilizer on trapped sand was tested on the 15-month-old dune-width panicum plots. Before and after cross-sectional profiles were surveyed on each fertilizer plot (two sections per 50- by 50-foot plot at fixed locations); resulting sand volumes are given in Table 50. The amount of sand trapped varied little

Table 50. Effect of various fertilizer treatments on sand-trapping efficiency of a bitter panicum dune.[1]

Treatment (pounds per acre)			Dry yield[2] (pounds per acre)	Volume of sand trapped (cubic yards per lineal feet of beach)			
Nitrogen	Phosphorus	Potassium		1973		1974	Difference
				May	Dec.	Mar.	Mar. –May
0	0	0	1,952	4.5	10.8	11.3	6.8
60	120	60	3,025	3.7	8.1	8.7	5.0
120	60	60	3,729	4.4	9.8	10.4	6.0
120	120	120	5,009	3.7	8.2	8.5	4.8
180	60	60	6,130	3.2	7.9	8.7	5.5
180	120	60	6,996	4.2	8.7	9.2	5.0

1. 0- to 600-foot dune-width panicum, north Padre Island. Fertilization was in May, June, and July 1973 (1/3 application each). Data are means of two cross sections in each of two 50- by 50-foot plots per treatment.
2. Yield is for dune-width panicum plots only.

Figure 41. Effect of fertilization on growth of bitter panicum. Upper photo shows bitter panicum on backslope of dune-width planting after 3 months; foreground and area to left of marker not fertilized while area to right was fertilized (180-120-60). Lower photo shows 10-month-old bitter panicum planting; foreground, after 4 months of fertilization (120-60-60), and background unfertilized.

among the five fertilizer treatments, but the unfertilized plots trapped nearly 1 cubic yard per linear foot more than the plots with the highest fertilizer applied. Composite cross sections of the two control plots and two 180-120-60 pounds per acre fertilized plots with the heaviest application and the greatest response showed distinct differences (Fig. 42). The unfertilized plots trapped sand more evenly across the dune, and the heavily fertilized plots trapped sand primarily at the front of the dune, forming a steep foreslope and backslope. This was also observed at several test plots on south Padre, e. g., the north 100 feet of a panicum dune (1,800 to 2,000 feet, North Section Fence) which was fertilized in 1972. A year later, the fertilized section had a high crest with steep slopes, but the unfertilized portion was lower, broad and even. These differences are still apparent 2 years after fertilization. Two fertilized 50- by 50-foot plots on the Pass No. 4 panicum planting (2-foot sand fence) show the same response. Apparently, the 300 to 400 percent increase in cover traps sand too effectively—the sand is trapped at the front of the dune rather than spreading over the entire dune width. Consequently, fertilization does not improve the sand trapping ability of an established bitter panicum planting, and may cause an undesirable situation by building a steep and narrow dune rather than a flatter, broader one.

e. Fertilizer Application Recommendations. Based on laboratory and field data, the following recommendations are made for fertilization:

(1) Recent Planting. Both species benefit by fertilization beginning the spring after planting, or 2 to 3 months after a spring planting. Fertilization at this time enables the planting to fill weak spots and to develop sand-trapping cover by mid-summer. Early transplant growth of unfertilized plantings is slow and sand may move through the planting which could be trapped with denser cover. This increase in cover is illustrated in the lower photo in Figure 41; the foreground section was fertilized from 4 to 6 months after planting while the background section was not fertilized. Fertilizer should be applied in two or three equal applications, spread over several months, preferably in late spring to summer. The best rates, from greenhouse data, would be 120-60-60 pounds per acre for sea oats, and 120-60-120 pounds per acre for bitter panicum. However, field data for bitter panicum indicate that any complete fertilizer with 120 to 180 pounds per acre of nitrogen will be satisfactory. Field data from an established sea oats dune showed no response to any fertilizer level, but observations from nurseries and recently transplanted beach plantings indicated that the same rates should be applied.

(2) Established and Growing Dunes. Sea oats did not respond to fertilizer; bitter panicum responded, but sand-trapping ability was not improved. Therefore, fertilizing a planting after the first summer is not necessary, except possibly for localized areas with poor cover.

(3) Nursery. In a nursery, both species should be fertilized annually with the same rates as suggested for a recent planting. If unfertilized, bitter panicum stands thin out after 2 to 3 years and the culms become small. Fertilization will restore size and density within a few months.

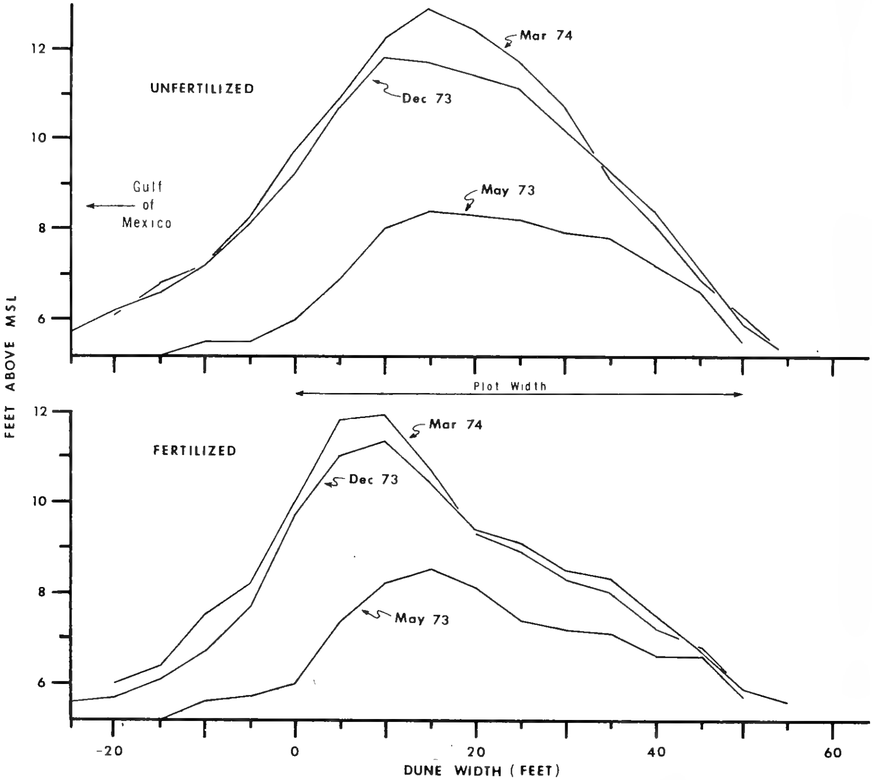


Figure 42. Mean cross-sectional profiles of unfertilized and fertilized (180-120-60) bitter panicum plots (north half, 1,200-foot dune-width panicum, north Padre). Initial planting in February 1972. Plots were surveyed May 1973 before fertilization and after December 1973 and March 1974. Each is the mean of four profiles of two each in two 50- by 50-foot plots per treatment.

f. Pests and Human Disturbance. Insect damage has occurred in limited areas from several different organisms (Table 51). One is a larval borer which occurs within sea oats stems near ground level; the plant typically turns brown and rots at or below the ground surface. Another, also a larval borer, smoothly cuts the stems of sea oats at an angle around the base of the plant up to 6 inches below the surface. Local infestations on the 1,200-foot sea oats dune have resulted in kills in areas of 5 feet in diameter; however, insect destruction has not been a problem in maintaining any of the dunes. Beetle damage to seed heads of sea oats is prevalent, but is not considered a problem unless seed production is desired.

Table 51. Collected insects which attack vegetation or reproductive material of sea oats.[1]

Order	Family	Species
Coleoptera	Melyridae	*Collops* sp. (adult)
	Mordellidae	*Mordellistena* sp. (larvae)
	Elateridae	*Glyphonyx* sp.
	Tenebrionidae	*Pechalius pilosus* (Champion)
Hemiptera–Homoptera	Pseudococcidae	*Distichlicoccus salinus* (Cockerell)
Hymenoptera	Encyrtidae	*Anagyrus* sp.
Lepidoptera	Pyralidae	*Rupela* sp.

1. Identified by Agricultural Research Service, USDA, Beltsvillè, Maryland.

Jackrabbits (*Lepus californicus*) regularly grazed exposed leaves of bitter panicum on established plantings, but were confined to small areas and had little effect on dune growth. However, on fresh plantings, especially of sea oats and recently (1973-74) bitter panicum, jackrabbits have caused severe, although sporadic, damage. The sea oats transplant was usually pulled from the ground, and chewed through at its base. Entire plantings have been decimated; e.g., the 1970 Pan Am sea oats planting, and the south half of the 1,200-foot dune-width planting, consisting of 10,000 transplants each, were totally destroyed. Most plantings remained untouched, while others suffered only light damage. Damage was unpredictable in extent and time of occurrence, and on one or several nights, from immediately to a month or more after planting. Before 1973, no damage to bitter panicum was observed. Jackrabbits would often destroy a row of sea oats while leaving an adjacent row of panicum untouched. In 1973-74, rabbits damaged bitter panicum culms more regularly than sea oats, and showed a preference for them. Damage to panicum was not detrimental to survival of the culm, since the exposed culm was chewed off at or near the base rather than pulled from the ground. Only in areas of drifting sand would ground-level pruning of panicum be harmful, since an undamaged plant may not be entirely buried or smothered, while a damaged plant may be covered with too much sand to penetrate.

In February 1974, a commercial rabbit and deer repellent (active ingredient: tetramethylthiuramdisulfide) was tested on transplants of bitter panicum and sea oats. The repellent was sprayed without dilution at the rate of 12 ounces per 100 plants. Cost of treatment per plant was 1.8 cents (1974), not including labor costs. The period between planting and collecting the data was without rainfall. Results (Table 52) showed a significant reduction of rabbit damage to panicum, but none for sea oats. The repellent would have to be nearly 100 percent effective for economical use. A more effective method against damage to sea oats was to plant the trimmed culms 14 inches deep, so that only a few inches of leaves were exposed.

Table 52. Effects of commercial rabbit repellent on jackrabbit damage to transplants.[1]

Repellent[2]	Culm chewed off near ground	Culm pulled from ground	Total damage
Bitter panicum (8 inches deep)			
Treated	34	4	38[3]
Untreated	63	4	67
Sea oats (8 inches deep)			
Treated	22	8	30[4]
Untreated	27	14	41
Sea oats (14 inches deep)			
Untreated	1	----	1[5]

1. Number of plants: 100.
2. Chaperone (brand) rabbit and deer repellent, Sudbury Laboratory, Inc., Sudbury, Massachusetts. Active ingredient: Thiram (tetramethylthiuramdisulfide).
3. Significant difference at $P_{0.05}$ level.
4. No significant difference.
5. Significant at $P_{0.01}$ level from other treatments.

Another deterrent to beach plantings was from free-ranging cattle before their removal. Usually they remained in mid-island, but mosquito infestations during wet, warm weather forced the cattle to the beach, especially at night. These circumstances resulted in cattle bedding down on the 1,200-foot sea oats planting. In November 1969, the cattle consumed nearly all exposed vegetation, which allowed winter winds to remove sand from around the plants. Damage was still noticeable in June 1970. To prevent more damage, a two-strand barbed-wire fence was constructed, which was partially effective. Cattle showed a preference for bitter panicum over shoredune panicum or sea oats; however, they ate the sea oats when a more palatable species was not available.

Human damage from vandalism and from apparent ignorance, has been a disturbing problem. Protective fences, both posts and wire, have been torn down, chopped down, and driven over. Sand fencing, used to protect irrigation pits, has been shredded. Survey marker posts, although painted and numbered, commonly are used for firewood. Concern for protection of natural and artificial foredunes has resulted in strict enforcement of protective measures on the national seashore. Camping and driving on vegetation is prohibited, and excessive foot traffic in critical areas is discouraged by information signs. Examples of the effects of human damage are shown in Figure 43.

6. Long-Term Considerations.

a. Dune Growth. After the initial 50-foot-wide planting, followed several months later by fertilization, the transplants begin active growth by sending out new tillers and an abundance of stiff leaves. The sand transported by prevailing onshore winds moves through the planting, either as individual grains, or as small, low dunes. When plant cover has attained a certain density (usually the first summer), the sand is moved into the planting and the leaves and stems disrupt wind movement, preventing the sand from moving out again. The plants exploit this fresh sand with more shoots, roots and tillers, and the process continues. When large amounts of sand are transported into the planting in a short period, e.g., during strong onshore winds in dry weather, the front of the planting traps the sand first until capacity is reached (near the tips of the leaves). More sand is swept across the slope and deposited immediately behind it, often forming a slip face 1 to 2 feet steep. The dune continues growing in this manner; sand reaches the back part of the dune only when the plants on the front part are covered nearly to the top.

b. Dune Growth: Sand Accumulation. After the first year following planting, the growing dune has the capacity to trap nearly all sand transported inland from the beach (Figs. 37 and 38). All major north Padre experimental plots were surveyed periodically. The growth at these sites is shown by mean cross-sectional profiles at approximately yearly intervals in Figures 37, 38, 44, and 45. Volumes of sand accumulated by the various plantings as of March 1974, (January 1974, for the south 400-foot sea oats) are given in Table 53, along with average yearly accumulation. Complete cross-sectional profile volumes from selected stations and means for all surveys, are given in Tables 54 and 55. The amount of sand available for dune building at the experimental plot sites has ranged from 3.3 to 5.2 cubic yards per linear foot of beach per year, with an average of 4.3 cubic yards per linear foot of beach per year. In comparison, a 50-foot-wide planting of American beachgrass in North Carolina trapped between 10 to 11 cubic yards per linear foot of beach in 3 years, or about 3.5 cubic yards per linear foot of beach per year (Savage and Woodhouse, 1968).

It is believed that a 50-foot-wide sea oats or bitter panicum planting has the capacity to trap considerably more than this amount, if enough sand becomes available. Similarly, Savage and Woodhouse (1968) reported that a 100-foot-square plot of sea oats in North Carolina accumulated as much as 16 cubic yards per linear foot of beach in 15 months. This was an abnormal situation, as sand was available from all directions, but it illustrates the

Figure 43. Problems encountered in maintaining vegetated dunes. Dune buggies destroy vegetation (upper left) which allows saddles to form in dunes (upper right). Heavy foot traffic (lower right) tramples vegetation and actuates blowouts. Unrestricted grazing (lower left) retards plant colonization.

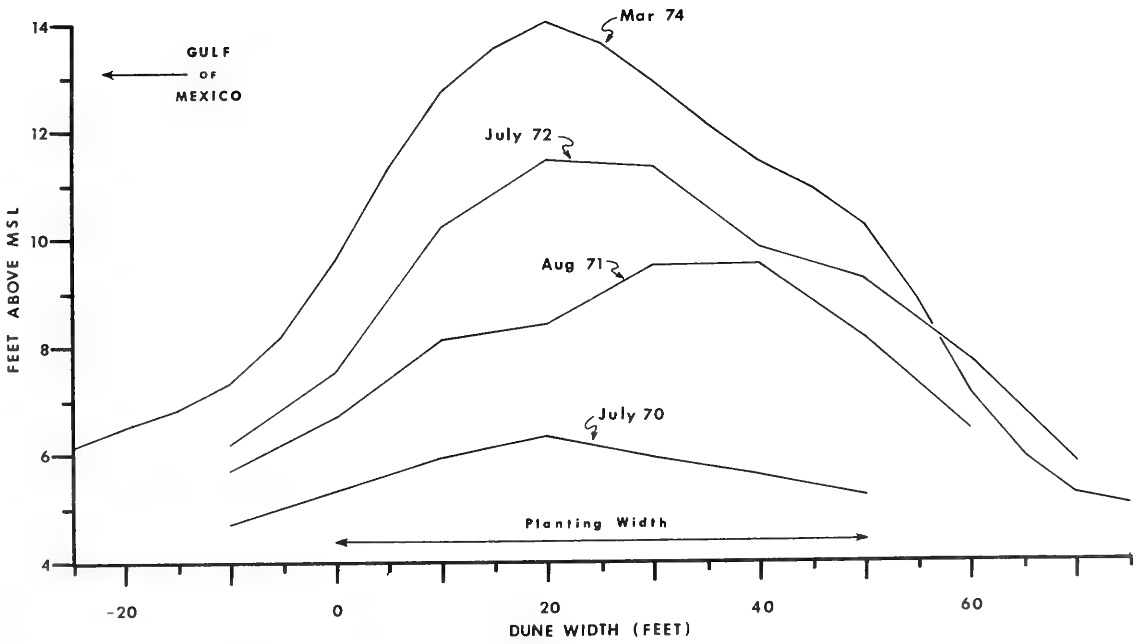


Figure 44. Mean cross-sectional profiles of 1,200-foot sea oats dune, north Padre, planted in March 1969. Each is the mean of 12 profiles (1970-72), or 24 profiles (1974). Planting surface is 4 feet MSL.

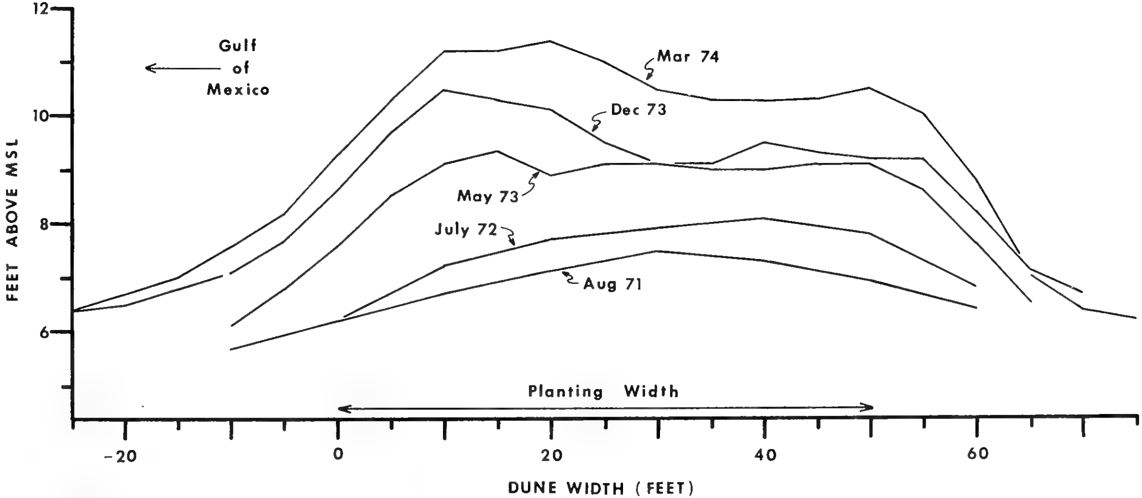


Figure 45. Mean cross-sectional profiles of 1,100-foot bitter panicum dune, north Padre, planted in February 1970. Each is the mean of 9 (1971-72), or 11 profiles (1973-74). Planting surface is 4.4 feet MSL.

Table 53. Sand accumulation in cubic yards per linear foot of beach on major plantings.

Study site	Planting	Section	Length (feet)	Width (feet)	Profiles (mean)	Sand volume	Accumulation per year (mean)
North Padre[1]							
1,200-foot sea oats	Mar. 1969	North	400		8	16.6	3.3
		Mid	400		8	22.5	4.5
		South	400		8	24.9	5.0
Total					**24**	**21.3**	**4.3**
1,100-foot bitter panicum	Feb. 1970	North half			6	19.3	4.7
		South half			6	17.0	4.2
Total					**12**	**18.2**	**4.5**
1,200-foot dune-width bitter panicum	Feb. and Apr. 1972	Major	0 to 600	east 50	24	9.4	4.3
			600 to 1,200	east 50	10	7.6	4.0
		Sub	0 to 300	east 50	12	8.6	4.0
			300 to 600	east 50	12	10.2	4.7
				west 50	5	1.1	0.5
		Total		**100**	**17**	**11.3**	**5.2**
			600 to 900	east 50	5	7.7	4.0
			900 to 1,200	east 50	5	7.5	3.9
				west 50	5	1.4	0.7
		Total		**100**	**5**	**8.9**	**4.6**
Dune-width extension, bitter panicum	Original 1969		55 to 120			12.8	
	Extension Apr. 1973		0 to 50		7	3.6	
Total			**0 to 120**			**16.4**	
South Padre[2]							
400-foot sea oats	Feb. 1969				2	17.2	3.5

1. As of March 1974.
2. As of January 1974 (data courtesy, U.S. Army Engineer District, Galveston, Texas).

Table 54. Sand accumulation in cubic yards per linear foot of beach for north Padre dunes constructed with sea oats and bitter panicum.[1]

Study site	Planting	Profile station	Month of survey											
			1970				1971			1972		1973		1974
			May	July	Aug.	Dec.	May	Aug.	Dec.	Apr.	July	May	Dec.	Mar.
1,200-foot sea oats	Mar. 1969	1 + 00	0.8	2.5	2.2	3.5	6.5	10.0	8.0	13.7	14.6	17.9	------	17.4
		4 + 00	0.6	3.1	1.9	3.5	8.6	11.8	14.6	15.3	15.8	15.0	------	17.4
		8 + 00	2.4	4.6	4.7	7.4	11.2	13.8	16.4	19.6	16.0	22.2	------	29.5
		12 + 00	5.0	7.7	3.5	4.5	8.7	10.4	10.0	15.8	14.0	17.6	------	23.8
Total[2]			**2.1**	**4.0**	**2.7**	**4.9**	**9.1**	**11.1**	**12.5**	**16.7**	**16.0**	**20.0**	------	**21.3**
1,100-foot bitter panicum	Feb. 1970	1 + 00	-----	-----	-----	-----	------	10.5	9.2	11.1	10.9	13.1	15.1	16.8
		4 + 00	-----	-----	-----	-----	------	9.4	11.6	11.7	12.5	14.2	19.5	20.9
		8 + 50	-----	-----	-----	-----	------	4.5	6.8	2.3	2.5	4.1	13.9	14.7
Total[3]			-----	-----	-----	-----	------	**6.9**	**8.6**	**7.4**	**10.0**	**11.7**	**14.5**	**18.2**
1,200-foot dune-width panicum, east 50-foot width	Feb. 1972	2 + 00	-----	-----	-----	-----	------	------	------	------	------	2.7	6.6	7.1
		4 + 00	-----	-----	-----	-----	------	------	------	------	------	4.1	8.7	9.3
Total (0 to 600 feet)[4]			-----	-----	-----	-----	------	------	------	------	------	**3.8**	**8.9**	**9.4**
	Apr. 1972	8 + 00	-----	-----	-----	-----	------	------	------	------	------	1.1	6.0	7.1
		10 + 00	-----	-----	-----	-----	------	------	------	------	------	0.5	8.3	9.6
Total (600 to 1,200 feet)[5]			-----	-----	-----	-----	------	------	------	------	------	**2.2**	**6.8**	**7.6**

1. Selected profile stations plus total mean (all profiles) are included.
2. Mean of 12 profiles (1970, 71, and 71), 42 profiles (1973), or 24 profiles (1974).
3. Mean of 9 profiles (1970, 71, and 72), or 12 profiles (1973 and 74).
4. Mean of 24 profiles.
5. Mean of 10 profiles.

Table 55. Sand accumulation for south Padre Island dunes.[1]

Location	Month of survey											
	1969		1970		1971				1972		1973	1974
	June	Dec.	Apr.	Sept.	Jan.	Mar.	July	Dec.	Apr.	Dec.	May	Jan.
Sea oats beach planting, February 1969 (south 400-foot north section)	–1.5	2.2	4.0	5.9	7.5	7.2	8.1	10.8	11.8	15.9	16.9	17.2
2-foot-high picket fence (four parallel rows) Pass No. 3[2]	------	-----	-----	-----	-----	-----	-----	-------	-------	3.1	3.1	5.4
4-foot-high picket fence (two tiers) North Section Fence 1,200 to 1,600 feet[3]	–1.0	2.7	3.3	4.6	6.2	5.8	7.3	10.8	11.0	11.0	11.8	12.7

1. Sand accumulation in cubic yards per linear foot of beach; each is the mean of two profiles. Data courtesy of U.S. Army Engineer District, Galveston. Sand-fence data part of a separate Corps of Engineers study.

2. Fence constructed in November 1971 was filled with sand by winter 1972–73; planted with sea oats and bitter panicum in monthly increments from November 1972 to July 1973.

3. Barren dune planted February 1973 after fences were filled. Sand accumulation in this section was above average for the 1-mile long North Section fence experiments.

potential capacity. These authors concluded that where annual sand movement was 3 cubic yards per linear foot of beach per year, a 35- to 40-foot-wide planting would trap all the available sand.

The 1,200-foot dune-width bitter panicum planting showed that the main limitation to dune growth in this area was not the capacity of the plants to trap sand, but the amount of blowing sand available to be trapped. For some reason, this amount was variable, even within similar areas of the same planting. For example, the north 400 feet of the 1,200-foot sea oats dune received considerably less sand than the middle and south 400-foot sections, and consequently grew at a slower rate (Fig. 46). The north half of the 1,100-foot bitter panicum dune initially grew faster than the south half, but now both are nearly equal (Fig. 47). The dune-width panicum plot is growing at a more uniform rate, despite differences in survival between the north and south halves.

A longitudinal profile along the crest of a section of the 1,200-foot sea oats dune (Fig. 48) shows the relative uniformity. This profile was surveyed in July 1974, and continued sand accumulation has resulted in increased elevations compared with previous figures and text from a March 1974, survey. In early stages of growth, this dune exhibited a tendency toward hummocks (peaks and troughs) which now have largely filled. This was a characteristic of monospecific sea oats plantings with relatively low survival, whereas bitter panicum dunes usually had a more uniform longitudinal profile even in early growth stages.

c. *Dune Growth: Lateral Spread of Vegetation.* Cross-sectional profiles of an American beachgrass dune in North Carolina (Savage and Woodhouse, 1968) showed that most sand was trapped at the front of the dune, and vegetation expanded 40 feet shoreward and 20

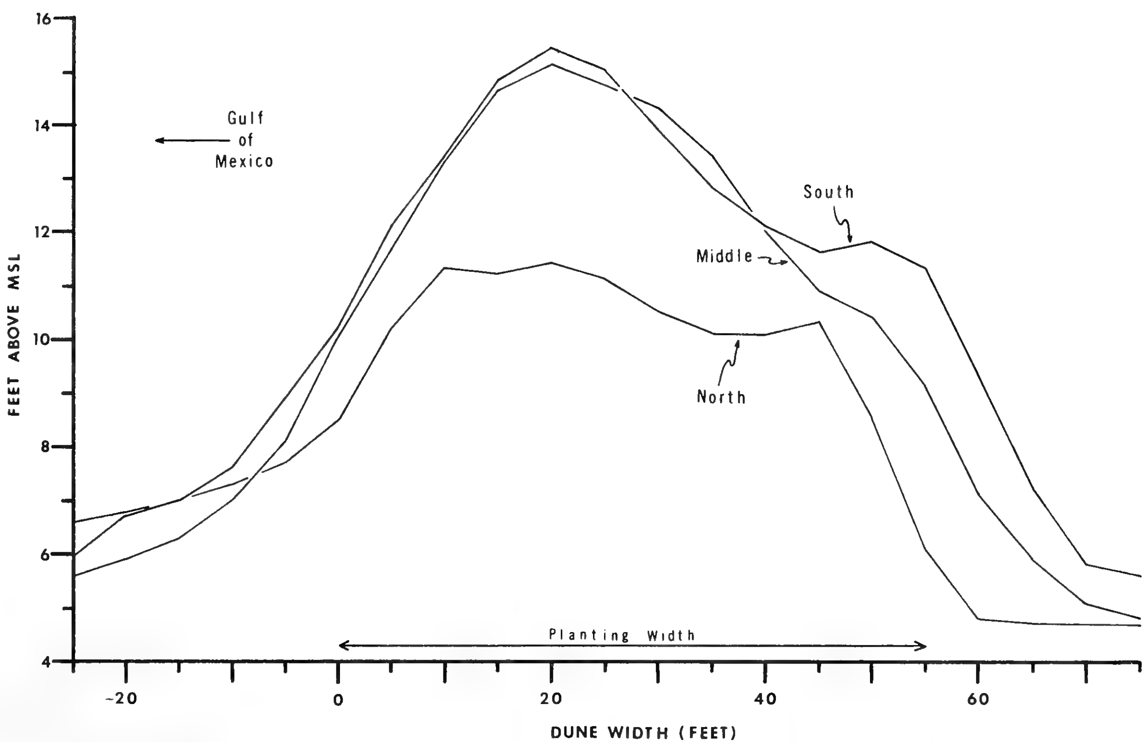


Figure 46. Mean cross-sectional profiles of north (0 to 400 feet), middle (400 to 800 feet), and south (800 to 1,200 feet) sections of 1,200-foot sea oats dune, north Padre, 60 months after planting (March 1974). Each is the mean of eight profiles. Planting surface is 4 feet MSL.

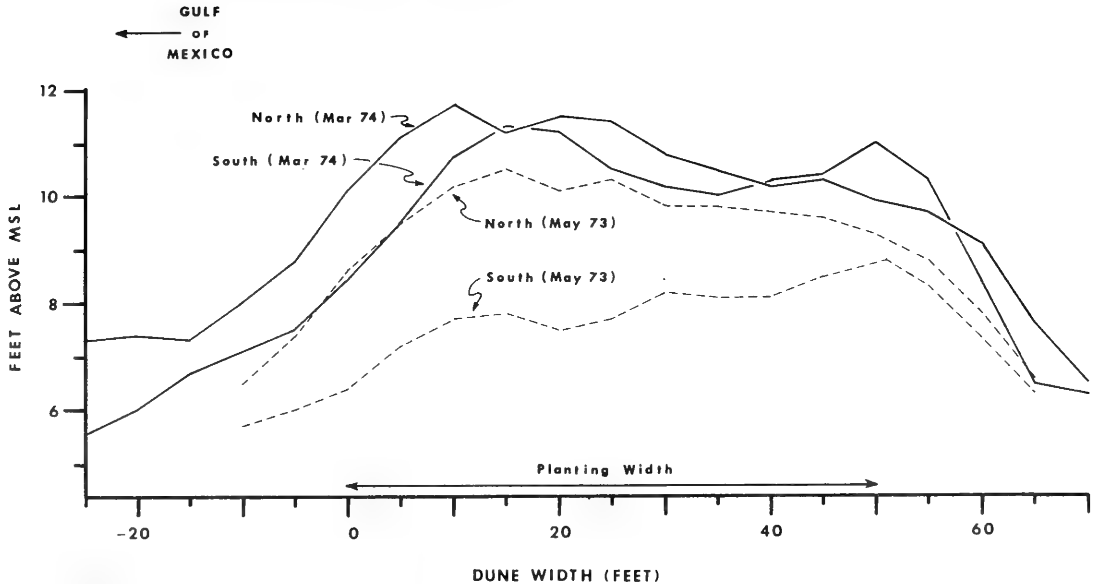


Figure 47. Mean cross-sectional profile of north and south halves of 1,100-foot bitter panicum dune, north Padre, in May 1973 and March 1974, 39 and 49 months after planting. Each is the mean of six profiles. Planting surface is 4.4 feet MSL.

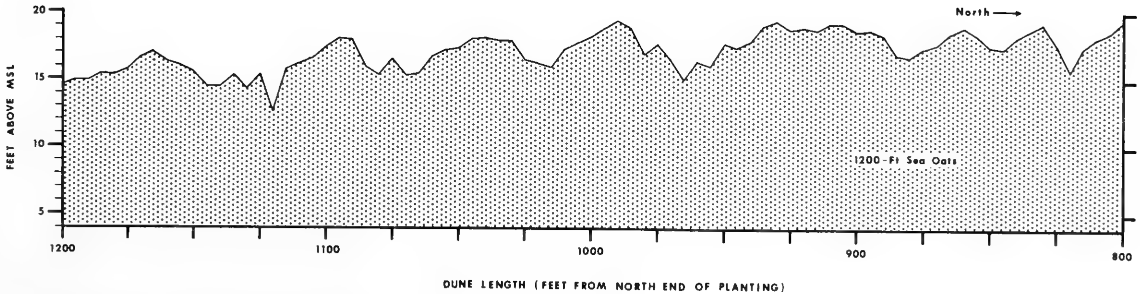


Figure 48. Longitudinal profile along crest of the south 400 feet (800 to 1,200 feet) of 1,200-foot sea oats dune, north Padre. Profile was surveyed in July 1974, 64 months after planting. Planting surface is 4 feet MSL.

feet landward in 3.5 years. Most of the resulting dune was actually shoreward of the front edge of the original planting. Padre Island sea oats and bitter panicum dunes have not responded in this manner. Growth has been vertical above the original planting, and only slightly laterally. After 5 years, the 1,200-foot sea oats dune vegetation averaged only 10 feet east of and about 8 feet west of the original planting. The 4-year-old bitter panicum dune has a comparable slow rhizomatic spread.

After 5 years (March 1974), the 1,200-foot sea oats dune had several peaks 18.1 feet above MSL or 14.1 feet above the planting surface, and an average on the south 800 feet of about 15.5 feet MSL, or 11.5 feet above the original surface. Thus, the vertical growth capacity of sea oats and bitter panicum exceeded their lateral growth potential (11.5 feet versus 10 feet for sea oats).

d. Dune Growth: Extending Dune Width. Due to the sand-trapping efficiency of both grasses, and to the slow rate of lateral spread, it is possible within 5 years to build a dune 11 feet above the planting surface but no greater than about 75 feet wide. This height offers excellent storm surge protection (Table 1), but the effective width may not be sufficient to withstand severe surges with prolonged wave attack. Therefore, a method for broadening dune width was tested in April 1973. A 50- by 400-foot strip of bitter panicum was planted immediately shoreward of an established bitter panicum dune planted 4 years previously. In another 4 years, or 8 years after the initial planting, the resultant dune should be over 100 feet wide and about 12 feet MSL across much of the width. The extension planting is now only 15 months old, but the rapid sand accumulation (Figs. 49 and 50) indicates that it is growing as predicted. It is too early to state conclusively the results of this experiment, but based on present growth and the growth configuration of other experimental dunes, this procedure is recommended for all plantings if a dune width in excess of 75 feet is desired. The second extension planting should not be made until the original dune has reached at least 12 feet MSL, since the extension will trap all available sand and the original dune will stop growing.

e. Dune Growth: Control (Unplanted) Beach. Reconstruction of foredunes by planting on a denuded backshore simulates a process that occurs naturally, although more slowly, by the interconnection of hummock dunes of seedling sea oats and other grasses. The artificial process can create in just a few years what probably takes 10 to 20 years to occur naturally. Before the 1,200-foot sea oats planting in March 1969, this area was devoid of vegetation and the backshore elevation was about 4 feet MSL. About 750 feet west of the shoreline, a barren dune field existed (Fig. 31), presumably comprised of mostly sand from the original foredune present as late as 1951. For comparison, a one-half mile barren section of beach immediately north of the sea oats dune has remained unplanted; all subsequent revegetation has been natural. This comparison may be biased in favor of the control area, since it is nearer undamaged dunes less than 1 mile to the north, and because the sea oats planting

Figure 49. Dune-width extension plot, north Padre. Upper photo: 3 months after extension planting, July 1973; 7-foot-high dune at extreme left was planted in 1969. Lower photo: 15 months after extension planting, July 1974.

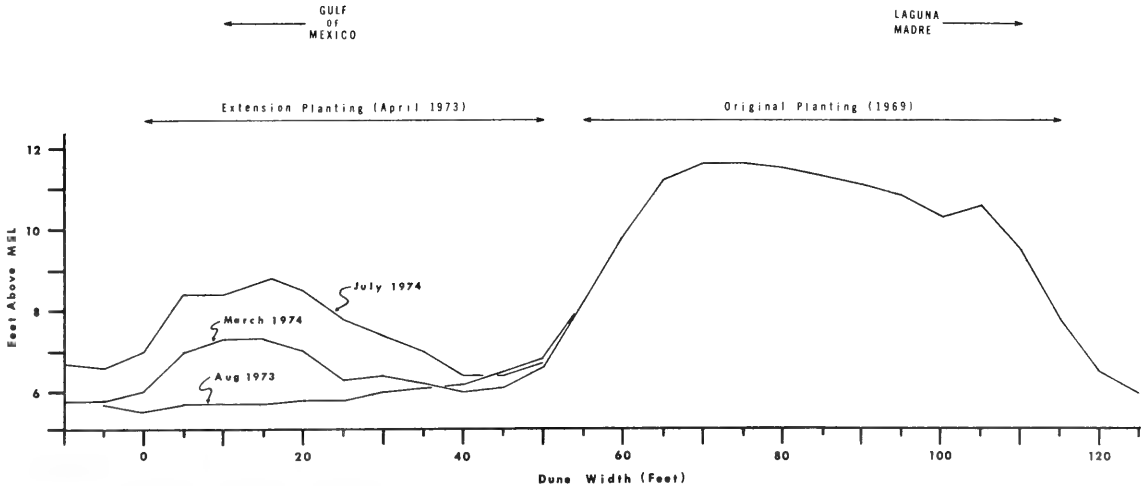


Figure 50. Mean cross-sectional profiles of dune-width extension plot, north Padre. Each is the mean of seven profiles. Planting surface of extension is 5.1 feet MSL.

may have been a contributing source of colonizing seeds. Cross sections from an 800-foot-long section of the control area (Fig. 51) compared with the 1,200-foot sea oats dune (Fig. 52) show that, since Hurricane Beulah in 1967 (the last destructive hurricane surge in this part of the coast), the control section has grown to an area of mostly low, unconnected hummock dunes, primarily of sea oats. The control area is shown in Figure 8. Beach profiles of the sea oats planting and control area are compared in Figure 53.

f. Invasion by Indigenous Flora. Natural invasion of plants into the artificial dune line has been a slow process. Most species occurring on the foreslope of natural foredunes (Table 8) do not presently occur on the foreslope of the artificial dune line, other than those originally planted. The reason is partly that accumulating sand is a limiting factor for many plants. Plants occur on the natural dunes after some stabilization has occurred. The artificial foredunes are still actively accumulating sand on the foreslope, and is one reason for the slow invasion rate. Another reason is the distance of over 1 mile for most plantings from the experimental plots to the undamaged dune line, where most colonizing seed stock originates. In November 1973, the 1,200-foot sea oats dune foreslope was sampled for species composition and biomass (Table 56). Only one species (railroad vine) occurred that

Table 56. Composition, by frequency and dry weight, of foreslope of 1,200-foot sea oats dune, north Padre Island, October 1973.[1]

Species	Relative frequency	Dry weight (lbs. per acre)	S $\bar{x}$
Uniola paniculata[2]	82.4	1,163.0	85.6
Panicum amarum[2]	6.2	143.0	64.1
Spartina patens[2]	4.3	16.5	11.6
Ipomoea Pes-caprae	0.5	2.7	-------
Bare ground	13.8	-----------	-------

1. All species sampled, 55 months after planting, are included. Sampled plots are 0.25 square-meter plots; N = 210 random plots. Foreslope is 0- to 25-foot basal of 50-foot-wide planting.

2. Species initially planted.

had not been planted. Woodhouse, Seneca, and Cooper (1968) reported that North Carolina plantings of American beachgrass are usually replaced by naturally invading sea oats within 10 years. This was explained by Seneca (1972a) as due partially to the greater temperature tolerance of sea oats. In the Padre Island plantings, an eventual increase in species diversity is expected, but the planted species should remain the dominant vegetation.

Invading plants found on the artificial foredunes in spring 1974 are listed in Table 57 with an abundance ranking for the foreslope and backslope of each plot. The backslope has more invading species and individuals than the foreslope, due to partial protection from salt spray and wind; also the backslope receives a diminishing sand supply as the dune grows,

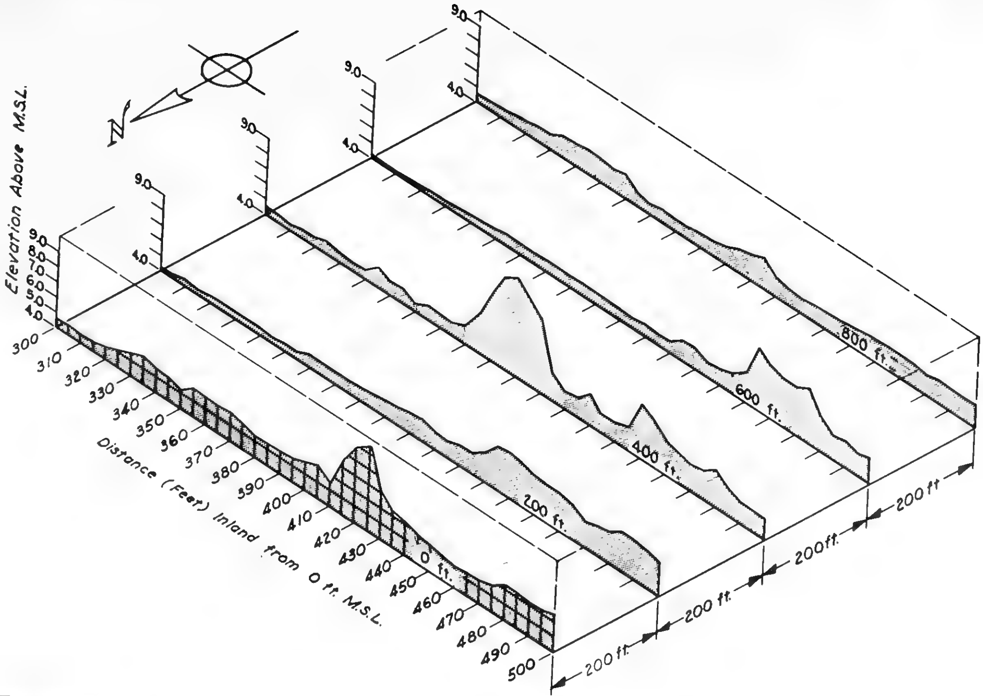


Figure 51. Five cross-sectional profiles (at 200-foot intervals) of 800-foot-long section of unplanted control beach, one-half mile north of 1,200-foot sea oats, north Padre. Profiles surveyed in March 1974.

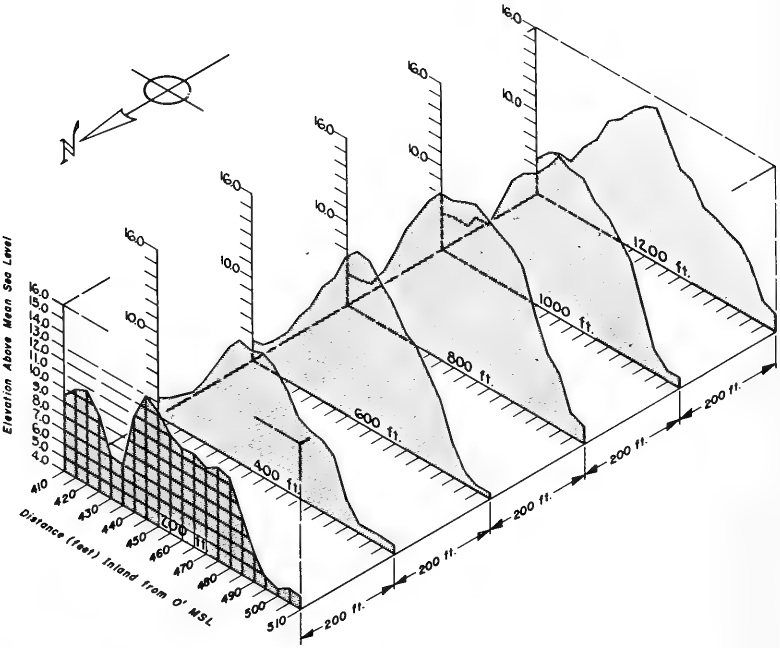


Figure 52. Six cross-sectional profiles (at 200-foot intervals) of 1,200-foot sea oats, north Padre. Profiles surveyed in March 1974, 60 months after planting. Planting surface was 4 feet MSL. Original 50-foot-wide planting extended from 435 to 485 feet inland from the shoreline.

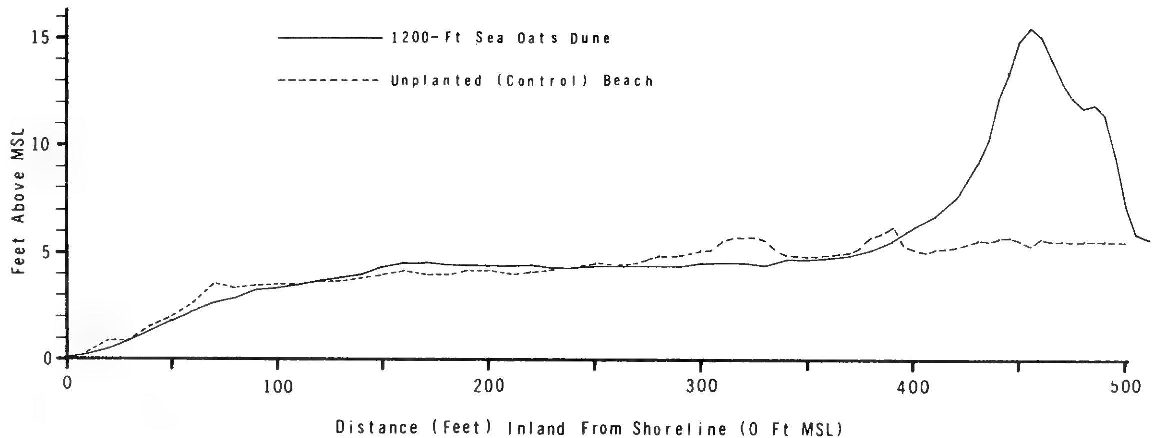


Figure 53. Cross-sectional beach profiles for the 1,200-foot sea oats planted dune, and a similar but unplanted beach one-half mile northward, north Padre. Each is a single profile, surveyed in March 1974.

Table 57. Natural invasion of unplanted species of plants into experimental plots on Padre Island, May 1974.

Family	Species	North Padre									South Padre	
		Sea oats 1,200 feet (62 months)		Bitter panicum 1,100 feet (51 months)		Dune-width panicum 1,200 feet (26 months) East | West (50-foot width)			Old species comparison plot[1] 400 feet (60 months)		Sea oats 400 feet (63 months)	
		A	B	A	B	A	B	C	A	B	A	B
Gramineae	*Cynodon dactylon*		2									
Cyperaceae	*Cyperus esculentus*		2									
	Fimbristylis castanea		2									
Chenopodiaceae	*Chenopodium ambrosioides*		2									
Aizoaceae	*Sesuvium portulacastrum*	3	2	3								
Leguminosae	*Baptisia leucophaea*		2		2					2		
Euphorbiaceae	*Croton punctatus*		3		3							
	Euphorbia ammanioides		2									
Onagraceae	*Oenothera Drummondii*		5		4			3	2			3
Umbelliferae	*Hydrocotyle bonariensis*		2									
Primulaceae	*Samolus ebracteatus*							3				
Gentianaceae	*Eustoma exaltatum*							2				
	Sabtia arenicola		2		2		2	6				
Convolvulaceae	*Ipomoea Pes-caprae*	4	4	5	3				3		4	4
	Ipomoea stolonifera				3							
Solanaceae	*Physalis viscosa*		4		2							
Scrophulariaceae	*Bacopa Monnieri*		2									
Compositae	*Erigeron myrionactis*		2			2	4					
	Senecio Riddellii		4							2		

1. At dune-width extension plot.
2. 1 to 3 individual plants or small clumps only in plot.
3. Occurs only locally as individual plants or small clumps; more frequent than above but fewer than 10 plants or small clumps.
4. Locally common, but not widespread; absent from many sections.
5. Fairly common; widespread.
6. Very common; widespread; represented in all sections of planting.

Columns: A = Foreslope (to crest). B = Backslope (leeward of crest). C = Flats (leeward of crest).

and thus achieves stability sooner. The most common and widespread colonizers of the backslope were beach evening primrose and railroad vine. The foreslope of all dunes contained only two species: railroad vine and sea purslane, neither of which was very common.

The slow invasion rate should not be considered undesirable to the long-term stability of the dune. All dunes are still actively growing, and are not near maturity. A more complex plant community should continue to develop, particularly on the lee side as the sand supply is eventually choked off.

g. Modifications to the Ecosystem. Dolan (1972b) reported that artificial barrier dunes on the Outer Banks of North Carolina increased beach erosion, narrowing the beach width from 660 feet to less than 98 feet since stabilization (about 30 years). This is one reason he concludes that a stabilized barrier dune ridge is detrimental to the long-term equilibrium of the island. As discussed earlier, there is no evidence that a similar process is occurring in areas of long-stabilized foredunes on northern Padre or Mustang Island, or as a result of the artificial dune line. Comparison of an unplanted beach section with a 5-year-old dune (Fig. 53) shows similar beach configurations to 400 feet inland where the artificial dune begins. Comparison of the same beach profile over a 2-year period (Fig. 54) also shows no real difference except for continued dune growth. Since the east coast erosion occurred during winter and tropical storm surges, monitoring Padre Island dunes through a severe storm is necessary to determine if this is also occurring. Additional beach profiles are presented in Figure 55 for the 2-year-old, 1,200-foot dune-width bitter panicum plot, and the recently planted (winter 1973-74) southernmost plot.

A profile of a natural foredune and beach is shown in Figure 56; photo of this site appears in Figure 7 (foreground). The extensive vegetation and dune growth shoreward of the foredune has been greatly curtailed in areas of heavy vehicular traffic, such as the beach in front of the experimental plots. The profile is representative of the backshore and foredune foreslope of the pedestrian beach, although in most of that area the natural foredune is higher and extends farther west.

Growing artificial dunes modify the environment to their leeward side in the following ways: (a) most sand blown inland from the beach is trapped and stabilized; the sand does not migrate farther inland to feed the barren dune fields and therefore, they gradually decrease in size; (b) inundations from storm surges penetrate no farther inland than the dune line, thus leeward areas are no longer subject to saltwater flooding and subsequent high soil salinity; and (c) salt spray is decreased in the shadow of the foredunes. The combination of decreased salt spray, and elimination of drifting sand, sand abrasion, and saltwater inundation has resulted in a rapid colonization of the leeward area by native plants (Fig. 57). The relative species composition of this area in September 1973, is shown in Table 58; a permanent transect established in the same area yielded the information in Table 59. Plant succession on south Padre, behind the North Section Fence dune, is not progressing as rapidly, nor with the same species (Table 60). Here the most important

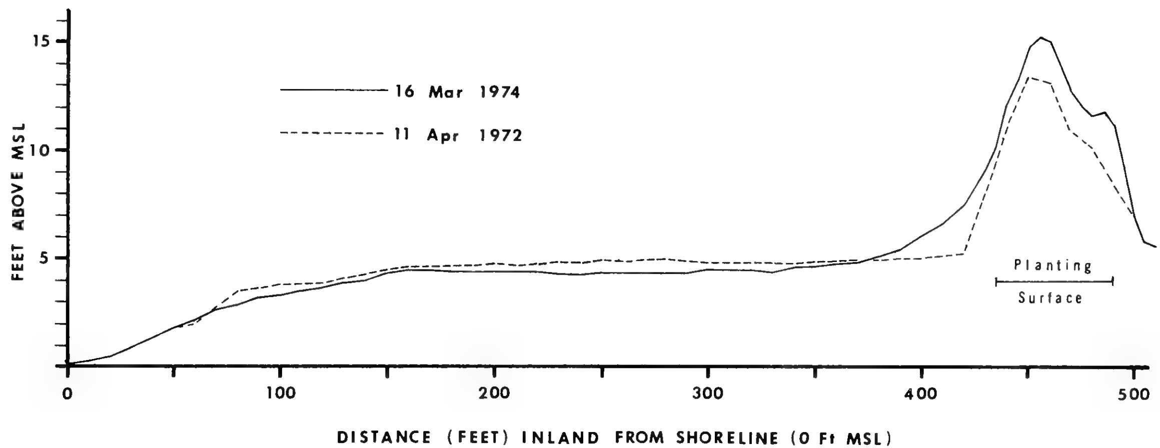


Figure 54. Cross-sectional beach and dune profiles for the 1,200-foot sea oats dune. Each is a single profile.

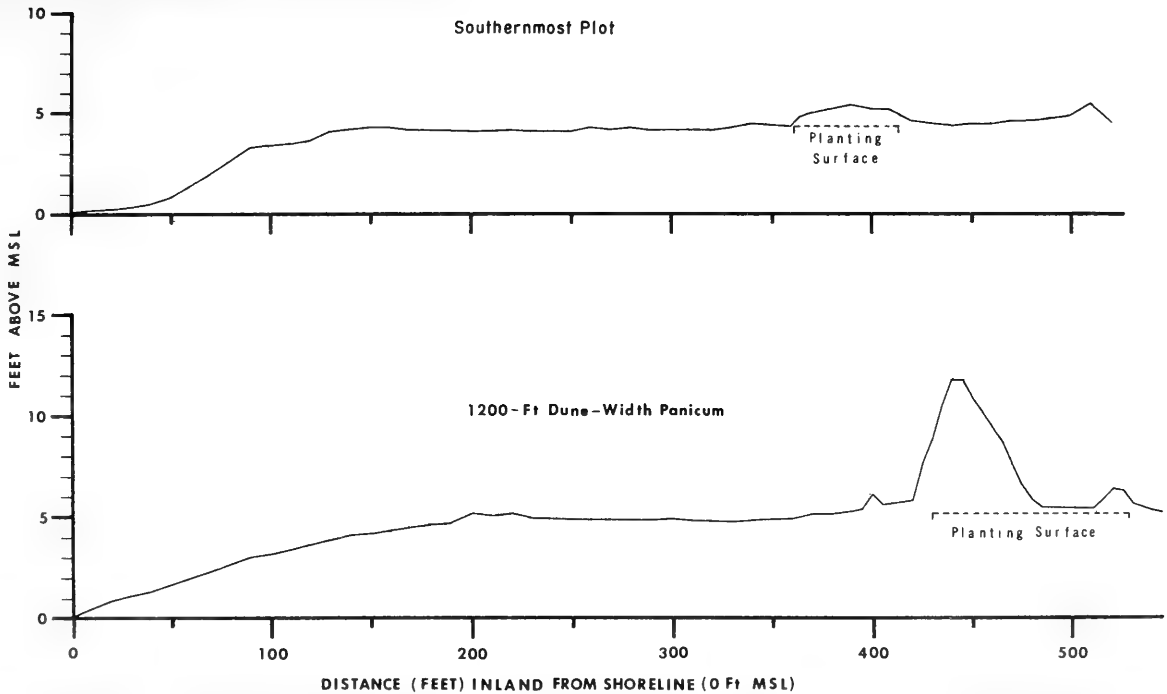


Figure 55. Cross-sectional beach and dune profiles for the southernmost plot and the 1,200-foot dune-width bitter panicum plot. Southernmost plot profile was planted in winter-spring 1973-74 and surveyed in July 1974. Dune-width plot was planted in February 1972 and surveyed in March 1974.

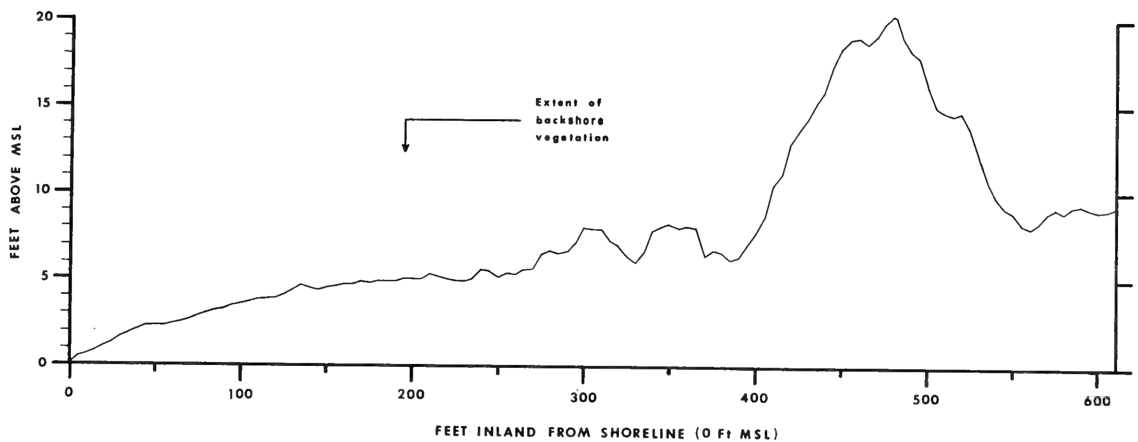


Figure 56. Cross-sectional single profile of natural beach and foredune, PAIS pedestrian beach. Profile (100 yards north of ranger station access road) was surveyed in July 1974.

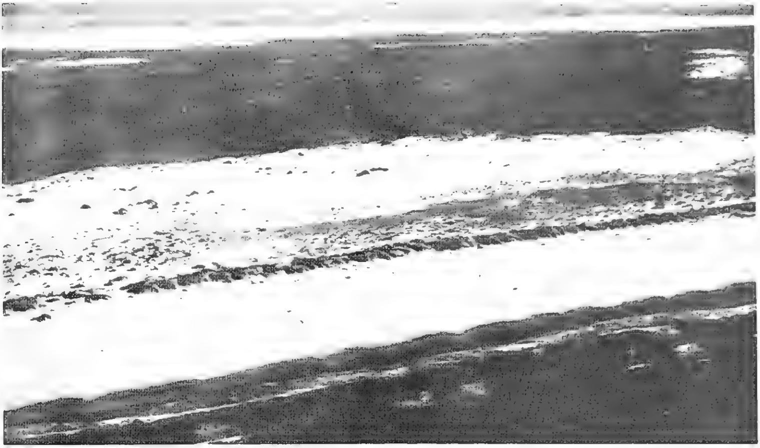


Figure 57. Natural invasion of plants into area protected from salt spray, wind, inundations, and blowing sand by the artificial dune line (1,200-foot sea oats dune). Upper aerial photo shows dune line in July 1973. Narrow dark line across center of photo is the 75-foot-wide, 11-foot-high artificial dune, backed by a 300-foot-wide strip of naturally invading species. A zone of barren migrating sand encroaches upon the vegetated plains in background, but the artificial dune has choked off its fresh sand source. Lower ground photo shows same area, viewed northwest from top of dune line, July 1974.

Table 58. Composition of vegetation leeward of 1,200-foot sea oats dune.[1]

North Padre, September 1973.	
Vegetation	Hits per 100 pins
Bare ground	83.6
Bacopa Monnieri	9.7
Uniola paniculata	1.6
Panicum amarum	1.1
Oenothera Drummondii	0.9
Sporobolus virginicus	0.9
Hydrocotyle bonariensis	0.7
Croton punctatus	0.5
Eleocharis caribaea	0.5
Fimbristylis caroliniana	0.4
Fimbristylis castanea	0.4
Sesuvium portulacastrum	0.3
Euphorbia ammanioides	0.2
Erigeron myrionactis	0.2
Cynodon dactylon	0.2
Five additional species	0.4

1. Area sampled = 1,000 feet long (north to south) by 200 feet wide (east to west) immediately west of artificial dune. Sampling procedure: 100 points (10-point, point-frame) along a 30-foot random-direction line at each of 30 random points. Total of 3,000 points. All hits counted.

Table 59. Composition of vegetation along 300-foot permanent transect west of 1,200-foot sea oats dune, September 1973.[1]

Species	Hits per 100 pins			
	0 to 100 feet	100 to 200 feet	200 to 300 feet	Total
Bacopa monnieri	13.4	17.8	25.6	18.9
Hydrocotyle bonariensis	2.9	0.8	1.5	1.7
Eleocharis caribaea	1.7	0.6	2.4	1.5
Sporobolus virginicus	1.1	0.3	2.9	1.4
Fimbristylis castanea	-------	3.9	0.3	1.4
Sesuvium portulacastrum	1.1	0.3	0.3	0.6
Erigeron myrionactis	-------	1.1	-------	0.4
Oenothera Drummondii	-------	0.8	-------	0.3
Croton punctatus	-------	-------	0.9	0.3
Eleocharis parvula	-------	0.6	-------	0.2
Scirpus americana	-------	-------	0.6	0.2
Panicum amarum	0.3	-------	-------	0.1
Baptisia leucophaea	-------	0.3	-------	0.1
Cyperus esculentus	-------	-------	0.3	0.1
Uniola paniculata	0.3	-------	-------	0.1
Bare ground (no hit)	79.4	75.0	67.4	74.0

1. Transect is east-west, originating 10 feet west of 450-foot mark of 1,200-foot sea oats dune, and extending 300 feet west. Markers are metal fenceposts at 100-foot intervals. Sampling method: 10-point, point-frame, with a total of 1,050 points. Frame placed end-to-end along transect. All hits per pin were recorded; all species are listed.

Table 60. Composition of vegetation leeward of North Section Fence south Padre Island, November 1973.[1]

Species	Frequency	Percent cover	Importance index
Fimbristylis castanea	55	1.2	66.0
Sesuvium portulacastrum	10	0.2	2.0
Uniola paniculata	5	0.9	4.5
Panicum amarum	1	1.0	1.0
Ipomoea Pes-caprae	2	0.2	0.4
Ipomoea stolonifera	1	trace	-------

1. One hundred 1-meter-diameter hoop samples in area west of 0 to 2,400 feet, North Section Fence (fence-build dunes) as follows: Two parallel north-south lines, each with 50 samples, 100 and 200 feet, respectively, west of the dune line.

species is a sedge, *Fimbristylis castanea*. The difference may be due to the soil surface on south Padre that is paved with large shells and shell fragments from previous surge overwash; on north Padre the surface is mostly fine sand. The large shells allow the surface layer to dry out quickly on south Padre and may inhibit seedling establishment of many species occurring on north Padre. Leeward of the 1,200-foot sea oats dune, the most common species is water-hyssop (*Bacopa Monnieri*), a prostrate mat-forming forb not found in dry sand.

VI. SUMMARY AND CONCLUSIONS

1. Best Adapted Species.

Bitter panicum (*Panicum amarum* Ell.) and sea oats (*Uniola paniculata* L.) are the two best adapted species, both for planting on the backshore for dune building, and for stabilizing existing dunes on the Texas gulf coast. Other native dune species, such as saltmeadow cordgrass and seashore dropseed, were tested and rejected due to poor survival, lack of vigor, or poor sandtrapping ability. Fifteen exotic species tested for potential use in beach plantings were either total or near-total failures.

2. Seeding.

Establishment by seed of sea oats on the backshore or on barren dunes is not recommended due to low germination rates and slow seedling growth. Bitter panicum seed is sterile, and must be established vegetatively.

3. Mixed Planting.

Bitter panicum usually is more successfully transplanted than sea oats and is easier to procure and handle. However, a mixed planting of bitter panicum and sea oats is recommended, since this reduces the chance of total stand failure, creates a more desirable polyspecific community, and uses the seed-reproduction capability of sea oats for natural recolonization of contiguous areas.

4. Sand-Trapping Capability.

Foredunes were most easily and successfully established by planting sea oats and bitter panicum directly on the barren backshore with a tobacco transplanter, and allowing the growing plants to trap and stabilize accumulating sand. Five years after planting with sea oats, a beach site had grown to a dune 11.4 feet high (15.4 feet above MSL), which contained 24 cubic yards of sand per linear foot of beach. Two years after planting, a bitter panicum dune was 7.4 feet high (12.6 feet above MSL) and contained 10.2 cubic yards per linear foot of beach. Average annual sand accumulation on all experimental sites was from 3.3 to 5.2 cubic yards per linear foot of beach, with a mean of 4.3 cubic yards per linear foot of beach. The main limitation of dune growth was not the trapping capacity of the plants, but the amount of blowing sand available.

5. Hurricane Washover Channels.

Vegetation could not be established on the original surface of two hurricane washover channels due to high soil salinity and surge wave action. The planting surface then was raised by spacing parallel rows of a 2-foot-high snow picket fence at 8- to 12-foot intervals to a 50-foot width. One year after erection of the fences, a broad flat dune relatively free of salt had formed, and then planted with both grasses with excellent results.

6. Fence-Built Dunes.

Barren dunes constructed with one to two tiers of 4-foot-high sand fencing were successfully stabilized by hand-transplanting bitter panicum and sea oats on the slopes. Preplanting irrigation was essential, while postplanting irrigation appeared to be useful only during drought. After planting, mulch-netting placed over the transplants eliminated wind erosion of the culms.

7. Planting Density.

Density of beach plantings of either species should be 2 feet between plants and rows, with only a single culm per hill. Use of closer spacing or larger clumps is more expensive and yields no benefit except when transplant survival is very low. Wider spacing of 3-foot centers is acceptable when transplant survival is near 100 percent. Survival rates on the backshore rarely were this high. Survival of 25 percent or greater for sea oats, and 50 percent or greater for bitter panicum should be considered very good. The main benefit to a planting of high survival was during the first year of growth. After this, cover became uniform and sand-trapping efficiency was at the maximum. However, transplant survival of less than 10 percent required replanting.

8. Planting Width.

The initial beach planting should be no wider than 50 feet, due to the sand-trapping efficiency of both species. Wider plantings are proportionally more expensive and do not result in increased dune growth. A broader dune can be achieved by a second 50-foot-wide planting immediately shoreward of the first dune, 4 to 5 years after the initial planting.

9. Nursery.

A nursery yielded a stand of uniform localized plant material, which reduced harvest time and effort and thus nursery establishment at least a year before transplanting is recommended. However, there was no survival advantage of nursery over wild stock.

10. Transplant Survival.

Transplant survival was influenced more by such variable parameters as soil salinity, soil moisture, precipitation, carbohydrate storage, and burial by drifting sand rather than seasonality. Sea oats was most successfully transplanted in mid-winter, but with proper soil conditions (low salinity and high moisture), this species was transplanted with adequate survival in all months. Bitter panicum had no optimum season for transplant survival, and was successfully planted in any month if soil conditions were favorable. Poorest time was in fall since active growth was delayed for 6 months after planting. The recommended time of transplanting for either species is winter through spring since climate and soil conditions are usually more favorable.

11. **Factors Influencing Survival.**

By multiple correlation analysis, environmental parameters were tested for their contributions to transplant success or failure. These data showed that no one factor accounted for the success of a planting, and that extreme drought or extreme salinity could cause total planting failure. Other variables, e.g., soil and air temperatures and carbohydrate storage, contributed to planting success or failure, but never were responsible for total stand failure. Both species survived best when soil moisture and precipitation were high, and soil salinity and carbohydrate storage were low.

12. **Critical Soil Salinity.**

Laboratory experiments to determine critical substrate salinity levels showed that shoredune panicum was least tolerant, followed by sea oats, while bitter panicum was most salt-tolerant. The critical levels which resulted in 50 percent reduction in survival over controls were (in micromhos per centimeter, 2:1 water-sand ratio): 1,830, 2,620, and 3,460, respectively.

13. **Saltwater Inundation.**

Occasionally, inundation of backshore plantings by saltwater was the cause of total planting failure, particularly during drought, or if accompanied by wave action, sand deposition, or extended ponding of saltwater. However, a minor surge of from 1 to 2 days was not always detrimental, and occasionally no adverse effects occurred.

14. **Sand Burial.**

Drifting sand of greater than 6 inches adversely affected transplant survival, and accumulations over 20 inches resulted in total failure.

15. **Sea Oats Culm Selection.**

The largest available culms of sea oats had higher survival and attained sand-trapping size more quickly than the smallest. However, all sizes made acceptable transplants.

16. **Bitter Panicum Culm Selection.**

Bitter panicum transplants survived equally well with or without an initial root system. Long ($>$ 1.5 feet) primary culms survived better than short ones ($<$ 10 inches). From fall through spring, mature primary culms were more successfully transplanted than tillers, but the latter were preferable from late spring through summer. During winter, 3-foot primary culms were broken in half and both halves planted with little loss of survival.

17. **Storage of Transplants.**

After harvesting, sea oats transplants were stored up to 4 days, and bitter panicum nearly a month in freshwater, with no loss of survival potential.

18. **Irrigation.**

Freshwater irrigation before planting was essential on fence-built dunes, and would be useful on beach plantings during drought. Postplanting irrigation did not improve transplant survival during a period of near-normal rainfall, but may be beneficial during extended droughts.

19. Fertilizer Applications.

All plantings should be fertilized during the first growing season after planting. The total rate should be split in two or three equal applications, and broadcast in late spring through summer. Laboratory experiments showed that for sea oats, 120-120-120 pounds per acre (nitrogen-phosphous-potassium) gave maximum shoot growth, while 60-120-60 yielded maximum root growth. Combined high yields of roots, shoots, and tillers occurred with 120-60-60. For bitter panicum, 120-60-120 pounds per acre gave the highest shoot weight, and 60-60-60 resulted in highest tillering. Field trials on established dunes showed that sea oats did not respond to any level of fertilizer, while bitter panicum increased growth in direct response to increased nitrogen. The heaviest nitrogen application (180 pounds per acre) yielded nearly 4 times the control. Any complete fertilizer of 120 to 180 pounds per acre nitrogen is recommended for either species for recently planted stands. Fertilization of established dunes, a year or more after planting, did not improve the sand-trapping capability.

20. Time-Cost.

With a tobacco transplanter and tractor, a 1-mile beach planting of sea oats, 50 feet wide with 2-foot centers, would require 500 man-hours, while a bitter panicum planting would require 287 man-hours.

LITERATURE CITED

ANDREWS, P. B., "Facies and Genesis of a Hurricane Washover Fan, St. Joseph Island, Central Texas Coast," Report of Investigations No. 67, Bureau of Economic Geology, University of Texas at Austin, Tex., Oct. 1970.

AUGUSTINE, M. T., et al., "Response of American Beachgrass to Fertilizer," *Journal of Soil and Water Conservation*, Vol. 19, No. 3, May-June 1964, pp. 112–115.

BARR, D. A., "Dune Grasses Respond to Fertilizer," *Beach Conservation*, No. 4, Beach Protection Authority, Queensland, Australia, June 1971, p. 2.

BEHRENS, E. W., "Hurricane Effects on a Hypersaline Bay," Lagunas Costeras, *Memoria del Simporio Internacional sobre Lagunes Costeres*, Mexico, 1969, pp. 301–312.

BERNARD, H. A., and **LeBLANC, R. J.**, "Resume of the Quaternary Geology of the Northwestern Gulf of Mexico Province," *The Quaternary of the United States*, Princeton University Press, Princeton, N.J., 1965, pp. 137–185.

BLAKE, J. E., "Report on the Route Toward Matamoros by Padre Island," National Archives Record Group No. 77, Records of the Chief of Engineers, Letters Received, Topographical Bureau, 10 March 1846, Corpus Christi, Tex., Feb 1846.

BLOODGOOD, D. W., **PATTERSON, R. E.**, and **SMITH, R. E., Jr.**, "Water Evaporation Studies in Texas," Bulletin No. 787, Texas Agricultural Experiment Station, College Station, Tex., 1954.

BODINE, B. R., "Hurricane Surge Frequency Estimated for the Gulf Coast of Texas," TM 26, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Washington, D.C., Feb. 1969.

BOKER, T. A., "Sand Dunes on Northern Padre Island, Texas," unpublished M.S. Thesis, University of Kansas, Lawrence, Kans., 1956.

BOYCE, S. G., "The Salt Spray Community," *Ecological Monograph*, Vol. 24, No. 1, 1954, pp. 29–67.

BROWN, R. L., "Permanent Coastal Dune Stabilization with Grasses and Legumes," *Journal of Soil and Water Conservation*, Vol. 3, No. 2, Mar.-Apr. 1948, pp. 69–74.

BROWN, R. L., and **HAFENRICHTER, A. L.**, "Factors Influencing the Production and Use of Beachgrass and Dunegrass Clones for Erosion Control: I. Effect of Date of Planting," *Journal of the American Society of Agronomy*, Vol. 40, No. 6, 1948a, pp. 512–521.

BROWN, R. L., and **HAFENRICHTER, A. L.,** "II. Influence of Density of Planting," *Journal of the American Society of Agronomy*, Vol. 40, No.7, 1948b, pp. 603–609.

BROWN, R. L., and **HAFENRICHTER, A. L.,** "Stabilizing Sand Dunes on the Pacific Coast with Woody Plants," Miscellaneous Publication No. 892, Soil Conservation Service, U.S. Department of Agriculture, Washington, D.C., Feb. 1962.

CARR, J. T., Jr., "Texas Droughts: Causes, Classification, and Prediction," Report No. 30, Texas Water Development Board, Austin, Tex., Nov. 1966.

CHAPMAN, V. J., "The Stabilization of Sand-dunes by Vegetation," *Biology and Civil Engineering*, Institution of Civil Engineers, Westminster, England, 1949, pp. 142–157.

CHAPMAN, V. J., *Coastal Vegetation*, Pergamon Press, Oxford, England, 1964.

COOPER, W. S., "Coastal Sand Dunes of Oregon and Washington," *Geological Society of America*, Memoir 72, June 1958, p. 169.

DAVIS, J. H., "Dune Formation and Stability by Vegetation and Plantings," TM 101, U.S. Army, Corps of Engineers, Beach Erosion Board, Washington, D.C., Oct. 1957.

DAVIS, R. A., Jr., "Beach Changes on the Central Texas Coast Associated with Hurricane Fern, September 1971," Vol. 16, Contributions in Marine Science, Marine Science Institute, University of Texas, Port Aransas, Tex., Mar. 1972, pp. 89–98.

DEPARTMENT OF COMMERCE, "Local Climatological Data. Annual Summary with Comparative Data," Corpus Christi, Tex., 1970.

DOLAN, R., "Barrier Dune Systems Along the Outer Banks of North Carolina: A Reappraisal," *Science*, Vol. 176, No. 4032, Apr. 1972a, pp 286–288.

DOLAN, R. , "Barrier Islands: Natural and Controlled," *Coastal Geomorphology*, Publications in Geomorphology, State University of New York, Binghamton, N.Y., 1972b, pp. 263–278.

DYKSTERHUIS, E. J., "The Vegetation of the Fort Worth Prairie," *Ecological Monograph*, Vol. 16, No. 1, 1946, pp. 1–29.

FISHER, J. J., "Barrier Island Formation: Discussion," *Geological Society of America Bulletin*, Vol. 79, No. 10, Oct. 1968, pp. 1421–1426.

FISK, H. N., "Padre Island and the Laguna Madre Flats, Coastal South Texas," Second Coastal Geography Conference, Coastal Studies Institute, Louisiana State University, Washington, D.C., 1959, pp. 103–151.

GAGE, B. O., "Experimental Dunes of the Texas Coast," MP 1-70, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Washington, D.C., Jan. 1970.

GARNER, L. E., "Sand Resources of Texas Gulf Coast," Report of Investigation No. 60, Bureau of Economic Geology, University of Texas, Austin, Tex., Mar. 1967.

GIBBS, R. F., and NASH, E., "Beach and Sand Dune Erosion Control at Cape Hatteras National Seashore," *Transactions American Society of Agricultural Engineers*, 1961, pp. 122–127.

GODFREY, P. J., and GODFREY, M. M., "Comparison of Ecological and Geomorphic Interactions Between Altered and Unaltered Barrier Island Systems in North Carolina," *Coastal Geomorphology*, Publications in Geomorphology, State University of New York, Binghamton, N.Y., 1972, pp. 239–258.

GORHAM, E., "Soluble Salts in Dune Sands from Blakney Point in Norfolk," *Journal of Ecology*, Vol. 46, 1958, pp. 373–379.

GRAETZ, K. E., *Seacoast Plants of the Carolinas for Conservation and Beautification*, UNC-SG-73-06, Soil Conservation Service, Raleigh, N.C., Feb. 1973.

HARRIS, V. M., "History of Cattle Raising on Padre Island," Vol. 1, South Texas Agriculture, 1965, pp. 1–16.

HAWK, V. B., and SHARP, W. C., "Sand Dune Stabilization along the North Atlantic Coast," *Journal of Soil and Water Conservation*, Vol. 22, No. 4, July-Aug. 1967, pp. 143–146.

HAYES, M. O., "Grain Size Modes in Padre Island Sands," *Field Trip Guidebook*, Gulf Coast Association of Geological Societies, 1964, pp. 121–126.

HAYES, M. O., "Hurricane as Geological Agents: Case Studies of Hurricanes Carla, 1961, and Cindy, 1963," Report of Investigation No. 61, Bureau of Economic Geology, University of Texas, Austin, Tex., Aug. 1967.

HOYT, J. H., "Barrier Island Formation," *Geological Society of America Bulletin*, Vol. 78, 1967, pp. 1125–1136.

HUNTER, R. E., and DICKINSON, K. A., "Map Showing Landforms and Sedimentary Deposits of the Padre Island Portion of the South Bird Island 7.5-Minute Quadrangle, Texas," Map I–659, Miscellaneous Geologic Investigations, U.S. Geological Survey, Washington, D.C., 1970.

HUNTER, R. E., et al., "Modern Depositional Environments and Processes, Northern and Central Padre Island, Texas," *Padre Island National Seashore Field Guide*, Gulf Coast Association of Geological Societies, Corpus Christi, Tex., 1972.

HYDER, D. N., and SNEVA, F. A., "Morphological and Physiological Factors Affecting the Grazing Management of Crested Wheatgrass," *Crop Science*, Vol. 3, 1963, pp. 267–271.

JACKSON, M. L., *Soil Chemical Analysis*, Prentice-Hall, Englewood Cliffs, N.J., 1958.

JAGSCHITZ, J. A., "Research to Rebuild and Stabilize Sand Dunes in Rhode Island," *Shore and Beach*, Vol. 28, No. 1, Apr. 1960, pp. 32–35.

JAGSCHITZ, J. A., and BELL, R. S., "Restoration and Retention of Coastal Dunes with Fences and Vegetation," Agricultural Experiment Station Contribution No. 1149, Bulletin No. 382, University of Rhode Island, Kingston, R.I., Jan. 1966a.

JAGSCHITZ, J. A., and BELL, R. S., "American Beachgrass (Establishment-Fertilization-Seeding)," Agricultural Experimentation Station Contribution No. 1150, Bulletin 383, University of Rhode Island, Kingston, R.I., June 1966b.

KEARNEY, T. H., "Are Plants of Sea Beaches and Dunes True Halophytes?," *Botanical Gazette*, Vol. 37, 1904, pp. 424–436.

KING, C. A. M., *Beaches and Coasts*, Arnold Publishers, London, England, 1959.

KUCINSKI, K. J., and EISENMENGER, W. S., "Sand Dune Stabilization on Cape Cod," *Economic Geography*, Vol. 19, No. 2, Apr. 1943, pp. 206–214.

LAING, C. C., "Studies in the Ecology of *Ammophila breviligulata*; Seedling Survival and its Relation to Population Increase and Dispersal," *Botanical Gazette*, Vol. 119, June 1958, pp. 208–216.

LLOYD, F. E., and TRACY, S. M., "The Insular Flora of Mississippi and Louisiana," *Bulletin Torrey Botanical Club*, Vol. 28, No. 2, 1901, pp. 61–101.

LOHSE, E. A., "Dynamic Geology of the Modern Coastal Region, Northwest Gulf of Mexico," *Finding Ancient Shorelines*, Special Publication No. 3, Society of Economic Paleontologists and Mineralogists, Tulsa, Okla., 1955, pp. 99–103.

LOHSE, E. A., and COOK, T. D., "Rio Grande Delta-South Laguna Madre-Geochronology of Mudflats through Varve Analysis," *Sedimentology of South Texas Field Trip Guidebook*, Gulf Coast Association of Geological Societies, Corpus Christi, Tex., 1958, pp. 52–61.

MASON, D. D., and FOLK, R. L., "Differentiation of Beach, Dune and Aeolian Flat Environments by Size Analysis, Mustang Island, Texas," *Journal of Sedimentary Petrology*, Vol. 28, No. 2, June 1958, pp. 211–226.

McGOWAN, J. H., et al., "Effects of Hurricane Celia—A Focus on Environmental Geologic Problems of the Texas Coastal Zone," No. 70-3, Geological Circular, Bureau of Economic Geology, University of Texas, Austin, Tex., 1970, pp. 1–35.

McLAUGHLIN, W. T., and **BROWN, R. L.**, "Controlling Coastal Sand Dunes in the Pacific Northwest," Circular No. 660, U.S. Department of Agriculture, Washington, D.C., Sept. 1942.

MILLING, M. E., and **BEHRENS, E. W.**, "Sedimentary Structures of Beach and Dune Deposits, Mustang Island, Texas," Vol. 11, Publications of the Institute of Marine Science, University of Texas, Port Aransas, Tex., Nov. 1966, pp. 135–148.

OOSTING, H. J., "Ecological Processes and Vegetation of the Maritime Strand in the Southeastern United States," *Botanical Review*, Vol. 20, 1954, pp. 226–262.

OOSTING, H. J., and **BILLINGS, W. D.**, "Factors Affecting Vegetational Zonation on Coastal Dunes," *Ecology*, Vol. 23, No. 2, 1942, pp. 131–142.

ORTON, R., et al., "Climatic Guide: The Lower Rio Grande Valley of Texas," MP-841, Texas Agricultural Experiment Station, College Station, Tex., 1967.

PALMER, P. G., "A Biosystematic Study of the Virgata Group of Panicum (Gramineae) in the United States," unpublished Ph.D. Dissertation, North Carolina State University, Raleigh, N.C., 1972.

PRICE, W. A., "Hurricanes Affecting the Coast of Texas from Galveston to Rio Grande," TM 78, U.S. Army, Corps of Engineers, Beach Erosion Board, Washington, D.C., Mar. 1956.

PRICE, W. A., "Environmental Impact of Padre Isles Development, South Texas," *Shore and Beach*, Vol. 39, No. 2, Oct. 1971, pp. 4–10.

PRICE, W. A., and **GUNTER, G.**, "Certain Recent Geological and Biological Changes in South Texas, with Consideration of Probable Causes," *Proceedings and Transactions of the Texas Academy of Science*, Vol. 26, 1943, pp. 138–156.

RANDALL, R. E., "Salt Measurement on the Coast of Barbados, West Indies," *OIKOS*, Vol. 21, 1970, pp. 65–70.

RECHENTHIN, C. A., and **PASSEY, H.**, "The Vegetation of Padre Island National Seashore," Report to Padre Island National Seashore, Soil Conservation Service, Temple, Tex., 1967.

SAUER, J., "Geographic Reconnaissance of Seashore Vegetation along the Mexican Gulf Coast," Series No. 21, Coastal Studies Institute, Louisiana State University, Baton Rouge, La., Sept. 1967.

SAVAGE, R. P., and WOODHOUSE, W. W., Jr., "Creation and Stabilization of Coastal Barrier Dunes," No. 2710, Agriculture Experiment Station Series, North Carolina State University, Raleigh, N.C., 1968.

SEELIG, W. N., and SORENSEN, R. M., "Historic Shoreline Changes in Texas," No. 165, TAMU-SG-73-206, Coastal and Ocean Engineering Report, Texas A. & M. University, College Station, Tex., 1973.

SENECA E. D., "Germination Response to Temperature and Salinity of Four Dune Grasses from the Outer Banks of North Carolina," *Ecology*, Vol. 50, No. 1, 1969, pp. 45–53.

SENECA, E. D., "Germination and Seedling Response of Atlantic and Gulf Coast Populations of *Uniola paniculata*," *American Journal of Botany*, Vol. 59, No. 3, Mar. 1972a, pp. 290–296.

SENECA, E. D., "Seedling Response to Salinity in Four Dune Grasses from the Outer Banks of North Carolina," *Ecology*, Vol. 53, No. 3, 1972b pp. 465–471.

SMITH, D., PAULSEN, G. M., and RAGUSE, C. A., "Comparative Accuracy and Efficiency in Determination of Carbohydrates from Grasses and Legume Tissue," *Plant Physiology*, Vol. 39, 1964, pp. 960–962.

STRATTON, A. C., "Beach Erosion Control in the Cape Hatteras National Seashore Recreational Area," *Shore and Beach*, Vol. 25, No. 1, Apr. 1957, pp. 4–8.

TAUSCHER, S. W., "Interim Report on Sand Dune Stabilization Experiments, Padre Island National Seashore, July 1966," Corpus Christi, Tex., 1966.

TSURIELL, E. D., "Sand Dune Stabilization in Israel," Soil Conservation Department, Ministry of Agriculture, Israel, June 1966.

U.S. ARMY ENGINEER DISTRICT, GALVESTON, "Report on Hurricane Carla, September 1961," Galveston, Tex., 1962.

U.S. ARMY ENGINEER DISTRICT, GALVESTON, "Report on Hurricane Beulah, September 1967," Galveston, Tex., 1968.

U.S. ARMY ENGINEER DISTRICT, GALVESTON, "Report on Hurricane Celia, 30 July to 5 August 1970," Galveston, Tex., Feb. 1971.

VAN DER BURGT, J. H., and VAN BENDEGOM, L., "The Use of Vegetation to Stabilize Sand-dunes," *Biology and Civil Engineering*, The Institution of Civil Engineers, Westminster, England, 1949, pp. 158–170.

WAGNER, R. H., "The Ecology of *Uniola paniculata* L. in the Dune Strand Habitat of North Carolina," *Ecological Monograph*, Vol. 34, 1964, pp. 79–96.

WALSH, B. N., "Some Notes on the Incidence and Control of Driftsands along the Caledon, Bredasdarp and Riverdale Coastline of South Africa," Department of Forestry Bulletin No. 44, Pretoria, South Africa, 1968, pp. 1–79.

WATSON, R. L., "Origin of Shell Beaches, Padre Island, Texas," *Journal of Sedimentary Petrology*, Vol. 41, No. 4, Dec. 1971, pp. 1105–1111.

WEINMANN, H., "Total Available Carbohydrates in Grass and Legumes," *Herbage Abstracts*, Vol. 31, No. 4, 1961, pp. 255–261.

WELLS, B. W., and **SHUNK, I. V.,** "Salt Spray: An Important Factor in Coastal Ecology," *Bulletin Torrey Botanical Club*, Vol. 65, 1938, pp. 485–492.

WESTGATE, J. M., "Reclamation of Cape Cod Sand Dunes," Bulletin No. 65, Bureau of Plant Industry, U.S. Department of Agriculture, Washington, D.C., 1904.

WESTRA, R. N., and **LOOMIS, W. E.,** "Seed Dormancy in *Uniola paniculata,*" *American Journal of Botany,* Vol. 53, No. 4, 1966, pp. 407–411.

WOODHOUSE, W. W., Jr., "Beach and Dune Stabilization with Vegetation on the Outer Banks of North Carolina," *Proceedings North Carolina Soil Science Society*, Vol. 6, 1963, pp. 72–76.

WOODHOUSE, W. W., Jr., and **HANES, R. E.,** "Dune Stabilization with Vegetation on the Outer Banks of North Carolina," TM 22, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Washington, D.C., Aug. 1967.

WOODHOUSE, W. W., Jr., SENECA, E. D., and **COOPER, A. W.,** "Use of Sea Oats for Dune Stabilization in the Southeast," *Shore and Beach*, Vol. 36, No. 2, Oct. 1968, pp. 15–21.

ZAK, J. M., "Sand Dune Erosion Control at Provincetown, Massachusetts," *Journal of Soil and Water Conservation*, No. 4, July-Aug. 1965, pp. 188–189.

ZAK, J. M., and **BREDAKIS, E.,** "Dune Stabilization at Provincetown, Massachusetts," *Shore and Beach*, Vol. 31, No. 2, Oct. 1963, pp. 19–24.

APPENDIX A

SPECIFICATIONS AND CONTRACT-PERFORMANCE GUIDELINES FOR THE CONSTRUCTION OF VEGETATED, STABILIZED FOREDUNES

This appendix is a synopsis of procedures to be followed for constructing or stabilizing foredunes. The sequence of events is illustrated in a flow diagram. Subsection categories and numbers in the appendix follow this figure. At the end of each subsection, reference is made to the appropriate section in the text for more detailed information.

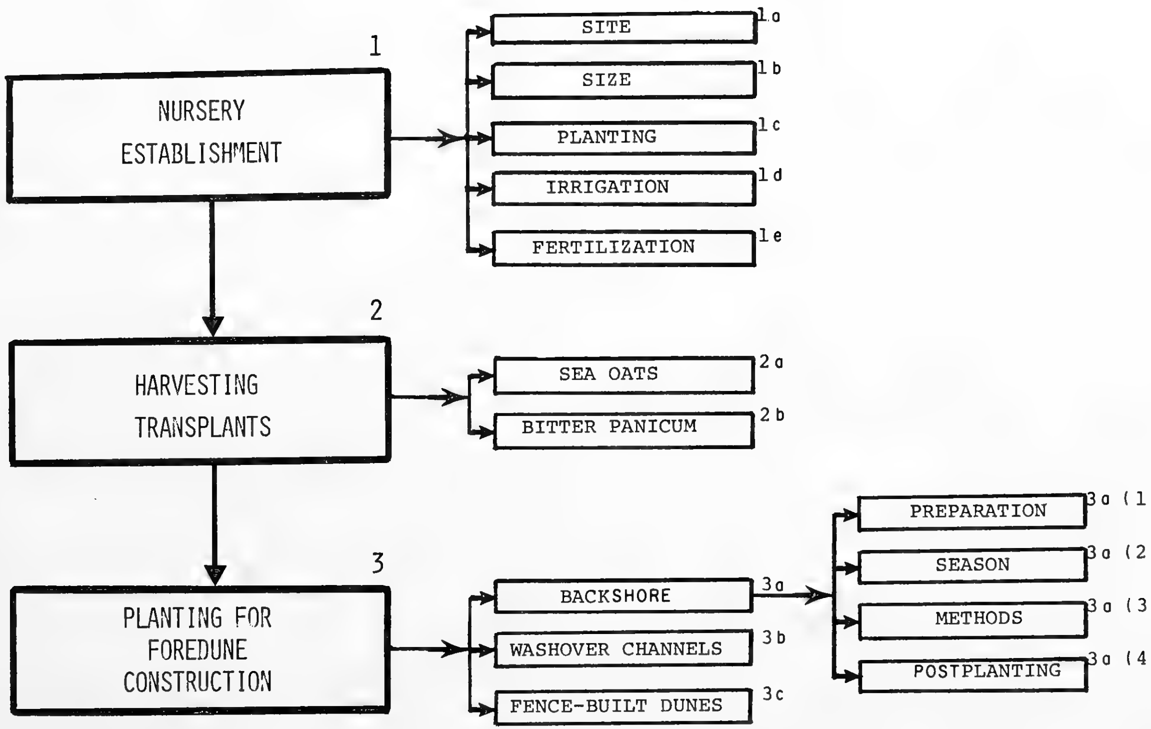
1. Nursery Establishment.

If the proposed planting is extensive, a nursery of bitter panicum should be established at least a year and sea oats 2 years before planting, unless adequate wild stock exists. A nursery ensures an abundant and easily procured supply of transplant stock of the two grasses used for dune stabilization, reduces harvesting effort and time, and yields transplants of more uniform size. Wild stock of sea oats may be used instead of nursery stock if it occurs as a recent colonizer (small clumps or low dunes) in a low flat area protected from accumulating sand. Procuring wild stock from large dunes (either actively growing or mature) is not recommended due to excessive harvesting time and effort. Wild bitter panicum stock may be procured from lee slopes of dunes where little fresh sand accumulates, or from recently colonized low protected plains (Sec. V, 2c).

a. Site. The nursery site should be located in a flat area away from the beach, or if near the beach, the site must be leeward of an established dune line. Of primary importance is minimal drifting sand. A barren, uncolonized deflation plain (following passage of a migrating dune field) is a good site. A mature grassland in mid-island may also be used, but should be graded to remove all vegetation 6 inches below the original surface, or fumigated well in advance of planting. Periodic weeding after planting is necessary (Sec. V, 2e).

b. Size. A 1-acre nursery of either bitter panicum or sea oats will yield a minimum of 100,000 transplants, enough for a beach planting 1.5 miles long and 50 feet wide. Density of bitter panicum culms large enough for planting can be as high as 400,000 per acre, and this number can be increased substantially by segmenting large culms into two or more pieces. A bitter panicum nursery denuded for transplants in winter will be at nearly full capacity by the following winter (Sec. V, 2d, 2g).

c. Planting. The nursery should be established in monospecific units for easier harvesting. Sea oats should be planted in mid-winter for first harvesting the following winter or preferably the second winter. Bitter panicum should be planted in mid-winter to late spring for harvesting the following winter. Planting is faster with a tobacco transplanter and tractor, and requires a crew of five. If the substrate is moist to the surface, hand planting with a shovel is nearly as rapid, but more tedious. Machine planting a 1-acre nursery with 2 feet between single-culm hills and 3 feet between rows to allow mechanical cultivation, requires about 31 man-hours for bitter panicum and about 56 man-hours for sea oats. Time



Flow Diagram: Specifications and contract performance guidelines for establishing stabilized foredunes.

will be increased if wild stock for the initial nursery is rare, scattered, or away from the planting site. Culms should be planted at least 8 inches deep so that drying of the soil at the root zone does not occur (Sec. V, 2e, 3f, 4b, 4f, 4i).

d. Irrigation. If the surface is dry to a depth of several inches, irrigation is necessary before planting. It is essential that at least the basal nodes of the culm be seated in moist sand (field capacity or at least 4 percent). Irrigation after planting is unnecessary if precipitation is near or above normal. During droughts, the nursery should be irrigated about twice monthly for several months after planting so that moisture at the root zone remains at or above field capacity.

Irrigation water can be obtained from an open pit, 40 to 50 feet square and 5 feet deep (2 to 3 feet below the water table), and can be dug with a backhoe in 3 or 4 hours. Salinity of the irrigation water should be less than 5,000 micromhos per centimeter; before excavation, the water table should be tested. A system of 1.5-inch flexible plastic irrigation pipe with sprinklers every 40 feet and powered by a portable centrifugal pump with a 7.5 horsepower gasoline engine was used effectively in the Padre Island tests, but any similar system is suitable. A 10-head system watered a 400- by 40-foot area at the rate of about 3.5 gallons per minute per head, or the equivalent of 1 inch precipitation every 4 to 5 hours. A full day of irrigation may be required to wet the substrate thoroughly (Sec. V, 4k, 5a).

e. Fertilization. The nursery should be fertilized for several months after planting, or when active transplant growth begins. A complete (nitrogen-phosphorus-potassium) fertilizer with a total rate of 120 to 180 pounds per acre of nitrogen should be applied. This rate is best split into two or three equal applications, and applied in late spring through summer. Annual fertilization may be necessary to maintain a dense stand of large culms in a nursery protected from accumulating sand (Sec. V, 5b).

2. Harvesting Transplants.

a. Sea Oats. Transplants should be dug carefully with a shovel to dislodge the culm intact, since the congested nodes are nearly always buried. Small clumps of sea oats 1 yard or more in diameter should be removed from the ground leaving a few culms and rhizomes for reestablishment. The individual culms are then separated by hand. All sizes of culms make acceptable transplants, although very small seedlings can not be handled easily and should not be selected. To reduce bulk, the distal part of the leaf blades can be removed with a machete, leaving about 15 inches of culm base. This is an essential step for machine planting since untrimmed culms will often lodge in the transplanter. The transplants are then tied in bundles of 100 or 200 plants, or packed base-first in bushel baskets. After digging, the transplants may be stored 3 to 4 days in freshwater by immersing the basket or base of the bundle. A longer storage period will reduce survival potential. Plants may be stored overnight or during the planting operation by partial burial in wet sand or by covering with a tarp, to minimize dessication (Sec. V, 2f, 3g).

b. Bitter Panicum. Culms are most easily pulled by hand. Roots are not necessary, and the culms can be broken off at ground level. Culms 1.5 to 3 feet in length should be selected over those under 10 inches. If over 3 feet long, the culm should be broken in half, and both halves planted. The distal part of the culm can be trimmed to reduce bulk; the basal part should be about 15 inches long. For machine planting, dead leaves must be removed from the culm when trimmed. Neither of these procedures is necessary for hand planting. Bitter panicum culms should be bundled or placed in bushel baskets and can be stored in freshwater for at least a month after harvesting with no loss of survival potential. Short-term storage is the same as sea oats (Sec. V, 2f, 3g).

3. Planting for Foredune Construction.

a. Backshore.

(1) Preparation. Backshore areas denuded by broad overwash or wind erosion, and which are generally between 4 to 6 feet MSL, can be easily and successfully restored by planting sea oats and bitter panicum directly on the beach surface. If surface sand is dry to a depth of several inches (during droughts in winter, and regularly in summer) an irrigation system may be installed and the substrate thoroughly wetted before planting. Otherwise, plant after a soaking rain. If many small dunes of barren sand occur, the area should be leveled. Subsurface (6-inch depth) sand should have a salinity of less than 2,000, and preferably less than 1,000 micromhos per centimeter (2:1 dilution, ml H_2O:gm dry sand). Irregular surges may inundate the backshore area, especially in winter and spring, and salinities will be above 2,000 micromhos per centimeter for a short period following inundation. (Sec. V, 3a, 4a, 4k).

(2) Season. Best results with sea oats usually can be expected in mid- to late winter. Bitter panicum can be planted at any season, but winter through late spring is recommended. Autumn for either species is generally poorer. Large plantings of both species are best made in January and February, since the climate is more favorable for physical labor and the substrate is less subject to severe evaporation. The condition of the substrate, i.e., high moisture content at surface and root zone, and low salinity, is the main factor in determining planting time. (Sec. V, 3a, 3b, 3f).

(3) Methods. Extensive beach plantings should be made with a tobacco transplanter and tractor, with the trimmed culms placed vertically on 2-foot centers, 8 inches deep, and one culm per hill. The planting should be 40 to 50 feet wide, and inland from the shoreline (MSL) about 400 to 500 feet. If the substrate is very moist to the surface, untrimmed culms may be placed horizontally in open 8-inch-deep furrows, and heel-closed. A mixed-species planting, consisting of three or four rows of bitter panicum to one row of sea oats is most desirable, but monospecific plantings may be used. In monospecific planting, bitter panicum is the better choice because it has higher survival than sea oats, is easier to procure and handle, and begins growth more quickly. Obtaining transplants and machine planting a 1-mile-long by 50-foot-wide strip require about 500 man-hours for sea oats and 287 man-hours for bitter panicum (Sec. V, 4f, 4i).

(4) Postplanting. Planting survival of less than 10 percent will require replanting; even a successful planting has local areas of poor or no survival which also must be replanted. A planting with 20 percent or greater survival, if reasonably uniform, should not require replanting other than local patching. Sea oats survival may be determined 2 or 3 months after planting regardless of season. Bitter panicum survival cannot be determined accurately until April or May for winter plantings, but for late spring to summer plantings, after 1 or 2 months. Ideally, a winter planting with poor survival should be replanted or patched as soon as possible—late spring or summer if soil conditions permit, or no later than the following winter.

The planting should be fertilized when active growth begins, and the best time is late spring through summer. For mixed plantings any complete fertilizer with a total 120 to 180 pounds per acre of nitrogen split in two to three equal applications should result in dense and uniform cover by the first autumn. Subsequent fertilization, after the initial postplanting, is not recommended except for local weak areas which are not effectively trapping sand.

If cattle are present or human use of the area is high, the planting should be protected for at least 1 year with a two or three-strand wire fence. About 4 or 5 years after the initial planting, another 50-foot-wide strip should be planted immediately shoreward to allow a resultant dune width of greater than 100 feet. The area should be graded before planting to remove small barren dunes. Established or colonizing small clumps of sea oats and bitter panicum should be left intact, but low sea purslane dunes should be removed (Sec. V, 3a, 5, 6a).

b. *Hurricane Washover Channels.* These channels, of lower elevation and much higher salinity than the barren backshore, require a special technique. Parallel rows of 2-foot-high picket snow fencing, spaced 8 to 12 feet apart to a 50-foot width, must be constructed across the channel 1 year before planting. After the fences have filled with sand to a nearly level surface, it should be planted. Earlier planting will result in burial and death of many transplants. Mulch-netting is not required. If the surface sand is dry, irrigate the substrate before planting. Subsequent irrigation (postplanting) is useful only during droughts. The surface may be planted by machine or by hand. Hand planting is preferred since plants can be placed 12 inches deep to minimize blowouts, and since the transplanter is not completely effective on the somewhat undulating surface. Planting season and fertilization rates are the same as for backshore plantings. The initial fence system and planting should be recessed 400 to 500 feet from the shoreline to allow a 50-foot-wide shoreward extension planting after 5 years to broaden the foredune width (Sec. V, 4d, 4f, 4k, 5a, 5b, 6d).

c. *Fence-Built Dunes.* Barren dunes constructed with one or several tiers of sand fencing can be vegetated and stabilized with sea oats and bitter panicum, but the effort and cost are greater than beach plantings of comparable size. It is essential to delay planting until the fences have filled to capacity with sand, which may be a year or more after erection of the last tier. Earlier planting will result in burial and loss of many transplants. An irrigation system to thoroughly moisten the planting surface is essential, and may require 2 or 3 days of successive preplanting irrigation. Since dry-sand drifts form quickly, it is not sufficient to rely on a soaking rain. All planting can easily be done by hand with two-man crews. Plants should be spaced on 2-foot centers, or as close as 1.5 feet. A mixed planting of bitter panicum and sea oats (ratio of 3 or 4 to 1) is recommended. Time of planting should be late winter to spring. The mid-winter climate is more suitable for extensive hand labor, but spring-planted culms begin growth more quickly. Immediately after planting, mulch-netting must be placed over the plants and secured to the ground with staples. The netting should be stretched tightly over the tops of the plants, so that it bends the exposed culm. Due to the exposed culms, the netting will not touch the soil in all places; however, it will function to reduce or eliminate wind erosion. No planted areas should be left unmulched since wind erosion and plant excavation will be locally severe. The netting should be continuous from the foreslope to the backslope. If mulched, the major deterrent to survival will be burial of backslope transplants by sand drifts originating from the beach. If the initial planting is not entirely successful, it will be necessary to replant and remulch the barren sections; this can be done in late spring, early summer, or the following winter.

Irrigation after planting may be useful during droughts and hot weather, since the elevated dune surface dries rapidly. With normal rainfall (2 or more inches per month) it is not necessary to irrigate after planting. During droughts, irrigate often enough to keep the subsurface sand moist (3 to 4 inches). Drying of the surface layer is not critical as long as the underlying sand is at field capacity. During winter, irrigation twice a month for 1 or 2 days should be sufficient. During spring or summer, more frequent irrigation may be needed.

The planting should be fertilized in the same manner as beach plantings. The irrigation system can be used to soak in the nutrients. Otherwise, apply the subsequent treatment after a heavy rain. Fertilization is needed only the first year to ensure uniform cover (Sec. V, 4c, 4f, 4k, 4m, 5a, 5b).

APPENDIX B

GLOSSARY OF GRASS TERMINOLOGY

annual—One season's duration from seed to maturity and death.

apical shoot—Shoot growing from the terminal end of a culm.

blade—Expanded part of a leaf.

culm—Stem of grasses, usually hollow except at the swollen nodes.

inflorescence—Flower cluster of a plant or the arrangement of flowers on the floral axis.

internode—Part of stem between two nodes.

lateral shoot—Shoot growing from one side of a grass culm as opposed to the terminal end of the culm. (For this study, a shoot developing from an elevated node or leaf axil as opposed to a basal node.)

node—Joint of a stem where a leaf is borne or may be borne. Buds are also commonly borne at the node.

panicle—Open, branching inflorescence, as in oats and some other grasses.

perennial—Living from year to year, not dying after once flowering.

primary shoot—Main stem of a grass clump or clone; the oldest stem of a clump. The first culm developed from a seed.

primary tiller—Lateral branch or shoot developing from buds of the primary shoot.

reproductive culm—Any grass stem that has developed an inflorescence at its terminal end. The inflorescence may be minute and unexposed.

rhizome—Underground stem or rootstock, with scales at the nodes. Forms buds at the nodes that may, under proper stimulus, develop into leafy shoots. Roots also develop from the nodes. New shoots are usually produced from the tip of the rhizome.

secondary tiller—Lateral branch or shoot developing from buds of primary tillers.

sheath—Tubular basal part of the leaf that encloses the stem, as in grasses and sedges.

shoot—Collective term applied to the stem and leaves, or any young growing branch or twig.

spikelet—Ultimate flower cluster in grasses and sedges consisting of two glumes and one or more florets (individual flower).

stem—Main axis of a plant, leaf-bearing and flower-bearing as distinguished from the root-bearing axis.

stolon—Horizontal stem usually above the soil surface. Forms buds at the nodes from which tillers may originate. Adventitious roots may also develop from the nodes. New shoots may arise from the tip of the stolon.

tiller—Branch from the axil of a lower leaf, as in grasses; i.e., a branch or shoot developing from a bud located at a node.

transplant—Shoot or culm removed from one location and replanted in another.

vegetative culm—Any grass stem that has not formed even a miniature inflorescence.

Dahl, Bill E.

Construction and stabilization of coastal foredunes with vegetation: Padre Island, Texas, by Bill E. Dahl, Bruce A. Fall [and others]. Fort Belvoir, Va., U.S. Coastal Engineering Research Center, 1975.

188 p. illus. (U.S. Coastal Engineering Research Center. Miscellaneous paper no. 9-75). (U.S. Coastal Engineering Research Center. Contract DACW72-69-C-0012; also Contract DACW72-72-C-0013).

Experiments to establish specifications and methodologies for beach grasses in constructing and stabilizing foredunes as storm surge barriers along the gulf coast are presented. Conclusions are based on 2.5 linear miles of experimental plots with beach plantings and fence-built dunes on Padre Island, Texas. Results of greenhouse experiments on the effects of nutrients and salinity on beach grass growth are also presented.

1. Grasses. 2. Sand dunes - Stabilization. 3. Shore protection. I. Title. II. Fall, Bruce A., joint author. (Series) (Contract)

TC203 .U581mp no. 9-75 627 .U581mp

Dahl, Bill E.

Construction and stabilization of coastal foredunes with vegetation: Padre Island, Texas, by Bill E. Dahl, Bruce A. Fall [and others]. Fort Belvoir, Va., U.S. Coastal Engineering Research Center, 1975.

188 p. illus. (U.S. Coastal Engineering Research Center. Miscellaneous paper no. 9-75). (U.S. Coastal Engineering Research Center. Contract DACW72-69-C-0012; also Contract DACW72-72-C-0013).

Experiments to establish specifications and methodologies for beach grasses in constructing and stabilizing foredunes as storm surge barriers along the gulf coast are presented. Conclusions are based on 2.5 linear miles of experimental plots with beach plantings and fence-built dunes on Padre Island, Texas. Results of greenhouse experiments on the effects of nutrients and salinity on beach grass growth are also presented.

1. Grasses. 2. Sand dunes - Stabilization. 3. Shore protection. I. Title. II. Fall, Bruce A., joint author. (Series) (Contract)

TC203 .U581mp no. 9-75 627 .U581mp

Dahl, Bill E.

Construction and stabilization of coastal foredunes with vegetation: Padre Island, Texas, by Bill E. Dahl, Bruce A. Fall [and others]. Fort Belvoir, Va., U.S. Coastal Engineering Research Center, 1975.

188 p. illus. (U.S. Coastal Engineering Research Center. Miscellaneous paper no. 9-75). (U.S. Coastal Engineering Research Center. Contract DACW72-69-C-0012; also Contract DACW72-72-C-0013).

Experiments to establish specifications and methodologies for beach grasses in constructing and stabilizing foredunes as storm surge barriers along the gulf coast are presented. Conclusions are based on 2.5 linear miles of experimental plots with beach plantings and fence-built dunes on Padre Island, Texas. Results of greenhouse experiments on the effects of nutrients and salinity on beach grass growth are also presented.

1. Grasses. 2. Sand dunes - Stabilization. 3. Shore protection. I. Title. II. Fall, Bruce A., joint author. (Series) (Contract)

TC203 .U581mp no. 9-75 627 .U581mp

Dahl, Bill E.

Construction and stabilization of coastal foredunes with vegetation: Padre Island, Texas, by Bill E. Dahl, Bruce A. Fall [and others]. Fort Belvoir, Va., U.S. Coastal Engineering Research Center, 1975.

188 p. illus. (U.S. Coastal Engineering Research Center. Miscellaneous paper no. 9-75). (U.S. Coastal Engineering Research Center. Contract DACW72-69-C-0012; also Contract DACW72-72-C-0013).

Experiments to establish specifications and methodologies for beach grasses in constructing and stabilizing foredunes as storm surge barriers along the gulf coast are presented. Conclusions are based on 2.5 linear miles of experimental plots with beach plantings and fence-built dunes on Padre Island, Texas. Results of greenhouse experiments on the effects of nutrients and salinity on beach grass growth are also presented.

1. Grasses. 2. Sand dunes - Stabilization. 3. Shore protection. I. Title. II. Fall, Bruce A., joint author. (Series) (Contract)

TC203 .U581mp no. 9-75 627 .U581mp

Dahl, Bill E.
Construction and stabilization of coastal foredunes with vegetation: Padre Island, Texas, by Bill E. Dahl, Bruce A. Fall [and others]. Fort Belvoir, Va., U.S. Coastal Engineering Research Center, 1975.
188 p. illus. (U.S. Coastal Engineering Research Center. Miscellaneous paper no. 9-75). (U.S. Coastal Engineering Research Center. Contract DACW72-69-C-0012; also Contract DACW72-72-C-0013).

Experiments to establish specifications and methodologies for beach grasses in constructing and stabilizing foredunes as storm surge barriers along the gulf coast are presented. Conclusions are based on 2.5 linear miles of experimental plots with beach plantings and fence-built dunes on Padre Island, Texas. Results of greenhouse experiments on the effects of nutrients and salinity on beach grass growth are also presented.
1. Grasses. 2. Sand dunes - Stabilization. 3. Shore protection. I. Title. II. Fall, Bruce A., joint author. (Series) (Contract)

TC203 .U581mp no. 9-75 627 .U581mp

Dahl, Bill E.
Construction and stabilization of coastal foredunes with vegetation: Padre Island, Texas, by Bill E. Dahl, Bruce A. Fall [and others]. Fort Belvoir, Va., U.S. Coastal Engineering Research Center, 1975.
188 p. illus. (U.S. Coastal Engineering Research Center. Miscellaneous paper no. 9-75). (U.S. Coastal Engineering Research Center. Contract DACW72-69-C-0012; also Contract DACW72-72-C-0013).

Experiments to establish specifications and methodologies for beach grasses in constructing and stabilizing foredunes as storm surge barriers along the gulf coast are presented. Conclusions are based on 2.5 linear miles of experimental plots with beach plantings and fence-built dunes on Padre Island, Texas. Results of greenhouse experiments on the effects of nutrients and salinity on beach grass growth are also presented.
1. Grasses. 2. Sand dunes - Stabilization. 3. Shore protection. I. Title. II. Fall, Bruce A., joint author. (Series) (Contract)

TC203 .U581mp no. 9-75 627 .U581mp

Dahl, Bill E.
Construction and stabilization of coastal foredunes with vegetation: Padre Island, Texas, by Bill E. Dahl, Bruce A. Fall [and others]. Fort Belvoir, Va., U.S. Coastal Engineering Research Center, 1975.
188 p. illus. (U.S. Coastal Engineering Research Center. Miscellaneous paper no. 9-75). (U.S. Coastal Engineering Research Center. Contract DACW72-69-C-0012; also Contract DACW72-72-C-0013).

Experiments to establish specifications and methodologies for beach grasses in constructing and stabilizing foredunes as storm surge barriers along the gulf coast are presented. Conclusions are based on 2.5 linear miles of experimental plots with beach plantings and fence-built dunes on Padre Island, Texas. Results of greenhouse experiments on the effects of nutrients and salinity on beach grass growth are also presented.
1. Grasses. 2. Sand dunes - Stabilization. 3. Shore protection. I. Title. II. Fall, Bruce A., joint author. (Series) (Contract)

TC203 .U581mp no. 9-75 627 .U581mp

Dahl, Bill E.
Construction and stabilization of coastal foredunes with vegetation: Padre Island, Texas, by Bill E. Dahl, Bruce A. Fall [and others]. Fort Belvoir, Va., U.S. Coastal Engineering Research Center, 1975.
188 p. illus. (U.S. Coastal Engineering Research Center. Miscellaneous paper no. 9-75). (U.S. Coastal Engineering Research Center. Contract DACW72-69-C-0012; also Contract DACW72-72-C-0013).

Experiments to establish specifications and methodologies for beach grasses in constructing and stabilizing foredunes as storm surge barriers along the gulf coast are presented. Conclusions are based on 2.5 linear miles of experimental plots with beach plantings and fence-built dunes on Padre Island, Texas. Results of greenhouse experiments on the effects of nutrients and salinity on beach grass growth are also presented.
1. Grasses. 2. Sand dunes - Stabilization. 3. Shore protection. I. Title. II. Fall, Bruce A., joint author. (Series) (Contract)

TC203 .U581mp no. 9-75 627 .U581mp