SR - 3

Dune Building and Stabilization With Vegetation

by

W. W. Woodhouse, Jr.

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This is the first comprehensive report on dune building and stabilization in the United States. The practical information on methods and dune plants is the result of more than 20 years of experimentation in coastal areas from the mouth of the Columbia River in Oregon through southern California and the Gulf of Mexico to Cape Cod, Massachusetts. The use of fences and vegetation for dune creation is discussed, and the labor and material requirements for dune creation and sand stabilization projects are summarized. The major plants
(continued)

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) suitable for dune building, their propagation and planting requirements, and the stabilization of dunes by various means such as matting, fences, and vegetation, are given for the major coastal regions of the contiguous United States. The techniques discussed are now applicable to these coastal regions.

PREFACE

This report is published to provide coastal engineers with the first comprehensive report on dune building and stabilization in the United States, the results of over 20 years of experimentation in the major coastal regions. The work was carried out under the coastal ecology research program of the U.S. Army Coastal Engineering Research Center (CERC).

This report is one of a series of reports to be published to form a Coastal Engineering Manual.

The report was prepared by W.W. Woodhouse, Jr., Professor of Soil Science, North Carolina State University, under CERC Contract No. DACW72-76-C-0006.

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R.M. Yancey was the contract monitor of the report, under the general supervision of E.J. Pullen, Chief, Coastal Ecology Branch, Research Division, CERC.

Comments on this publication are invited.

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

JOHN H. COUSINS
Colonel, Corps of Engineers
Commander and Director

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CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.852	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.01745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1]To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$.
To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

DUNE BUILDING AND STABILIZATION WITH VEGETATION

by
W.W. Woodhouse, Jr.

I. INTRODUCTION

This report describes the state-of-the-art of utilizing natural processes in the growth and protection of coastal dunes. These dunes may appear in the form of barrier dunes or dune fields near the shore or as dune ridges and dune fields of various kinds farther inland. This report deals primarily with the barrier-type dunes that form in continuous ridges, usually parallel to the beach, and tend to act as barriers to storm tides and waves (Fig. 1).

1. Formation.

Barrier dunes are usually formed through the trapping of sand by dune vegetation. This vegetation has the special adaptation that enables the dunes to establish, grow, and trap sand in a harsh environment. In the absence of such vegetation, the sand tends to drift into migrating or "live" dunes and dune fields that move back and forth with the wind. Where onshore winds dominate, the dunes coalesce into large sand masses and migrate inland, engulfing everything in their paths (Fig. 2). This also occurs when the vegetation on stabilized dunes is seriously damaged or destroyed. Extensive areas of migrating coastal dunes have developed on various coasts because of fire, lumbering, grazing, and foot and vehicular traffic. Migrating dunes were a concern of the colonists on Cape Cod as early as 1714 (Westgate, 1904).

Barrier dune formation by vegetation usually begins with the entrapment of seeds or plant material in debris deposited back of the beach berm by storms or very high tides. Initially, these may develop as a series of small dunelets formed around individual seedlings or clumps of seedlings, and enlarge and eventually grow together into a continuous dune (Fig. 3). The irregular front is later cut back to form a dune "line" by storm surge and waves. In more favorable circumstances, large numbers of seedlings establish in debris along a continuous drift line, and grow a continuous dune from the start.

In either case, the natural development of a substantial barrier dune depends on a fortuitous sequence of events and circumstances: the deposition of debris plus sand at the right time and place, followed by suitable seeds or plants and the continued deposition of sand, together with a year or two of favorable growing conditions without excessively severe storms. However, the complete sequence does not occur on most coasts every year and is very rare on some coasts. The early phases frequently develop on many coasts, but the embryo dunes are usually destroyed by storm activity before gaining sufficient mass and elevation to survive normal weather events. However, it is a process which can be simulated, managed, and utilized as an engineering tool (Fig. 4).

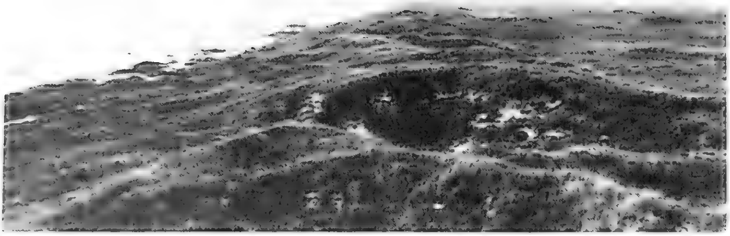

Figure 1. Large stable barrier dune, Padre Island, Texas.

Figure 2. Live dune encroaching on forest vegetation (Kill Devil Hills, North Carolina).

Figure 3. Sea oats dunelets forming in front of a barrier dune.

Figure 4. Dune developing around a planting of dune grasses.

2. Use.

Coastal barrier dunes are valuable to coastal protection in several ways. Continuous barrier dunes serve as flexible barriers to storm surges and waves, and are of particular value in affording protection to low-lying backshore areas and in helping to preserve the integrity of low barrier islands. For example, adequately stabilized and carefully protected foredunes play a significant role in the sea defenses of Holland (Adriani and Terwindt, 1974). Where there is an adequate natural sand supply, dunes provide protection more effectively and at a lower cost than a seawall.

Well-developed barrier dunes perform another important function by providing stockpiles of sand to nourish the beach during storm attack. Storm waves erode sand from the berm and foredune, much of which is deposited immediately offshore in a bar formation, which allows the beach profile to adjust to the energy of the storm (Fig. 5). In the absence of the dune sand reservoir, sand for storm profile adjustments must come from either the shore behind or the beach. In a stable beach-dune system, sand removed from berm and dune by storms is returned to the beach and berm by calm weather between storms. Thus, it is available to rebuild the dune, a necessary process in maintaining a dynamic equilibrium within the beach-berm-dune system. Coastal dunes are also used for water storage and recreation, and are highly valued as wildlife habitats.

The use of dunes must be carefully controlled, and their management should always include provisions for repair and restoration, as required.

II. DUNE BUILDING

The creation of new barrier dunes or the rebuilding of damaged or incomplete foredunes may be done (a) mechanically, by moving sand into place by truck, bulldozer, pipeline dredge, etc., and grading it to suitable form, or (b) by trapping blowing sand by means of sand fences or vegetation or a combination of these, where sand supply and wind pattern permit. The latter method utilizes natural forces to create dunes in the same way they develop in nature. Man speeds up and guides the natural process. When this can be done, it is usually the most economical method. The natural way tends to discourage the placement of dunes in inappropriate or unnatural locations and is aesthetically pleasing.

1. Sand Movement.

Sand grains are transported by wind in three ways (Bagnold, 1941): (a) in suspension; (b) by saltation, bounced along as the impact of falling grains dislodges others; and (c) as bedload or surface creep, rolled across the surface. Since movement in suspension may be ignored except in the case of very fine sands or extremely high winds, sand accumulation methods are designed primarily to control surface creep and saltation (Fig. 6).

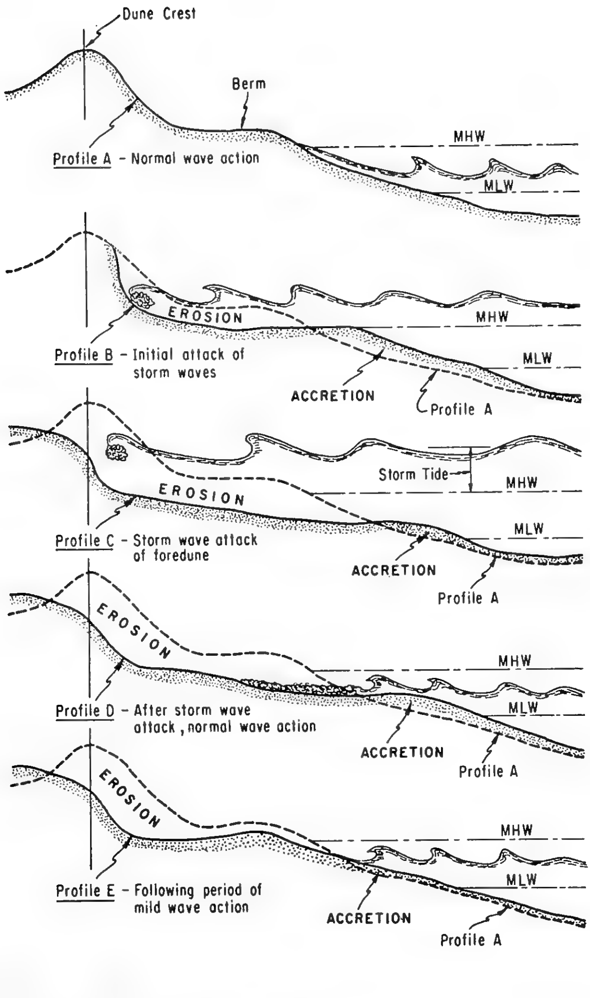

Figure 5. Beach profiles before, during, and after attack by storm waves.

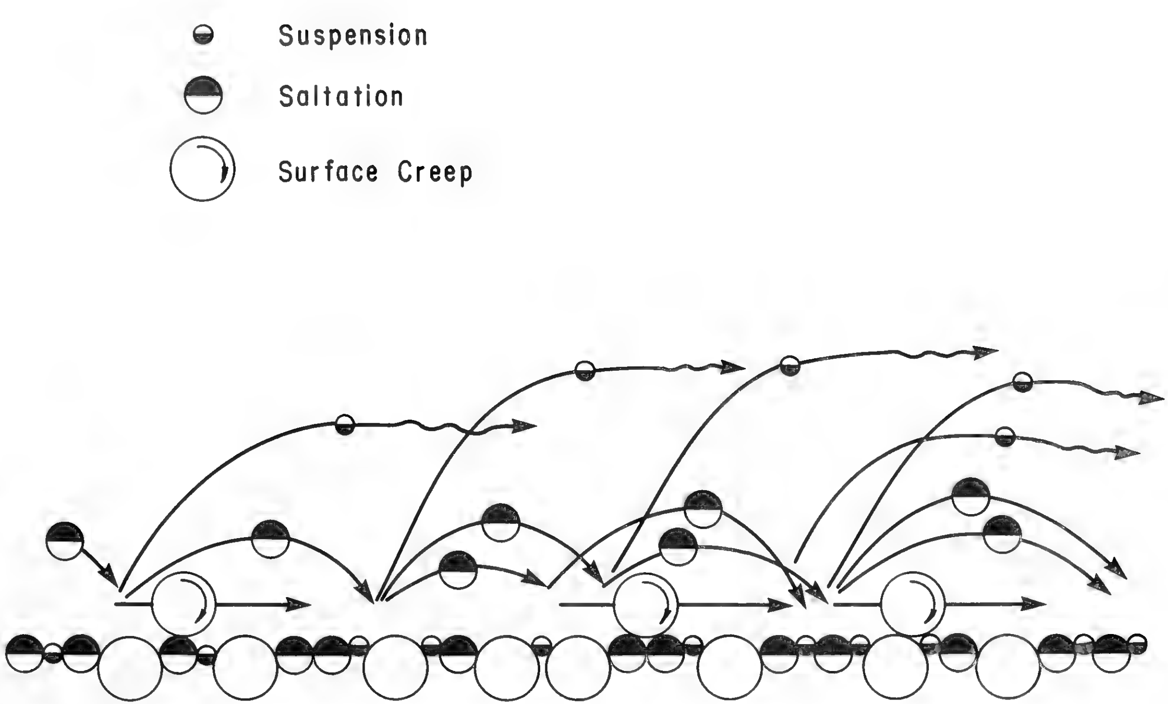

Figure 6. Schematic diagram showing wind movement of sand.

Location of a barrier dune can have a major influence on its durability and utility. Well-vegetated dunes are effective against storm tides and are capable of withstanding moderate degrees of overtopping, but they are highly vulnerable to undermining through beach recession and persistent wave attack. In the placement of a new barrier dune, an allowance should be made for the normal shoreline fluctuations characteristic of the site. Serious problems of dune maintenance may often be avoided or minimized by locating the foredune back from mean high water (MHW) far enough to allow for a reasonable amount of seasonal fluctuations. Dutch workers (Blumenthal, 1964) suggest that the minimum distance between the toe of the dune (sand fence) and MHW should be 200 meters.

It is also important to consider the nature of dune growth in locating a barrier dune. Fully vegetated dunes expand only toward the sand source, usually the beach, and a relatively narrow strip of vegetation will, in most cases, stop all wind-transported sand. This means that, where possible, allowance should be made for seaward expansion of the dune with time. Also, if two dunes are desired, the first must be developed landward and enough space left between it and the sea for the second or frontal dune.

On many low-lying coasts the crest of the storm berm is the highest point in the beach-dune area with the surface sloping back from it. This places the base of a new barrier dune below the elevation of the storm berm, making it more susceptible to overtopping during the early stages. It may also encourage ponding of water coming over the storm berm, resulting in water pressure, salt buildup, and destruction of vegetation along the toe of the dune. Where this problem exists, dune location must always represent a compromise.

2. Fences.

Sand fences slow sand movement by reducing wind velôcity in their immediate vicinity (Phillips, 1975). These fences are widely used to accumulate blowing sand. When properly designed and installed they can be very efficient sand-trapping devices. Savage (1963) obtained accumulations of 4.5 to 6 cubic meters of sand per meter of beach for single-slat fences and up to 8.5 cubic meters of sand per meter for double fence sections within a 7- to 8-month period. In a multiple fence experiment (Savage and Woodhouse, 1968), 39 cubic meters of sand per meter was trapped in 3 years using six fences starting with two 1.2-meter fences, 5 meters apart and adding fences in pairs as the earlier installations filled.

a. Types. Almost any material that forms a porous barrier to the wind may be used to construct a sand fence. Porosity is essential--a solid barrier will cause turbulence and scouring and may result in the loss rather than the accumulation of sand.

Earlier research involved driving pickets, composed of wooden sticks, boards, bamboo, reeds, etc., into the sand along lines to form "fences"

(Lehotsky, 1941; McLaughlin and Brown, 1942). All of these worked satisfactorily provided the pickets were placed so as to provide 25- to 50-percent porosity and were securely anchored in the sand. It was necessary to keep the top of the fence even to produce a uniform dune ridge.

Extensive use has been made of brush fences constructed either by burying the basal end of the brush in a trench or by clamping the brush together between poles or strips (Stratton and Hollowell, 1940) and fastening the units to posts, similar to the present wooden slat-type fence. Properly designed brush fences are very efficient sand trappers. Savage (1963) found them superior to the slat type but almost twice as expensive because of the high labor requirements. With the increase in labor costs since then, brush fences and the various versions formed by individual pickets have largely been replaced by prefabricated fences made from either wood or fabric.

(1) Slat Fence. The standard slat fence is constructed of wooden slats 1 centimeter by 3.8 centimeters by 1.2 meters, spaced 3.2 to 3.8 centimeters apart, held together by four or five double wires, twisted between each slat (Fig. 7). If durability is needed, wood may be treated with preservative and coated wire used. However, if the fence is effective, it is usually completely covered before serious deterioration occurs. If the cutting of the fence to form a 60-centimeter height is a possibility, the four-wire version is preferable. Fence is normally packaged in 15.2-meter rolls for ease of handling.

Slat fence is attached to posts for support. Various types of posts have been used but the standard arrangement (Savage, 1963) involves the use of 5.2-centimeter by 10.4-centimeter by 1.8-meter posts made from less expensive grades of lumber, set 60 centimeters deep, spaced 3 meters apart, with diagonal 2.5- by 15-centimeter braces at 9- to 12-meter intervals and on ends (Fig. 8). The fence wires are stapled to the posts. Where sand is exceptionally soft, it may be necessary to set posts deeper than 60 centimeters which usually increases the difficulty. Galvanized pipe has been used as posts and removed after the fence fills.

Slat fence is usually installed with the bottom at ground level. The effective height can be increased by raising the fence 30 centimeters above the ground but the fence will not fill as early and will be more susceptible to storm damage. The use of the 1.8-meter fence is usually impractical due to the effort required to set posts deep enough to support it.

The slat fence is fairly easy to install. A six-man crew, with materials available at the site and using a mechanical post-hole digger, can install 12.2 meters of fence per man hour. The present cost (1978) of the standard 1.2-meter slat fence, in quantity, is about $1.25 to $1.50 per meter.

(2) Fabric Fence. A number of fabrics made of weather-resistant synthetics have been used to construct sand fences in recent years (Fig. 9).

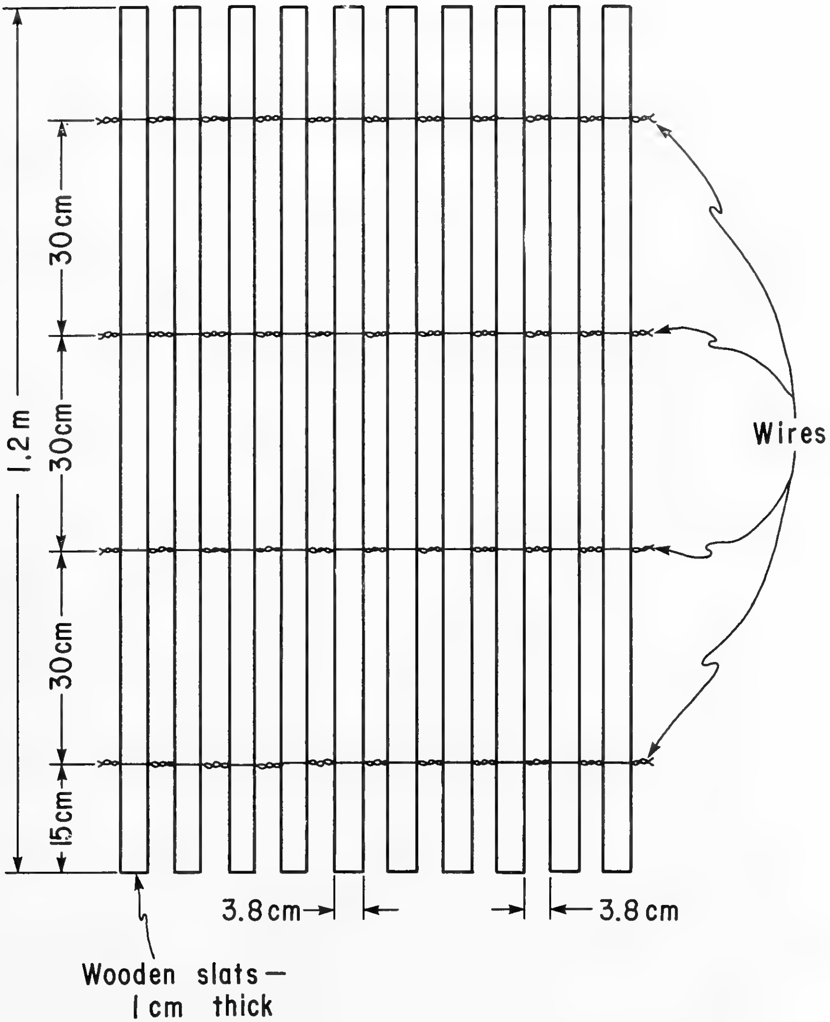

Figure 7. Typical wooden slat fence.

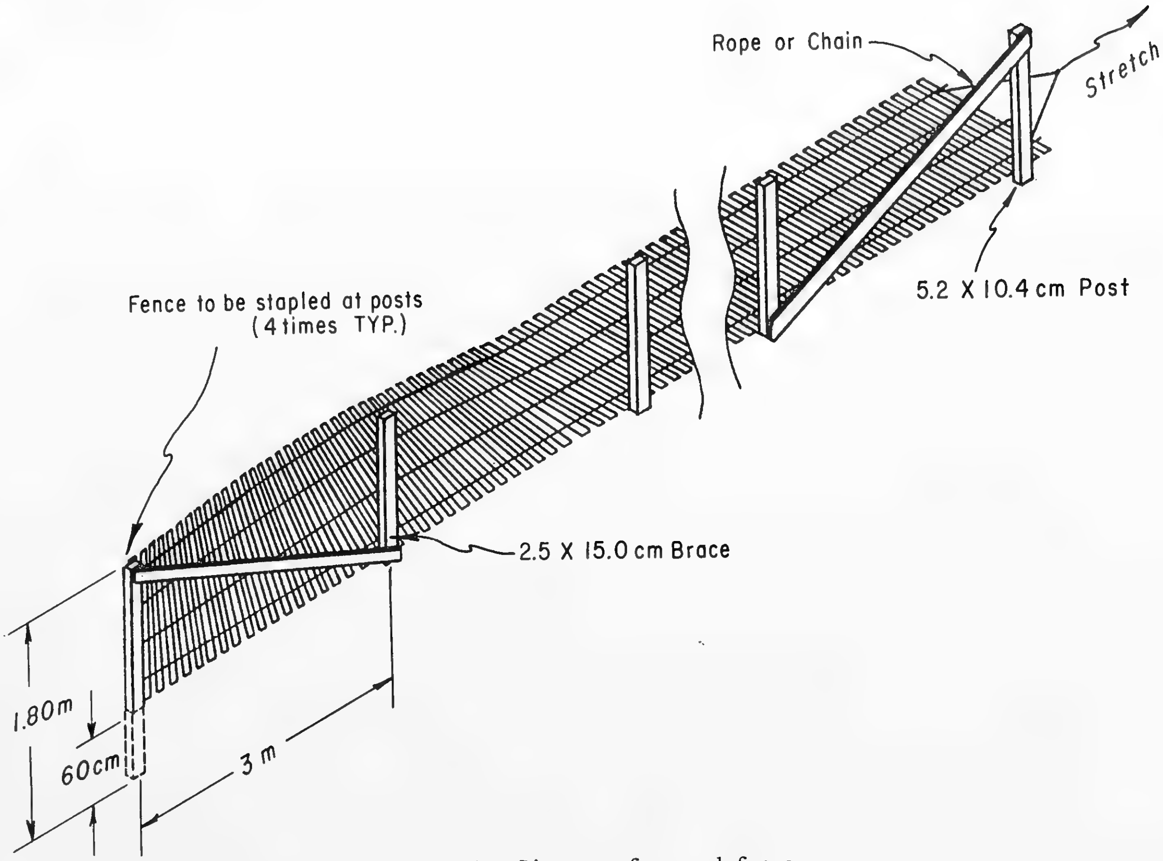

Figure 8. Diagram of a sand fence.

Figure 9. A typical fabric sand fence.

Fences of these materials have certain advantages over the standard slat fence. They are lighter in weight, less bulky, generally easier to handle, and may be more durable. Installation is similar to that of slat fence. The fabric is fastened to posts for support. These are usually 5.2-centimeter by 10.4-centimeter by 1.8-meter wood, set 3 meters apart, 60 centimeters in the ground with diagonal 2.5- by 15-centimeter braces at 9- to 12-meter intervals.

Fences made of several synthetics and covering a 40- to 86-percent range of porosities, have been compared with the 50-percent porous slat fence (Savage and Woodhouse, 1968). The results indicate that the fabric fence is effective in trapping sand provided the porosity is within a suitable range and the fence is adequately supported.

The critical importance of porosity is shown in Figure 10. Very little sand was trapped at porosities of 80 percent or above and the volume of sand trapped increased in an essentially linear fashion to the highest density tested. Unfortunately, the range of fabric densities did not reach the point beyond which increasing density appeared to decrease effectiveness. However, in light of what is known generally regarding the effect of porosity (Phillips, 1975), the maximum density tested (60-percent closed, 40-percent open) probably approached that limit.

Although fabric fences have some obvious advantages, mainly of convenience, and when properly installed with suitable porosities, appear to be roughly equal to slat fence, there are certain problems. All fabrics tested had a pronounced tendency to sag (between posts) under sand accumulation (Savage and Woodhouse, 1968). The sand appeared to adhere to the fabric to a greater degree than to slats and as the sand settled, it tended to take the fence down with it, greatly reducing the effective height. This was successfully corrected by attaching the top of the fabric to a tautly stretched wire which was in turn stapled to the posts. This greatly improves functioning of the fabric but adds to both the material and labor costs. Fabric fences are competitive with slat fences in purchase price, but their installation costs are slightly higher.

Fabric fences have another disadvantage which can become serious in populated areas. They are susceptible to vandalism because of their net-like appearance. This aspect definitely limits their usefulness in areas frequented by the public, unless the fences can be effectively protected.

b. Methods. Field tests of dune building with sand fences have been conducted at Cape Cod, Massachusetts, Core Banks, North Carolina, and Padre Island, Texas. The results of field and wind tunnel studies by Bagnold (1941) and Manohar and Bruun (1970) have been reviewed and summarized (Phillips, 1975). The following are guidelines and suggestions based on these works plus some years of observation of sand fences operating under a variety of conditions.

(1) A fence porosity of about 40 to 50 percent appears to be the most efficient in catching sand.

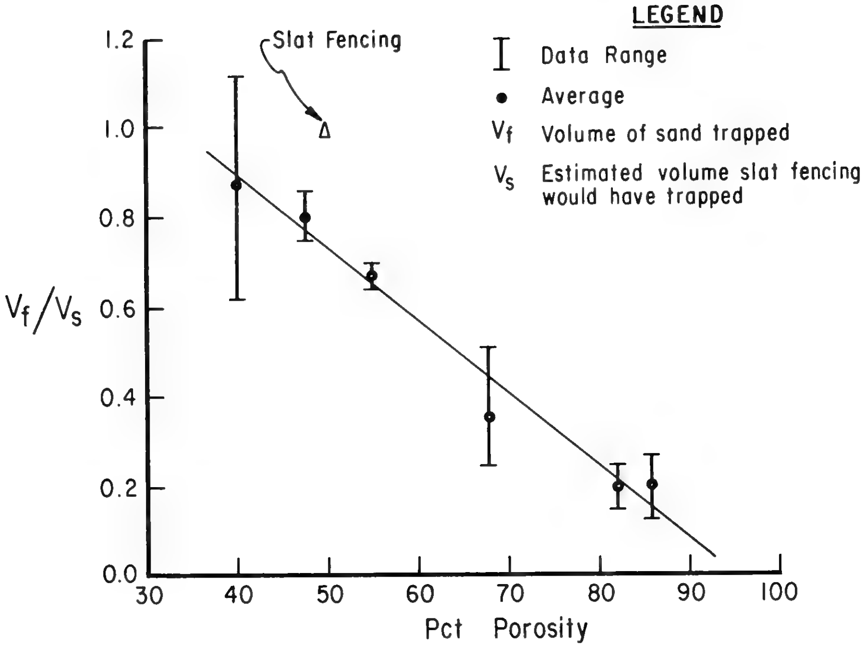

Figure 10. Effect of porosity of fabric fence on volume of sand trapped.

(2) The standard wooden fence made of slats 3.8 centimeters wide by 1.0 centimeter thick seems to be the most practical and cost-effective type of sand fence. It is readily available in the United States and may be called either a snow or sand fence.

(3) Fences should be installed parallel to the shoreline. It is not necessary that they be perpendicular to the prevailing wind. Fences are often filled by winds blowing at a sharp angle to them if sufficient sand is moving.

(4) Placement of the fence at a proper distance shoreward from the berm crest is critical. If placed too close it will be exposed to wave attack and will likely fail. A location too far back of the berm may encourage ponding of water in front of the resulting dune, causing the dune to wash out and fail. The proper distance must be determined for each site. Distance from the berm will usually be more than 90 meters shoreward except on rapidly prograding beaches where it should be less.

(5) Straight fence alinement has usually been more effective than zigzag and side-spur patterns in accumulating sand on large installations. However, where strong winds occasionally blow parallel to the fence, sand moving along the fence will be lost around the fence ends. This may become a significant factor for short fences of less than 200 meters long (Woodhouse, Seneca, and Broome, 1976). In such cases, the addition of lateral spurs may be useful.

(6) Dunes are usually built with sand fence in one of two ways: (a) by installing a single fence and following it with additional single-fence lifts as each fence fills (Fig. 11); or (b) by installing double-fence rows with the individual fences spaced about 4 times fence height (4h) apart (5 meters in the case of 1.2-meter fence) and following these with succeeding double row lifts as each fills (Fig. 12).

(7) Single rows of fence are usually the most cost effective particularly at the lower windspeeds, but double fences are likely to trap sand faster at higher windspeeds. Laboratory studies (Manohar and Bruun, 1970) indicate that a single fence ceases to trap sand at windspeeds above 58 kilometers per hour while a double fence continues to be effective above that windspeed.

(8) Dune height is increased most effectively by positioning succeeding lifts near the crest of the existing dune. However, under this system, the effective height of succeeding fences decreases and difficulties arise in supporting fence near the dune crest as the dune becomes higher and steeper.

(9) Dune width is increased by installing succeeding lifts parallel to and about 4h away from the existing fence. The dune may be widened either landward or seaward in this way if the dune is unvegetated.

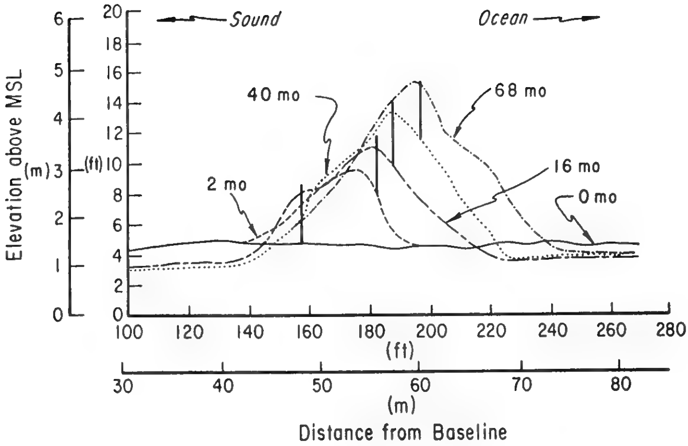

Figure 11. Sand accumulation by a series of four single-fence lifts.

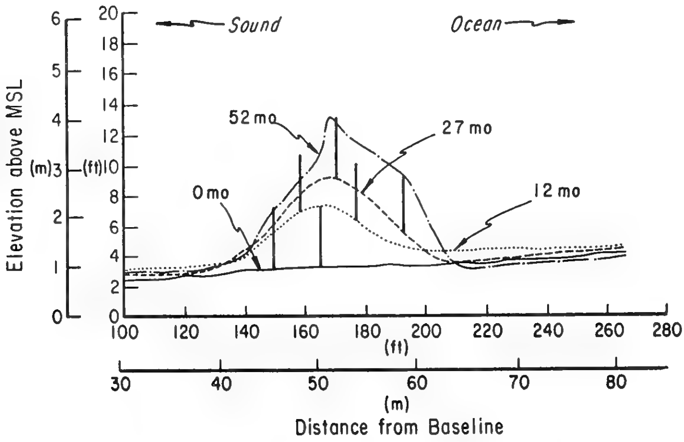

Figure 12. Sand accumulation by a series of three double-fence lifts.

(10) Accumulation of sand by fences is not constant and varies widely with location, season of the year, and from year to year. Fences may remain empty for months following installation, only to fill within a few days by a single storm. In order to take full advantage of available sand, fences must be observed regularly, repaired if necessary, and new fences installed as existing fences fill. Usually where appreciable sand is moving, a single 1.2-meter fence will fill within 1 year.

c. Results. Extensive dunes have been built using sand fences on the Atlantic, gulf, and Pacific coasts of the United States as well as along the coast of northern Europe. Sand accumulation rate depends on the amount of moving sand and varies widely. It may range from in excess of 10 cubic meters per meter of beach per year to less than 1 cubic meter per meter of beach.

d. Limitations. While sand fences are very effective in trapping windblown sand, when the fences are filled they have little or no further effect on sand movement. Fence-built dunes must be stabilized or the fence will deteriorate and release the sand.

Except for certain specialized applications, vegetation is the only feasible long-term means of stabilizing sand dunes. Although some fence-built dunes become vegetated naturally under unusually favorable circumstances, the planting of vegetation on fence-built dunes is usually essential to their survival. The construction of dunes with fence alone is only the first step in a two-step operation.

e. Advantages. Fences have two initial advantages over planting which often warrant their use before or with planting: (a) Sand fences can be installed during any season, and (b) the fence is fully effective as a sand trap as soon as it is installed. There is no waiting for trapping capacity to develop in comparison with the vegetative method.

Consequently, a sand fence can be useful in accumulating sand before planting or while planted vegetation is becoming established. For example, the trapping of blowing sand to form a foredune along the mid-Atlantic coast could begin any month in the year using sand fence. Trapping by planting could only be accomplished by planting in late winter or spring and no substantial accumulation would develop for several months later in the summer.

Moreover, on extensive dunes and dune fields, the volume of sand moved by strong winds may be too large to permit the unassisted establishment of vegetation. Plants may be blown out before establishment.

3. Vegetation.

a. Role. Sand dunes are built and stabilized naturally by vegetation. Vegetation is usually less expensive, more durable, more pleasing aesthetically, and tends to be self-repairing when damaged. A vegetative cover is the only practical means of long-term stabilization of sand dunes, except for certain specialized methods such as covering with crushed stone or asphalt.

Where both sand fence and vegetation are to be used to build a barrier dune, planting should begin as early in the process as feasible. The higher the dune grows, the more difficult and expensive planting becomes. Large fence-built dunes usually can be planted only by hand; machine planting is often possible on low dunes at an earlier stage. For example, one or two "half-fences" (60 centimeters high, obtained by cutting rolls of standard 1.2-meter fence in half) can be very effective in building a low ridge that is still amenable to machine planting but substantial enough to reduce the hazard of storm tides. Half-fences also may be installed in new plantings to speed up sand trapping temporarily but not accumulate enough sand to smother the plants.

Dune plants are especially effective in stopping and holding wind-borne sand. Their growth produces a surface roughness which decreases wind velocity near the ground, thereby reducing the ability of the wind to move sand. Equally important, the plant stems and leaves above the sand surface strongly interfere with sand movement by saltation and surface creep. Consequently, penetration of windblown sand in a stand of dune grass is usually limited to 1 meter or less along the leading edge. As the grass fills and becomes buried, sand spills farther and farther into the interior of the stand. In addition, a cover of foredune plants tends to regenerate trapping capacity by growth even as it fills because the plants are stimulated to grow by the deposition of sand around them.

Once sand grains enter the dune grass stand, they are protected from the wind by the surrounding growth as long as sufficient vegetation protrudes above the surface. Observations following storms suggest that vegetative growth is far more important in protecting dunes against both wind and water erosion than root growth. An adequate vegetative mat protects the dune surface from scouring by wave and current action and actually promotes sand deposition, as well as shielding the surface from wave action.

The beach environment is generally harsh for plant growth. Success requires a combination of special adaptations by the species grown there. This is especially true of the more active zone of barrier dune systems where, for example, plants must be able to tolerate rapid sand accumulation, flooding, salt spray, sandblast, wind and water erosion, wide temperature fluctuations, drought, and low nutrient levels.

In spite of the severe limits these requirements place on the plant species, plants capable of stabilizing coastal dunes do occur in most coastal regions with enough rainfall to support plant growth. This includes a wide range of climates--from humid to semiarid and from cold to tropical.

b. Vegetation Zones. It is helpful to group dune plants into broad categories based on their place in the dune complex. The majority of coastal dune systems in the United States fit into a division of three vegetation zones similar to that by Davis (1957): (1) the pioneer zone, (2) the scrub or intermediate zone, and (3) the forest zone (Fig. 13). The zones are arranged in order of increasing distance from the sea and in order of increasing age.

The location, extent, and nature of these zones vary widely depending on a number of factors such as coastal topography, climate, nature and rate of erosion and deposition, and sea level changes. The pioneer zone is sometimes lacking due to recent severe storms or to persistent long-term beach recession. Forest cover will not develop on many low, narrow barrier islands and on dry coasts such as those in southern California and southern Texas. However, in extreme cases of erosion and beach recession, both the pioneer and intermediate zones may be lost leaving the forest zone next to the beach. Also, on very high coasts (where salt spray is confined near the surf zone) forests may develop close to the sea. This also occurs around the Great Lakes where salt spray is absent.

(1) Pioneer Zone. This is the area of recent or continuing sand movement that usually occurs on the upper beach and foredunes. It is wide on prograding beaches, less on stable sites, and narrow to nonexistent on receding coasts. Vegetation in a typical pioneer zone is limited to a few species of grasses, sedges, and forbs that can withstand salt spray, sandblast, sand burial, flooding, drought, as well as wide temperature fluctuations and low nutrient supply. New barrier dunes develop in this zone and the pioneer plants are usually used to build new dunes or to stabilize bare dunes. This report is focused primarily on the pioneer plants.

(2) Scrub or Intermediate Zone. This is a highly variable, ill-defined area lying immediately behind the more active pioneer zone. It consists of secondary dune ridges and swales, flats, deflation plains, and occasionally includes the back slopes of large foredunes. Plants in this zone include, in addition to the pioneer species, forbs, shrubs, and in some cases, stunted trees. The area receives little fresh sand and nutrient levels are usually low. This results in a scrubby, starved appearance of the vegetation. Growth and vigor, particularly of the remaining pioneer species, is substantially lower than in the active zone but the intermediate zone plants are adapted to these conditions and are valuable as stabilizers. Some intermediate species are planted for ornamental purposes and as wind breaks. In nature, the plants tend to invade and gradually replace the pioneers as soon as an area becomes sufficiently stable and oceanic influence is sufficiently reduced. This is why these plants are not usually planted in the pioneer zone.

This zone is normally considered a progression in the ecological succession toward the stable climax forest, away from the highly changeable, unstable state of the pioneer zone. Sand movement decreases or ceases completely. The area is populated by a wider variety of plants

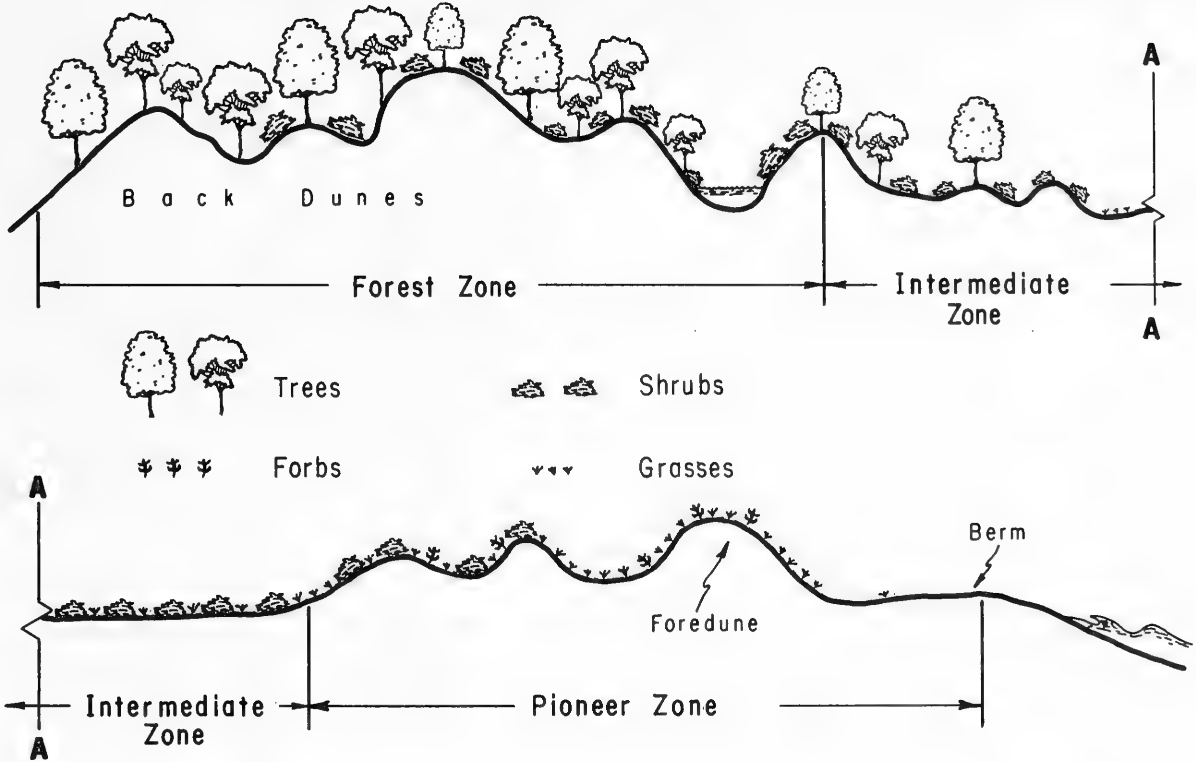

Figure 13. Schematic representation of vegetation zones on a low, sandy seacoast.

and the processes of soil development start. This continues as long as protection from the sea is provided. However, from the standpoint of stabilization, the plant cover on the typical intermediate zone affords less protection against wind and water erosion than does the cover on a well-vegetated foredune in the pioneer zone. Many intermediate zone plants cannot withstand sand burial and the thin, open ground cover is less resistant to wind and water erosion.

Where continued protection is required and especially where overtopping by storm tides is a threat, it may be desirable to delay the ecological succession and retain a protective cover of vigorous pioneer zone plants. Although the reasons for the decline in vigor of pioneer species as sand accumulation decreases are not well understood, nutrient supply associated with the fresh sand can be a major factor. Some sand-starved, declining stands of both American beachgrass (*Ammophila breviligulita*) and sea oats (*Uniola paniculata*) have been revived through the application of fertilizers (Woodhouse and Hanes, 1967). Fertilization has been reported as useful in maintaining plant vigor in diverse regions (Atlantic coast, Oregon, Texas, and Europe).

(3) Forest Zone. Forests form on dunes only after a substantial period of soil development and only on sites with considerable protection from salt spray and flooding. The vegetation varies from the dense thickets of trees, shrubs, and vines of the maritime forests of the South Atlantic and gulf coasts to the coniferous, hardwood, and mixed open tree forests of the Great Lakes dunes.

After dune stabilization with pioneer and intermediate zone species, trees have been planted successfully to convert large mobile dunes and dune fields to forests (Lehotsky, 1941; McLaughlin and Brown, 1942). However, trees are not planted in the barrier dune environment, and are not desirable where the dune protects the backshore. Trees will shade out the pioneer and intermediate species and leave the dune unprotected and unable to regenerate cover quickly following a severe disease, insect outbreak, or fire. Fire was probably a major factor in the initiation of large mobile dunes in the Pacific Northwest.

The major pioneer species extend over much wider ranges, geographically and climatically, than do the plants of the intermediate and forest zones. However, the number of species is usually much greater in the more stable areas.

c. Coastal Regions. The coasts of the continental United States should be divided into regions for planting purposes. These regions deviate from those drawn along climatic boundaries. Climatic effects become somewhat blurred and distorted in the narrow band near the water where barrier dunes occur. The localized maritime influence on fog, humidity, frost, temperature fluctuations, etc., enables some foredune species to range across a variety of climatic zones. Divisions along species adaptation lines are more useful in dealing with those plants.

(1) North Atlantic Region. The North Atlantic region extends from the Canadian border to the Virginia Capes with a shoreline of about 1,660 kilometers. For planting purposes, the mid-Atlantic region is combined with the North Atlantic region. American beachgrass is the dominant foredune plant for this region.

(2) South Atlantic Region. This region covers a rather wide range, climatically, from the Virginia Capes to Key West, a shoreline distance of about 1,900 kilometers. The Atlantic coasts of central and southern Florida are arbitrarily included in this region, because their separation is not useful from the narrow view of barrier dune building and protection. Many subtropical and tropical plants are used in the southern half of the Atlantic coast of Florida near the beach for ornamental purposes but the dune-building species do not differ significantly from the remainder of the region. The northern boundary of this region coincides with the northern limit of sea oats. Sea oats is the dominant foredune plant of this region.

(3) Gulf of Mexico Region. This region includes the gulf coast of Florida and extends around the gulf to the Mexican border, a distance of about 2,600 kilometers, but about 500 to 600 kilometers is marshy with no beach or dune development. Climate varies from humid to semiarid but foredune species planted, primarily sea oats and bitter panicum (*Panicum amarum*), are the same throughout the region.

(4) North Pacific Region. This region extends from the Canadian border to Monterey, California, a distance of about 1,450 kilometers. The southern limit is based on the transition zone between the grass-dominated communities to the north and the forb-dominated communities to the south (Barbour, DeJong, and Johnson, 1976). European beachgrass (*A. arenaria*) and American dunegrass (*Elymus mollis*) dominate this region.

(5) South Pacific Region. This region extends southward from Monterey, California, to the Mexican border for about 650 kilometers of coast that has a pronounced decrease in rainfall from north to south. Dominant plants are forbs such as sea fig (*Carpobrotus* spp.), sagewort (*Artemisia pcynocephala*), beach bur (*Ambrosin* spp.), and sand verbena (*Abrona* spp.).

(6) Great Lakes Region. This includes all of the shores of the Great Lakes within the United States. However, dune development is confined largely to the Michigan and Indiana shores of Lake Michigan. American beachgrass and Prairie sandreed (*Calamovilla longifolia*) are dominant.

d. Major Foredune Plants. Bare dunes and dune fields along the coasts of this country are stabilized by usually planting with a small group of pioneer plants, perennial dune grasses. The major grasses are: European beachgrass on the North and South Pacific coasts; American dunegrass on the North Pacific coast; American beachgrass on the North Pacific, North Atlantic, and Great Lakes coasts; bitter panicum along the South Atlantic and gulf coasts; sea oats on the South Atlantic and gulf coasts; salt-meadow cordgrass (*Spartina patens*) on the South Atlantic and gulf coasts.

These plants are used because they multiply dependably and economically, can be readily harvested, transported, stored, and planted. The plants thrive in blowing sand, trap sand well, and are relatively free of serious pests. These plants live from one year to the next, providing year-round protection to the sand surface.

There are other plants that invade the pioneer zone and contribute substantially to the process in each geographical region. None are widely planted for initial stabilization because they fail to meet one or more of the above criteria. There are many plants that, given extra care, will grow in the pioneer zone for ornamental or other specialized purposes. Some of these may find wider use as more is known about their requirements. A few species, such as the omnipresent sea rocket (*Cakile* sp.), may precede the dune grasses into the pioneer zone, but are capable of building only embryonic dunes. These species give other plants a chance to build more substantial dunes by temporarily trapping sand, seeds, and debris.

(1) American Beachgrass. A cool season dune grass native to the North and mid-Atlantic and Great Lakes coasts, and probably the most widely used species for initial stilling of blowing sand. It is almost the only species planted for this purpose along the Atlantic coast south to the Carolinas and around the Great Lakes. Limited use has been made of this grass in the Pacific Northwest. American beachgrass is a vigorous, erect grass which grows in dense clumps and is capable of rapid lateral spread by rhizomes. It can usually be recognized in the fruiting stage by the dense, cylindrical spikes or seed heads (Figs. 14 and 15). There are two varieties of American beachgrass: Cape, a vigorous coarse-stemmed type adapted to the North Atlantic coast; and Hatteras, a fine-leaf type selected for early vigor on the coasts of the Carolinas. Characteristics of American beachgrass are:

(a) Easy to multiply vegetatively (fiftyfold increase per year is possible), and readily available commercially.

(b) Easy to harvest, store, and transplant manually or by machine.

(c) Long transplanting season with good survival rate (normally 90 percent).

(d) Grows rapidly and becomes an effective sand trapper by middle of the first growing season.

(e) A cool weather grower that starts growth in early spring and, where conditions are favorable, continues well into the fall.

Figure 14. Growth habit and spread of American beachgrass under sand accumulation.

(f) Spreads outward 3 to 4 meters per year, and produces the most gentle seaward dune slopes of all the species (Woodhouse, Seneca, and Broome, 1976).

(g) Vigorous rhizome system makes it very effective at filling open stands and excellent for maintenance and repair of plantings.

(h) Responds vigorously to fresh sand (will grow through 1.2 meters of accumulating sand in one growing season) (Fig. 15).

(i) Fades rapidly when sand and nutrient supply is cut off, and tends to be short-lived in the intermediate zone unless fertilized.

(j) Affected by heat and drought in the southern part of its range where it is usually replaced within a few years by better adapted species such as sea oats and bitter panicum.

(k) Very susceptible to a soft scale, *Eriococcus carolinae* (Campbell and Fuzy, 1972), throughout most of its Atlantic coast range and to Marasmius blight, a fungus pest (Lucas, et al., 1971), along the South Atlantic coast.

(2) European Beachgrass. A species very similar to American beachgrass (Fig. 16), that was introduced in the late 1800's to the Pacific coast where it has become widely distributed by planting and natural spread. This is the marram grass of the British Isles and northern Europe, and probably the dune grass most extensively planted in the past. It is the principal grass used along the Pacific coast for the initial stabilization of large areas of blowing sand and the building of foredunes. Characteristics of European beachgrass are:

(a) Exceptionally easy to multiply vegetatively (a hundred-fold increase per year is not unusual under nursery conditions), and available commercially.

(b) Easy to harvest, store, and transplant, but will not tolerate as high a temperature as American beachgrass.

(c) Long transplanting season, with excellent survival under proper conditions, and suitable for machine or manual transplanting.

(d) Grows rapidly and responds vigorously to a plentiful sand supply (grows through as much as 60 centimeters of sand per year).

(e) Rhizomes shorter than those of American beachgrass apparently cause steeper seaward dune slopes (no documentation

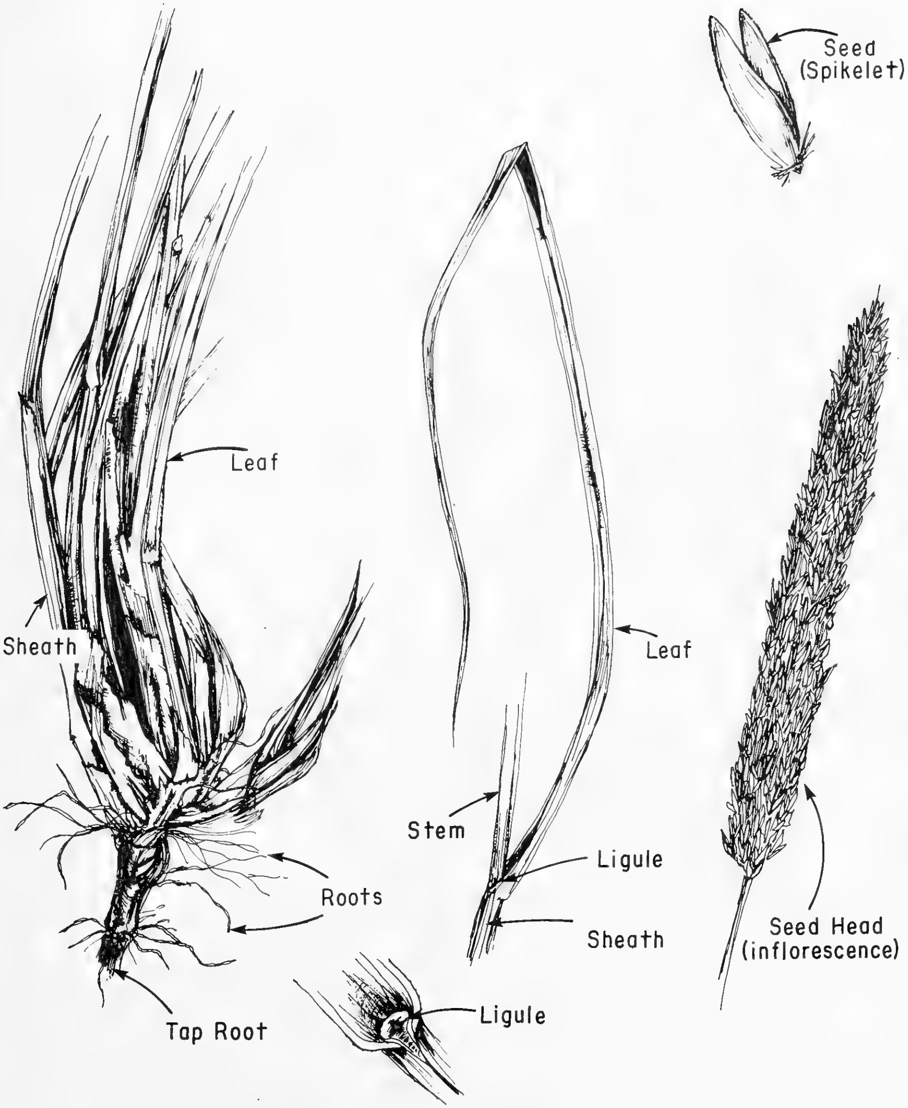

Figure 15. Morphological features of American beachgrass.

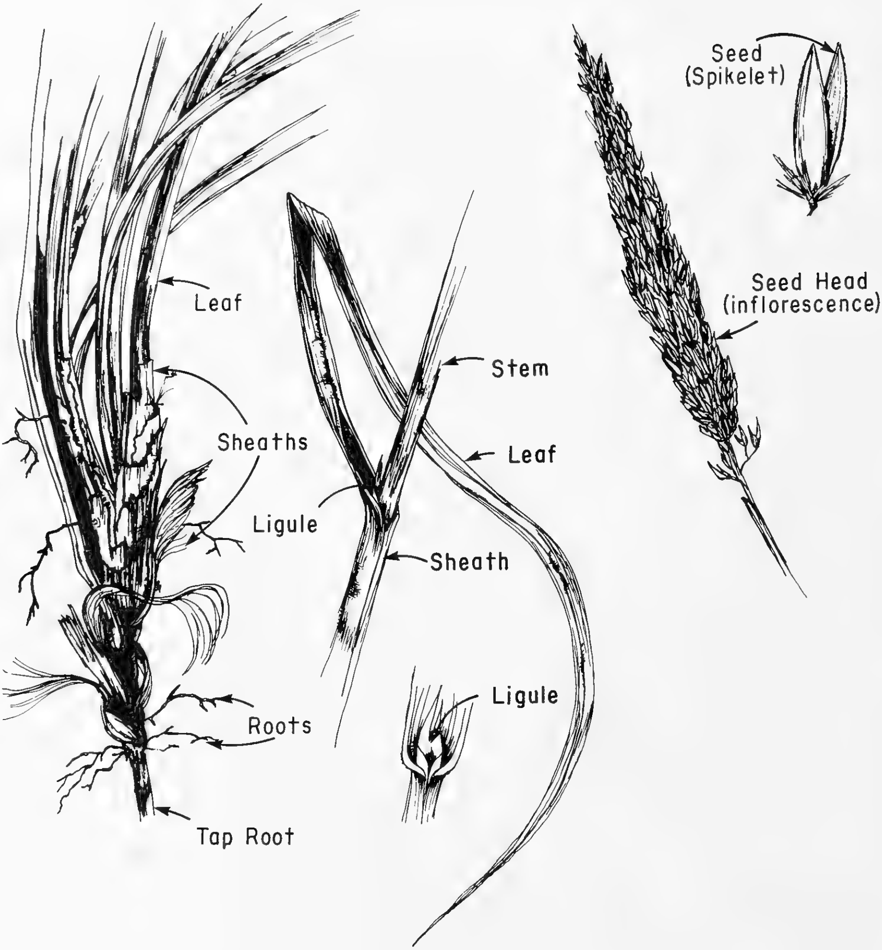

Figure 16. Morphological features of European beachgrass.

available) and are less effective in filling open stands or for maintenance and repair, therefore, good initial stands are critical.

(f) Definitely a cool weather grass, very sensitive to high temperatures at transplanting. Poor survival can be expected whenever air temperature exceeds 16° Celsius during or immediately following transplanting. This characteristic may account for the lack of use of this plant on the Atlantic coast.

(g) Fertilizer application is essential for success on large mobile dunes.

(h) Vigor declines rapidly with stilling of sand, making it short-lived in the intermediate zone and requiring reinforcement by planting of intermediate species, particularly on large dunes.

(3) Sea Oats. A native warm season dune grass occurring from about the Virginia Capes southward into Mexico and on some islands in the Carribean Sea. Similar in appearance to American beachgrass but with generally larger stems, more decumbent growth habit, and more open stands (Figs. 17 and 18). The grass tends to dominate active foredunes throughout much of its range. Its striking appearance, particularly when in flower or fruit, has made legal protection necessary in some States to avoid excessive harvest for ornamental purposes. Characteristics of sea oats are:

(a) Difficult and slow to multiply vegetatively, less than half as fast as American beachgrass. Subject to pest problems when grown away from the beach. Commercial availability is very limited.

(b) Spread into dune and beach areas is primarily by seeds. Plants can be grown from seeds but are subject to pest problems in the field. The grass is an erratic seed producer and seed heads are heavily preyed upon by insects, birds, rodents, and people.

(c) Early growth of transplants and seedlings is very slow and survival is erratic. Consequently, plantings of pure stands usually are only marginally effective as sand trappers during the year of establishment; therefore, it should rarely be planted alone. Mixed with bitter panicum (southern range) and American beachgrass or bitter panicum or both (northern range), sea oats will tend to increase with time.

(d) Trapping capacity develops rapidly after the first year and even very spotty stands become effective with time.

(e) It is more tolerant of reduced sand and nutrient supply than American beachgrass; therefore, it persists longer and provides more cover in the intermediate zone.

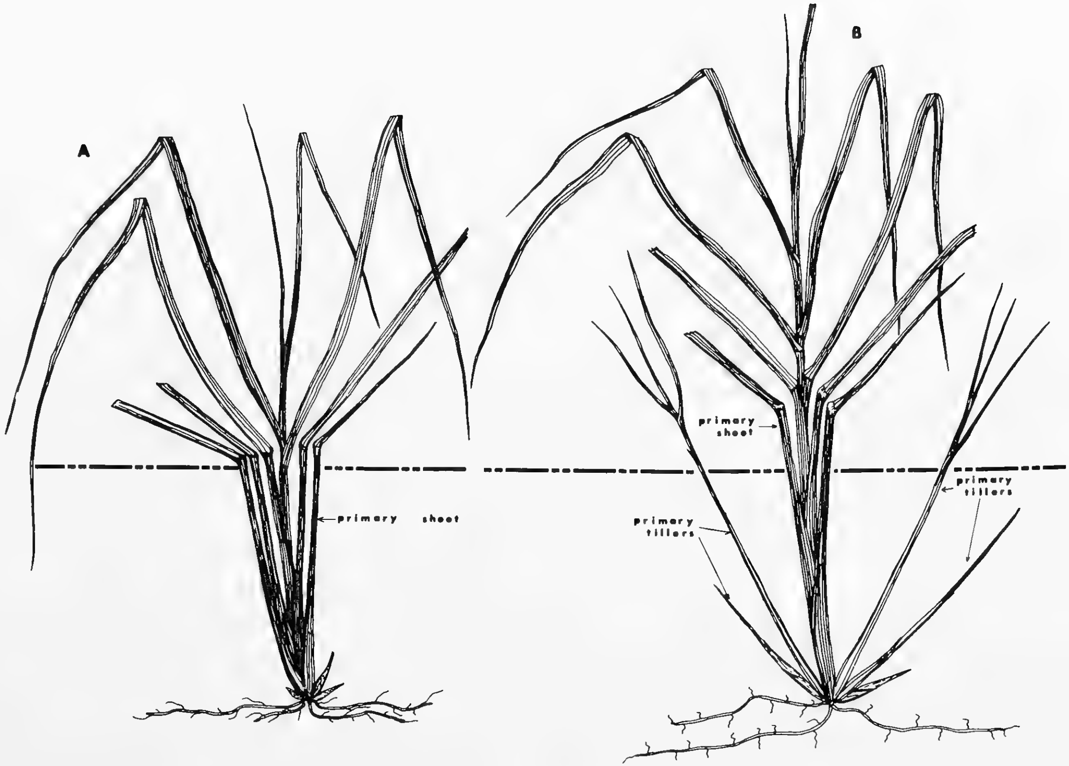

Figure 17. Growth habit of sea oats. Stems at planting (A); same transplant after several months (B). Growth is from primary tillers arising from basal nodes and elongation and development of centermost leaves. All growth tissue is subterranean.

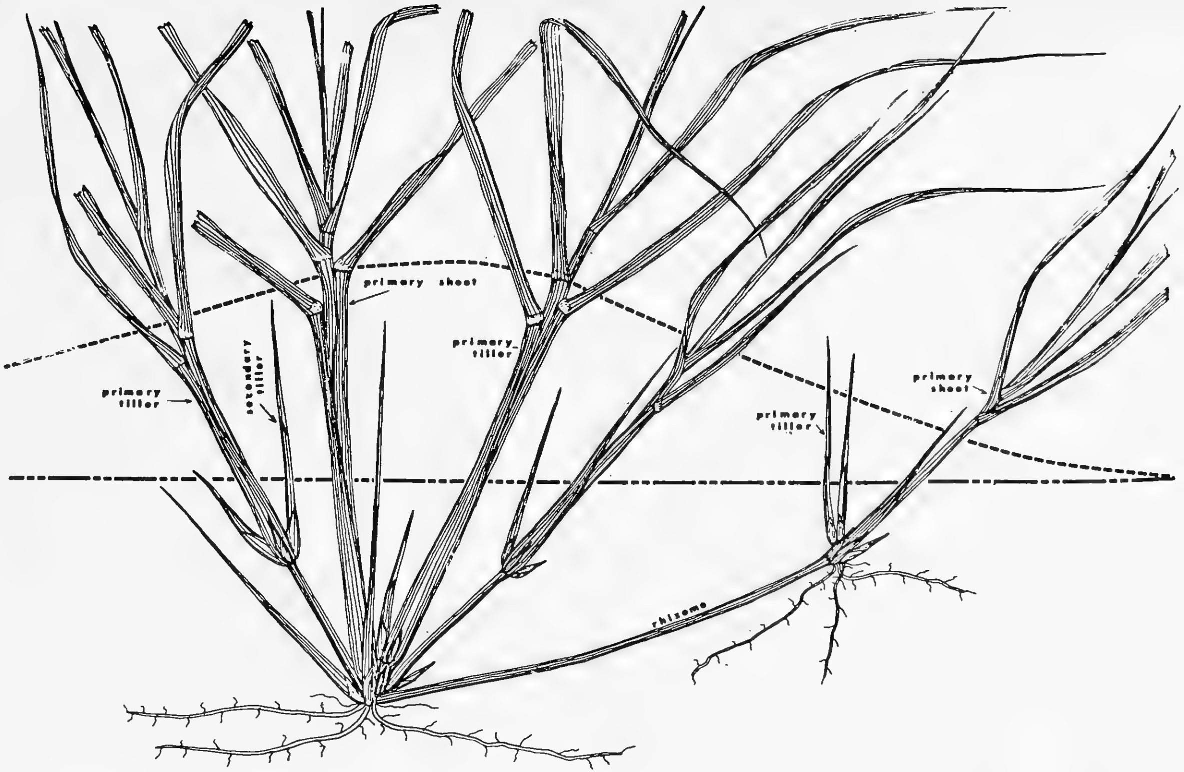

Figure 18. Sea oats at end of first summer. Basal nodes have given rise to a complex of primary tillers. Note the rhizome with a primary shoot and tillers which will form another clump.

(f) This grass is relatively free of pests in the dune environment.

(g) The stiff upright growth habit and short rhizome system produce rapid sand accumulation near margins of vegetation. The slow lateral spread produces steep seaward dune slopes.

(h) A summer grower that grows only during warm weather, which makes the growing season short in the Carolinas but almost year round on the south Texas coast.

(i) Tolerance to heat and drought is high, and rarely exhibits drought symptoms.

(4) Bitter Panicum. A strongly rhizomatous perennial warm season grass which spreads by branching at the nodes (Figs. 19 and 20). It is generally less erect and has shorter leaves than sea oats and the beachgrasses. Bitter panicum has received serious attention only recently. It is apparently native to the mid and South Atlantic and gulf coasts but had disappeared from most dune and beach areas long ago because of overgrazing by livestock (Dahl, et al., 1975). Since it rarely, if ever, produces viable seed, it is slow to reinvade without the help of man or storm activity. Now that grazing has largely been eliminated, this dune grass is increasing throughout much of its range. It does have substantial value as a sand-stilling grass from about the mid-Atlantic coast to Mexico, as the initial stabilizer in the southern half of the region, and as a companion to other pioneer foredune plants elsewhere (Dahl, et al., 1975; Seneca, Woodhouse, and Broome, 1976). Characteristics of bitter panicum are:

(a) Easy to multiply under nursery conditions but commercial availability is limited; the supply could be quickly expanded if demand develops.

(b) Rarely, if ever, produces viable seeds; therefore, must be propagated vegetatively.

(c) Free of serious pests under both nursery and dune conditions.

(d) Easy to harvest, store, and transplant. Survival of transplants is substantially superior to that of sea oats but inferior to American and European beachgrasses. The transplanting season is long.

(e) Growth is erratic the first year. Some transplants may start new growth immediately while others delay for some time.

(f) Sand trapping is efficient and the plants spread laterally in a way similar to sea oats. Dune slopes are more gentle.

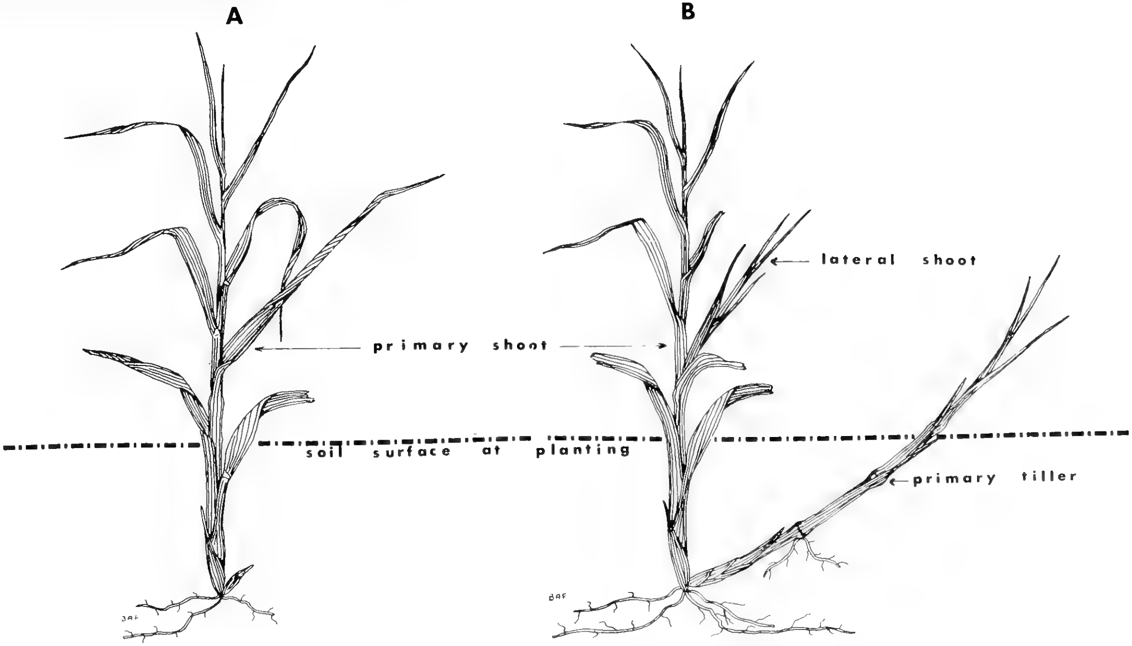

Figure 19. Growth habit of bitter panicum. Stem (A) soon after transplanting; spring growth (B) several months after planting. Growth is from a lateral shoot and a primary tiller.

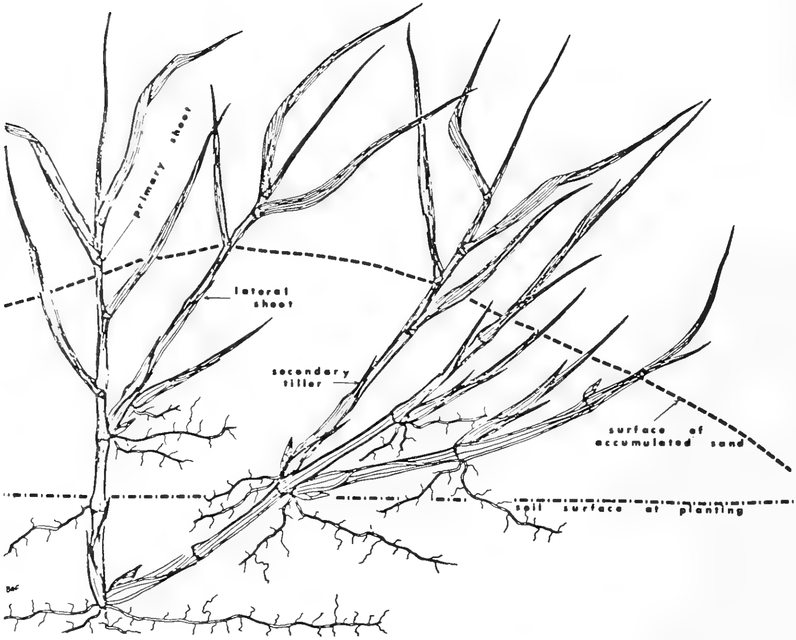

Figure 20. Bitter panicum growth at end of first summer. Lateral growth is shown in only one plant. Transplant has grown vertically and horizontally with accumulation of sand. Lateral shoot is buried and has rooted and formed a tiller and new buds. Primary tiller has given rise to secondary tillers which are in turn forming tertiary tillers at the buried nodes.

(g) Cannot withstand as rapid a sand accumulation as American beachgrass or sea oats, and is particularly susceptible to burial during the establishment period.

(h) Wide variety of plant types are found in the field--creeping to erect, and delicate to robust. The best types for dune planting have not been determined and better propagation methods are needed.

(5) Saltmeadow Cordgrass. This plant has smaller, more pliable leaves and stems than any of the other dunegrasses and offers less resistance to the wind; therefore, it is not as effective as a dune builder. However, saltmeadow cordgrass is very tolerant of salt and flooding and it seeds profusely, spreading readily by seeds. This grass is often among the first to invade low-exposed sites along the mid and South Atlantic and parts of the gulf coasts. It often initiates new dunes on low flats that may later become occupied by plant species better adapted to high dry conditions (Fig. 21). It is widespread along the Atlantic and gulf coasts. Characteristics of saltmeadow cordgrass are:

(a) Easy to transplant where moisture is adequate but difficult on dry dunes. Plants are occasionally found on old high dunes where they apparently grew with the dune.

(b) Survival depends on type of planting stock. Plants must be young and uncrowded. Stock from old dune stands is usually unsatisfactory.

(c) Tolerant of reduced sand and nutrient supply. Persists longer under intermediate zone conditions than other pioneer zone species.

(d) Has a long planting season on suitable (moist) sites, winter through early summer.

(6) American Dunegrass. This grass was apparently the only perennial dune grass occurring along the Pacific coast from British Colombia to southern California before the introduction of European beachgrass in the late 1800's. The same species occurs also around the Great Lakes and along the North Atlantic coast. Whether or not this is the same variety as the Pacific coast grass is not clear. Early workers (McLaughlin and Brown, 1942) found European and American beachgrasses much easier to multiply and transplant. Consequently, little attention has been devoted to the propagation and use of American dunegrass until recently (Barbour, 1976). It has not been planted enough to know its role and value in building and stabilizing dunes. The grass invades foredune areas throughout most of its range and is capable of building foredunes. It has replaced European beachgrass on some older foredunes in the Pacific Northwest. American dunegrass seems to have a potential for more use as its requirements are better understood. Certainly, it seems to warrant further attention, particularly on the Pacific coast,

Figure 21. Saltmeadow cordgrass initiating the development of a dune.

where dune planting is presently done almost exclusively with exotic European beachgrass. Characteristics of American dunegrass are:

(a) More difficult to multiply than the beachgrasses, and is not available commercially.

(b) Must be transplanted while dormant; therefore, has a shorter transplanting season than the beachgrasses.

(c) Very temperature sensitive, and should not be transplanted when temperature is likely to exceed 14° Celsius.

(d) Appears to be especially palatable to rabbits. This may account for poor survival in many cases.

(e) Although the value of this grass in dune stablization is not clear, it may have a potential to reduce the hazards of the monoculture of European beachgrass. The advent of a serious pest in a monoculture could be catastrophic in many exposed sites.

e. Propagation Techniques. Most of these plants produce viable seeds and at times spread into dune areas by seeds, but direct seeding is not usually a satisfactory means of establishing initial cover in the pioneer zone. In bare sand, seeds will too often become uncovered or buried too deeply before they can germinate and the seedlings become established. Consequently, with few exceptions, planting of foredunes is done vegetatively.

Adequate supplies of healthy planting stock are essential to any successful dune planting and the acquisition of plants is usually a major item of expense in planting projects. There are two principal sources: (1) nursery-grown plants, usually produced for this purpose from vegetative sprigs, but sometimes from seed; and (2) plants obtained by thinning natural or cultivated established stands.

Established stands are satisfactory and practical sources, particularly where small quantities are required. The best plants are usually found in back-dune and deflation plain areas where they are uncrowded and have not trapped large quantities of sand. The removal of planting stock from these stands reduces the cover only temporarily because the rhizomes left in the ground will usually revegetate early in the next growing season. Plants from foredunes are difficult to dig and make poor planting stock. Also, digging leaves the foredunes temporarily vulnerable to erosion.

Although established stands are often suitable sources of plants for small projects, the availability and harvesting expense usually dictate the need for nursery-grown material for large projects. This presents no particular problem with the more widely grown species if sufficient lead-time, 1 to 2 years, is allowed for plant production. The market is usually quite erratic with surges in demand resulting largely from the occurrence of damaging storms and the initiation of large projects. Since it is difficult to hold planting stock in the nursery more than 1 or 2 years, commercial producers do not usually keep large stocks on hand. This makes planning essential to the successful planting of large projects.

(1) American Beachgrass. This plant is relatively easy to produce under nursery conditions. It can be multiplied either vegetatively or by seeds, but the vegetative method is normally preferred (Fig. 22). Direct seeding is usually uneconomical because seed supplies are unreliable and weeds are difficult to control in seedling stands.

Figure 22. American beachgrass nursery midway in the first growing season.

(a) Soil Selection. Any well-drained soil may be used and it is not necessary that the site be near the sea. Production of American beachgrass will be higher on the more productive soil and both planting and harvesting are easier on soils of a sandy nature (sands, sandy loams, and sandy clay loams) than on heavier soil. Since weed control often presents the greatest difficulty, emphasis should be placed on selecting relatively weed-free fields.

(b) Soil Preparation. A well-pulverized seedbed, suitable for the planting of normal field crops, is necessary to facilitate transplanting. Hard or cloddy seedbeds in heavy soils will lead to shallow planting and interfere with firming of the soil around the plants. At very weedy sites, fumigation with methyl bromide is advisable before planting. This requires a well-pulverized seedbed that is moist but not wet, and mild temperatures. Soils should be tested before planting and where nutrient levels are low, fertilizer applied.

(c) Transplanting. Plants should be set in winter or early spring, one stem per hill, 45 to 60 centimeters apart in rows spaced 75 to 100 centimeters, depending upon available cultivation equipment. Planting should be to depths of 10 to 20 centimeters in moist soil and the soil pressed firmly around the base of the plants to avoid air pockets. Most mechanized transplanters, such as are used to set tomato, pepper, tobacco, etc., can be readily adapted to the planting of beach grass. Machine planting is preferable to hand planting under nursery conditions since it will ensure more uniform spacing for ease of cultivating.

(d) Culture. Cultivation is necessary to control weeds but should be avoided where weed growth can be suppressed by other means. Fumigation with methyl bromide, where fully effective, should result in adequate weed control the first year. Most summer annual weeds can be controlled by the application of 1.5 kilograms per hectare of Simazine in the spring (follow timing directions for corn). Spray should be directed to the base of the plant to avoid the leaves. One or two nitrogen topdressings can be applied during the growing season on less fertile soils. Apply 40 to 60 kilograms of nitrogen per hectare and adjust the dosage to maintain healthy color and good growth. Excessive nitrogen application is wasteful and may be detrimental. Supplemental irrigation immediately following transplanting can be helpful to settle the soil around the plants, and may increase production when used later in the season under very dry conditions. However, irrigation is not essential in the production of this plant since it tolerates long, dry periods under dune conditions.

(e) Harvesting. Planting stock of American beachgrass may be harvested during the winter or early spring after one growing season. The individual clumps are loosened with a shovel or by a tree digger or plowing devices. They are then lifted by hand, shaken free of excess soil, and separated into individual "plants" of one to five stems. These may be transplanted immediately, stored for short periods by heeling-in out-of-doors, or held for a month or more in cold storage at about 0° Celsius. Plants may be stacked upright in tubs or boxes for movement of short distances. However, where more handling and time may be required, package the plants in bundles of 500 to 1,000 stems, and wrap tightly in paper in a manner similar to that used for forest tree seedlings.

Avoid excessive drying of the basal part of the plant. Dipping the lower 10 to 13 centimeters in a clay slurry before packaging seals the base and gives a margin of safety during storage, transport, and planting.

Tops of bundled plants often require trimming to a length of 45 to 60 centimeters to facilitate machine planting and to reduce bulk and weight for handling and storage (Fig. 23). However, there is some advantage

Figure 23. Planting stock of American beachgrass.

in leaving plants untrimmed when hand planting critical sites because the excess top growth will trap sand and protect the new plant during establishment.

Planting stock may be carried over in the nursery through the second and sometimes the third growing season with some increase in yield over the first year. However, after the third season, plants become too crowded, quality declines, and rodent infestation may become a problem, making it advisable to destroy the material and make a fresh start.

Normal harvesting operations leave large numbers of rhizomes behind. Consequently, if the field is left undisturbed, a dense volunteer crop of beachgrass will usually appear the next growing season. Such stands are capable of yielding substantial numbers of plants if fertilized and kept free of weeds. However, harvesting of these broadcast stands is more laborious than for row plantings and weed control is more difficult. As harvesting is usually the most expensive step in the production of planting stock, it is normally more economical to plant a new field each year than to attempt to harvest volunteer plants.

(2) Sea Oats. Propagation of this plant is different and more difficult than that of American beachgrass. Sea oats will not thrive on sites very far from the dune environment, and even under the best conditions, multiplication is slow. The reasons for this are not clear, but it is known that in inland locations this grass falls prey to at least two pests: a "helmethesporiumlike" leaf spot or rust and a stem borer, similar to the Hessian fly, neither of which are serious pests in the dune environment. The leaf disease can be controlled by carefully timed spraying with Daconil or Bravo; the stem borer with a systemic insecticide. However, the most satisfactory nurseries have been within a few hundred feet of the sea (e.g., Padre Island).

(a) Soil Selection. Sites in back-dune swale and deflation plain areas are preferred for field-scale production of sea oats. Care should be taken to assure protection from sand encroachment and storm-tide damage on such sites. In the absence of such sites, sandy, well-drained soils farther inland may be used, but disease and insect control will probably be required.

(b) Soil Preparation. A clean, weed-free area is essential for satisfactory nursery production. Foredune species do not compete well with weeds and the cost of hand weeding of nursery areas soon becomes prohibitive. Sea oats are especially vulnerable to competition because of slow initial growth. Since the more productive back-dune and deflation plain planting sites are usually occupied by vegetation, eradication of the growing plants and dormant seeds is the first step. This may be done on the clean sites by cultivation, but heavily vegetated areas will require fumigation with methyl bromide.

(c) Planting. Sea oats nursery areas may be established by transplanting wild plants, direct seeding, or transplanting started seedlings in peat pots from a greenhouse. The best wild plants are obtained from young clumps that have not yet become deeply seated. These are usually found on young deflation plains or on wide areas in front of the foredune. The clumps may be divided into single stems and set 15 to 20 centimeters deep in moist soil 45 to 60 centimeters apart. Rows should be spaced for mechanized cultivation.

Direct seeding is feasible when seed supplies are adequate and a high degree of weed control is assured. However, sea oats seedlings start very slowly and are vulnerable to insect and disease damage as well as to weed competition the first year. For this reason, direct seeding is not recommended.

The initial period of slow growth can be circumvented by starting seedlings in peat pots in the greenhouse during the winter and transplanting them to the nursery in early spring. Although this step increases cost, it may save most of a whole growing season in startup time. Seeds of the more northern populations of sea oats require a period of about 30 days of cold storage to break dormancy (Seneca, 1972). Peat pot-grown seedlings may be transplanted directly to the dunes but these tend to be more expensive than planting stock from nursery beds.

(d) Management. Plants will respond to small amounts of fertilizers (30 to 40 kilograms of nitrogen, 10 to 20 kilograms of phosphate per hectare) on sites that are low in nutrients. Excessive fertilization will stimulate weed growth and should be avoided. Cultivation should be avoided except when required for weed control. Although some usable transplants are produced the first growing season, sea oats that remain undisturbed through the second growing season will result in more and stronger plants.

(e) Harvesting. Sea oats are harvested by loosening the sand around individual clumps with a shovel or other tools, lifting the clump by hand and shaking it free of excess sand. It is usually not possible to pull unloosened plants without excessive damage. Clumps are then hand-separated into transplanting units of one or more healthy, vigorous stems. Transplants may be stored upright in tubs or baskets for handling or packaged in bundles as described for American beachgrass.

Care must be taken to avoid excessive drying of the base of the plant. Dipping the lower 10 to 13 centimeters in a clay slurry, immediately after processing, is suggested. When plants are not to be transplanted immediately, they may be held for periods of a week or so by heeling-in in moist sand. Sea oats plants do not store well in water (Dahl, et al., 1975).

(3) Bitter Panicum. This plant multiplies readily under nursery conditions, grows well on any well-drained soil, and has no serious pests. As with other dune grasses, nursery manipulation and harvesting are more convenient on sandy soils.

(a) Soil Selection and Preparation. Any well-drained, sandy, weed-free soil is satisfactory. The site does not need to be near the sea. A well-pulverized seedbed should be prepared and, on very low fertility soils, a complete nitrogen, phosphate, and potash (NPK) fertilizer applied as for corn. Fumigate with methyl bromide if necessary for weed control.

(b) Planting. Wild stock may be planted. Seeds are not produced; therefore, only vegetative parts are planted. The best wild transplants come from backshore and young deflation plain areas and the back slope of foredunes where sand accumulation has been minimal. Plants are pulled by hand. They usually break off at the ground surface in the winter when brittle, but come up with roots and rhizomes attached during the growing season. Rooted and rootless stems (culms) are equally satisfactory for transplanting. From spring to fall, two types of panicum stems are available: (1) primary stems from the previous year's growth which have flowered and are firm and brittle, and (2) tillers which are actively growing stems. Tillers survive and grow best following transplanting during the growing season; primary stems are best when planting from fall to spring (Dahl, et al., 1975). Long primary stems may be divided to form 30- to 50-centimeter transplants. The upper and lower halves survive equally well. It is also possible to stretch planting stock supplies by planting large stems horizontally in furrows. Care must be taken to bury only to a depth of 10 to 15 centimeters, and the stem tip should be left uncovered. This type of planting will result in a new plant at almost every node.

(c) Harvesting. Planting stock may be harvested from nursery plantings after one growing season. Plants are pulled by hand or, in large-scale production, mowed and raked to obtain the top growth. The smaller stems, typical of old, dense stands, do not make as satisfactory planting stock as the larger, more robust stems, typical of young, well-fertilized stands.

Pulled or mowed plants may be heeled-in in moist sand for short periods. This species may be stored up to a month by immersing the lower half in freshwater (Dahl, et al., 1975). Plants may be stacked in tubs or baskets for transplanting. For more extensive handling, bundling and clay-dipping, as described for American beachgrass, is suggested.

Theoretically, a bitter panicum nursery can be left in place and harvested year after year if weeds are controlled. In practice, plants may become too crowded after 2 years or more and it is advisable to make a new start.

(4) Saltmeadow Cordgrass. This is probably the most plentiful of the dune grasses along much of the Atlantic and gulf coasts, occurring widely on low flats and deflation plains. However, it is difficult to obtain good planting stock from the wild. Stands on moist sites become dense and crowded, making harvesting difficult. Plants on dry infertile deflation plains lose vigor and survive poorly when transplanted. The best transplants are from rapidly growing, uncrowded young stands with

relatively large stems. Plants are harvested by loosening soil around clumps with a shovel and hand lifting. Although very little nursery production of this plant has been done, it appears that there may be more to be gained by it than with any other dune species in terms of both transplant quality and economy. It is unlikely that it will be planted extensively in the beach and dune zones unless nursery-grown plants become available.

(a) Soil Selection and Preparation. This grass may be grown on both inland and coastal sites. The prime requirement appears to be a clean, sandy loam soil with a moderately good moisture holding capacity. The seedbed should be well pulverized and if necessary, fumigated with methyl bromide.

(b) Planting. Saltmeadow cordgrass can be grown from seed but for planting stock production, sprigging on 45- to 60-centimeter centers in rows 75 to 100 centimeters apart is best. Use two- to four-stem transplants from young vigorous stands, set 10 to 15 centimeters deep in moist soil. Although not essential, supplemental irrigation is often helpful since this species has a higher moisture requirement than the other dune grasses.

Excellent transplants of this species can be produced in the nursery in one growing season. They may be harvested by loosening individual clumps with a shovel or by lifting with a tree digger or similar tool. Clumps should be cut into smaller five- to eight-stem units for transplanting. The units may be stored temporarily by heeling-in in moist sand, or stacked upright in tubs or baskets, preferably bundled and clay-dipped for handling and transport as described for American beachgrass.

On the basis of very limited experience, planting stock may be held over in the nursery for 1 or 2 years with no detrimental effect if plants do not become crowded and lose vigor. In that case, it is best to start a new planting.

(5) European Beachgrass. This is the easiest of the foredune species to propagate, and can be produced most efficiently in nurseries. However, much of the planting stock for large stabilization projects in the Pacific Northwest came from the extensive established stands in that region.

(a) Soil Selection. Any sandy, well-drained soil will serve. Much of the production has been on dune sand, but it is better that the nursery site not be exposed to substantial sand movement. The more protected sites should be weed-free. Because this plant is temperature sensitive, nursery production probably should be kept well within the modifying influence of the water.

(b) Soil Preparation. Little preparation is required in dune sand except the removal of existing vegetation. Fumigation with methyl bromide is advisable for weed control. Soil should be tested and nutrient deficiencies corrected.

(c) Planting. European beachgrass may be seeded in the nursery but in view of seed costs and availability, transplanting is more practical. Nurseries should be stocked during the winter or early spring when the air temperature is likely to remain at or below 16° Celcius for several days and the soil is moist. Plantings spaced 30 to 45 centimeters apart in rows, one stem per hill, is best for limited supplies of planting stock. However, where plants are available, closer spacing will greatly increase production per hectare. Brown and Hafenrichter (1948) obtained the highest production from five stems per hill spaced at 30 by 30 centimeters. However, they were working on dune sand under exposed conditions which probably placed a premium on early stabilization. Machine planting is preferred, and plants should be set 15 to 30 centimeters deep.

(d) Culture. Cultivation should be avoided except where essential for weed control. Production will usually be increased by the application of 40 to 60 kilograms of nitrogen per hectare soon after spring growth begins. Fertilization is essential for strong nursery stock on sands and infertile soils.

(e) Harvesting. Plants in nurseries may be pulled by hand with little or no digging. Plants from dune stands are harvested by cutting them about 5 to 8 centimeters below the surface to leave one or two underground nodes, using a sharp, flat-blade garden spade with a straight cutting edge, 15 to 20 centimeters wide. Clumps are lifted, shaken free of excess soil, cleaned of trash, the underground stems broken back to one or two nodes, and separated into individual one- to five-stem transplants. These may be heeled-in in narrow trenches or stacked upright in tubs or boxes for local handling or packaged for shipping or long-term storage in bundles of 100 to 1,000 plants with the lower half wrapped in paper to avoid drying, as is done with forest seedlings. Dipping the lower 8 to 10 centimeters in a clay slurry before packaging provides an economical deterrent to drying and a desirable margin of safety against careless handling and planting.

No data are available on suitable temperatures for cold storage of European beachgrass. The optimum temperature, 0° Celsius, for American beachgrass is probably satisfactory for this species.

Stems should be trimmed to an overall length of about 50 centimeters after packaging for easy handling, storage, and transplanting.

(6) American Dunegrass. This species is considerably more difficult to propagate than the beachgrasses (McLaughlin and Brown, 1942; Brown and Hafenrichter, 1948) so attention has been focused largely on the beachgrasses and little specific information is available on the culture of this dunegrass. Therefore, the following suggestions are speculative.

(a) Soil Selection. As the grass thrives under foredune conditions, nurseries probably should be located on very sandy soil close to the sea. Sites should be weed-free since this species is not as competitive as the beachgrasses. Fumigation should be used for weed control.

(b) Soil Preparation. Little or no preparation is required in sand. Tillage to loosen hard-packed sites may be needed to facilitate transplanting.

(c) Planting. American dunegrass should be transplanted in the same way as American beachgrass. Plant 15 to 20 centimeters deep and 45 to 60 centimeters apart in rows 75 centimeters to 1 meter apart. Since planting material is not likely to be plentiful and the plant spreads, planting one stem per hill is advisable. The transplanting of dormant plants appears to be the key to survival for this species. The dormant period in the Pacific Northwest extends from late November to the end of February. The temperature probably should be below 14° Celsius at planting and for several days thereafter.

(d) Culture. This plant thrives under the rapid sand accretion and, therefore, probably responds to fertilization. Suggested application rate is 40 to 80 kilograms of nitrogen per hectare from a soluble source in early spring or as soon as new growth begins.

(e) Harvesting. Harvest only during the dormant season. Plants may be loosened with a shovel, lifted, shaken free of sand and dead trash, and broken into one- to five-stem plants. Cutting of stock a few centimeters below the surface with a sharp shovel may be necessary if sand has been deposited during the current growing season. Plants may be stored during cold weather by heeling-in. They may be stacked in baskets, boxes or tubs, or clay-dipped and packaged for handling as described for beachgrass. Trim tops to 50 centimeters for easy storage, handling, and transplanting. Take extra care to avoid drying and overheating. Planting should be as prompt as possible after digging.

f. Planting and Maintenance.

(1) Soil Moisture. Water is essential to the establishment of plants. The low water holding capacity of sand can cause serious failure of plantings. However, compensating factors in the beach and dune system often make it possible to work around this problem. On low-lying beaches in the Atlantic and gulf coast barrier islands, the water table is always close to the surface. Dahl, et al. (1975) found that moisture on the backshore (elevation, 1.3 to 1.6 meters MSL) was adequate at a depth of 15 centimeters except during extreme droughts. Moisture content was usually at or above field capacity, the water table was usually within 60 centimeters of the surface, and capillary action kept the sand moist. These sands drain excess water readily and surface drying is extremely fast but total water loss is low. The layer of dry sand minimizes evaporation losses from below the surface as long as the layer remains. Consequently, even on elevated surfaces such as fence-built dunes where the water table is not near the surface, the sand may remain moist a few centimeters below the surface for considerable periods of time. Dune

plants have various specialized adaptations for surviving substantial periods of low moisture. The least tolerant stage lies between transplanting and the development of a new root system that is adequate to extract moisture throughout a large volume of sand. Consequently, transplanting must be set deep enough for root development to occur before complete drying. On most U.S. coasts, the sands are usually moist during most of the recommended transplanting season; lack of moisture is a problem only in unusually dry seasons.

Moisture content is more important in the gulf coast where temperatures remain relatively high throughout most of the year, rainfall is erratic, and evaporation rate exceeds precipitation. Dahl, et al. (1975) found it necessary to irrigate fence-built dunes and other elevated areas behind the backshore before planting, primarily to firm the sand, except during and soon after heavy rains. They used sprinklers supplied by water pumped from open-pit wells dug immediately behind the dune line. Water was applied at the rate of about 0.5 centimeter per hour; it took about a day to wet the sand to a depth of 15 centimeters. The ground water was excessively saline at times but up to about 3 parts per thousand was tolerated by the plants.

Irrigation after planting is not generally worthwhile. Sand does not dry rapidly below the 15-centimeter level and irrigation does not raise the water table. Consequently, if the planting zone is moist from rainfall or preplanting irrigation, further watering adds little. Small-scale plantings where intensive management is possible may justify irrigation of the planting. Irrigation may be used under extreme drought conditions and to leach out salt following inundation by saltwater. However, the plants that are well adapted to the dune and beach environment, and have adequate moisture at planting, usually grow and survive with little added help.

Irrigation is sometimes the only way to firm the surface and prevent dry sand from refilling holes or furrows before plants can be inserted. Hand planting requires less than a 5-centimeter depth of dry sand but a mechanical transplanter can operate through a layer twice as thick. When the dry layer exceeds these limits, the only alternatives are to irrigate or wait for rain.

(2) Salinity. Salinity is a potential inhibitor to plant growth along any seashore. Salt is deposited on beaches and dunes in substantial quantities by salt spray or by flooding.

Fortunately, the potential of salt damage to the establishment and growth of dune plants is greatly tempered by the rapid leaching of the dune sands. These sands have almost no retentive capacity for salt and only a small amount of rainfall is required to remove salt from the plant zone. Dune plants can tolerate moderate concentrations of salt and some of them do not absorb salt through their leaves. All can tolerate some salt in their root zone. In the upper beach and coastal dunes, the lighter freshwater tends to float on top of the heavier seawater. In humid climates percolating rainwater causes the development of lenses of fresh to mildly brackish water on top of the saltwater under even the smallest dunes (Berenyi, 1966) and may create substantial reserves of freshwater under larger dune systems. This resistance to mixing may also allow plants an escape from salt damage following flooding. If the sand is moist, the seawater will drain off with little infiltration into the freshwater and little or no effect on the plants, except in low spots where it becomes trapped and evaporates, leaving a high concentration of salt.

Another possible mechanism in reducing the salt effect of inundation is the rise of the water table in the beach and dune area that accompanies a general rise in the tide level. The freshwater lense tends to rise with the water table leaching salt from the root zone.

Salinity is not usually a major barrier to the establishment of adapted foredune species on most U.S. coasts, but it can become a serious problem in the gulf coast where low sites have to be planted under conditions of warm to hot temperatures, low and erratic rainfall, and high evaporation rates. Dahl, et al. (1975) observed this in planting hurricane surge washovers on South Padre Island. They constructed a broad flat dune across a washover pass by trapping sand with 60-centimeter sand fences to leach out salt so bitter panicum and sea oats could survive. This lowered the subsurface salinity from 15 parts per thousand to near zero in 1 year.

Dahl, et al. (1975) also planted exposed back beaches and protected areas on North and South Padre Islands to study the effect of inundation on survival of transplants. Results were erratic--some plantings were essentially eliminated by storm surges and some were little affected. In general, established plantings were more tolerant to exposure but the increased survival on protected sites could not be attributed to only salinity differences. Drifting sand appeared to be equally important in several instances.

(3) Fertilization. Dune and beach sands undergo extensive leaching during formation, transport, and deposition. Consequently, they are inherently low in most nutrients essential to the growth of higher plants. In nature, most dune plants persist under a chronic deficiency of these nutrients. While typical dune species are well adapted to a low nutrient regime, most respond noticeably to fertilizers. This does not mean that the general use of fertilizers in the dune and beach system is desirable, but that fertilization can be a useful management tool.

Fertilization is useful for rather definite and restricted purposes: to speed up the establishment of new plantings, increase growth, and increase sand-trapping capacity, and thus improve their chance of survival; and to revive declining stands to maintain protective cover in areas receiving a reduced or intermittent sand supply.

Response to fertilizers is usually most pronounced on old, leached sands in back-dune and deflation plain areas that are cut off from fresh sand supplies. Response is likely to be much less on sites with active sand accretion. However, the initial establishment period is usually the most critical for dune plantings and even a moderate acceleration of growth at this point may mean the difference between success and failure, particularly on the more exposed sites. Fertilization, by reducing the limitations imposed by nutrient supply, enables better plant growth during favorable periods. Fertilization is usually discontinued in the active sand zone as soon as plants are established.

Most pioneer species, especially the major dune builders, lose vigor very rapidly when they no longer receive fresh sand. They may die out altogether and be replaced by plants of the intermediate zone that are much less effective in sand trapping and stabilization. This is the normal succession in this situation and unless there are practical reasons to do so, there is no point in interfering with it. However, the effect of fresh sand, or the lack of it, on pioneer dune plants is in part, at least, a nutrient effect and it is possible to revive sand-starved stands through fertilization. This is very useful whenever it becomes necessary to restore or maintain a vigorous foredune-type cover on areas that become cut off from fresh sand. Specific suggestions for fertilizer use are presented for the geographic regions later in this section.

Suggested fertilizer schedules are based on the use of standard commercial nitrogen and phosphate materials or mixed fertilizers of nitrogen and phosphate. Conventional soluble sources are surprisingly effective in light of the inability of dune sand to retain nutrients. This is apparently due to the interception of nutrients as they leach downward through the extensive root systems of dune grasses. Response is largely to nitrogen and sometimes to phosphorous. Consequently, a ratio of 3 parts nitrogen to 1 part of phosphate makes a good dune fertilizer. Occasionally, it may be more convenient to use commercially available fertilizers containing potassium, in addition to nitrogen and phosphorus. The potassium will do no harm but observable response to potassium or micronutrients is unlikely as long as the dune grasses are subjected to salt spray which supplies them. Where the suggested fertilizers are not readily available, waste can be minimized by alternating one application of 8-8-8 (8 percent N, 8 percent P_2O_5, 8 percent K_2O) or 10-10-10, for example, with two or three applications of a straight nitrogen source, such as ammonium nitrate, to approximate the suggested amounts of nitrogen and phosphate. Slow-release materials, particularly those containing slowly soluble nitrogen, reduce both leaching losses and the number of applications needed; however, results with these have been inconclusive. Most slow-release fertilizers are not fully effective unless placed deep enough to remain moist most of the time. Some slow-release materials have been used to speed establishment of American beachgrass by placing a small amount in each planting hole at time of planting. Although this promotes rapid growth for a year or two, it may overstimulate the plants, causing extensive die-out later, particularly if fertilization is not maintained at the same level. All slow-release materials are considerably more expensive than conventional sources.

Conventional fertilizer materials should be broadcast by ground or aerial equipment, and always pelleted or granulated to minimize drift. A helicopter is particularly well suited, provided the area involved is large enough to warrant its use. The advantages of using a helicopter are: better distribution of the fertilizer, no wheel-track damage to dune cover, a good distribution of the pellets of granules under windy conditions because the down blast from the rotor prevents pellet drift, and helicopter landing requirements permit loading close to the area to be fertilized.

g. Dune Building by Geographic Regions.

(1) North Atlantic Region.

(a) American Beachgrass. This grass is native to the North Atlantic coast and the only plant regularly used as the initial stabilizer in the foredune zone. It is easy to multiply under nursery conditions and to transplant, grows rapidly when transplanted, and is exceptionally effective in trapping sand and stabilizing dunes. It is usually planted in pure stands which makes the planted areas subject to rapid deterioration in the event of serious pest damage.

Recently, severe losses of American beachgrass stands in North Carolina have been caused by infestations of a soft scale, *Eriococcus carolinae* (Campbell and Fuzy, 1972). This pest appears to be widely distributed along the mid-Atlantic coast and probably occurs on the North Atlantic coast. For this reason, immune species should be interplanted with American beachgrass to reduce this hazard.

Disease is a factor which affects the vegetation and the resulting dunes. Marasmius blight was first observed in 1965 on Ocracoke and Hatteras Islands, but was not fully identified until some years later (Lucas, et al., 1971). This disease was subsequently found to be destructive to American beachgrass and to have profound effects on the development of these experimental dunes. Dune growth and configuration were materially affected by blowouts and other species spread into what would otherwise have been dense stands of American beachgrass. Damage varied widely from year to year, but some losses were observed during each growing season thereafter, except in 1973 where no development of Marasmius blight was observed anywhere along the North Carolina coast (Woodhouse, Seneca, and Broome, 1976).

Damage first occurs in distinct patches, roughly circular or oval in shape, that vary from 1 to 2 feet in diameter. All plants in the patch die simultaneously. Losses are usually limited to the interior of each section behind the zone of active sand accumulation. Losses from this disease are inhibited by rapid sand encroachment. Consequently, the front of a growing American beachgrass dune tends to remain intact even though severe, disease-induced blowouts occur immediately behind the zone. Also, new grass stands escape damage through the first, and usually the second growing season, enabling such plantings to establish a continuous front line before losses begin.

1 Planting Methods. Planting is done by hand on small areas and rough or steep terrain, and by machine on large, smooth sites. In hand planting, plants are inserted in individual holes opened with a shovel, spade, or dibble. This is best done by two-man teams, one opening the hole while the other inserts the plant and firms the sand around it. Machine planting is done with tractor-drawn transplanters designed to set crop plants such as tobacco, tomato, cabbage, etc. Most machines can be readily adapted to transplanting beachgrass by extending the openers or shoes to provide a deeper furrow in which to set the plant. Both one- and two-row machines are used. Wheel tractors are faster on smooth, relatively level sites; crawlers are needed on rougher sites.

2 Depth. American beachgrass should be planted 20 to 25 centimeters deep or deeper (30 to 35 centimeters) in loose, dry sand. The plants must be set deep enough for the basal parts to remain in moist sand until new roots develop to anchor them and new top growth can emerge to trap sand. The deeper they are placed in the moist sand, the less chance of being blown out before becoming established. Shallow planting is the most common cause of failure. It is difficult to open holes or furrows to the proper depth in hard-packed sand, and it is more difficult to keep them open long enough to insert plants through a thick layer of dry, loose sand. This problem can usually be overcome by using more power, but if the sand is dry, it may be necessary to irrigate or wait for rain.

3 Planting Date. This plant transplants exceptionally well and can be transplanted satisfactorily when dormant or growing. It has a long transplanting season. It can be transplanted successfully in New England from October through May with the preferred period running from February through April (Jagschitz and Bell, 1966; Zak, 1967).

4 Planting Stock. Transplants should have one to several healthy, vigorous stems (culms) (Fig. 23). Multiple stems planted in the same hill need not be attached to each other. Larger plants are preferred because the first year growth is definitely related to the number of stems planted per unit area. Consequently, on critical sites where rapid stabilization may be essential, five or more stems per hill are suggested. However, normally spaced plantings of one stem per hill will cover well in the first growing season and there is little difference in multiple-stem plantings the second year. Planting stock represents a significant part of the total cost of a planting so one to three stems per hill are usually planted on all but the most critical sites. The critical sites are the windward slopes of large, mobile dune areas that receive unusually large volumes of sand, blowouts in or between dunes, and areas vulnerable to storm waves.

5 Spacing. The exact spacing and pattern is important in the design of a dune grass planting. Spacing that is too wide will usually result in partial or total failure; spacing too close is wasteful. Planting costs are roughly proportional to the number of hills planted. For example, a 30-centimeter spacing requires four times as many hills per unit area as a 60-centimeter spacing and costs about four times as much.

The spacing and pattern should be determined by the characteristics of the site and the objective of the planting. A strip of American beachgrass, 8 to 12 meters wide, planted 45 centimeters on centers will, with normal development, effectively stop the movement of windblown sand in the last half of the first growing season. Small blowout areas should be planted at a spacing of 45 centimeters or less. Stabilization of a large area of bare sand will require a spacing of 45 to 60 centimeters. This means that the cost of planting may be significantly affected by the planting pattern. For example, in building a barrier dune, it is essential that part of the strip be planted at a density that will stop sand movement sometime during the first year. The plants should be spaced at 45 centimeters. It is not necessary to plant the entire width of the planned dune at this density. Further, the use of a graduated spacing pattern will result in a wider, more stable dune and will cost less.

A graduated pattern that has been used successfully to build barrier dunes where sand accumulation was 3 to 6 cubic meters per front meter is shown in Table 1.

Table 1. A graduated planting pattern to build a foredune.

No. of rows	Row spacing (m)
4	1.20
4	0.90
4	0.60
4[1]	0.45
4	0.60
4	0.90
4	1.20

[1]Center of dune.

With this planting pattern, the dune growth is more rapid near the center of the planted strip for the first 2 or 3 years, and the dune will slope gently to the outer edges. Sand accumulation will increase near the edges as the more widely spaced plants fill in and increase trapping capacity. The dune cross section will attain a stable form (Fig. 24). Planting costs are less than half that required for a uniform dense spacing.

6 Fertilization and Management. American beachgrass responds well to the addition of nutrients, and the judicious use of fertilizers is useful in the management of this plant. Plant response varies widely--it is least under the condition of rapid sand accumulation and greatest on old, leached sands in back dunes and deflation plains. Growth on sites not receiving fresh sand may be increased up to tenfold by fertilization. Response is chiefly to nitrogen and occasionally to phosphorus. Fertilization is used primarily for two purposes: (a) during establishment, to improve survival; and (b) to maintain a vigorous protective cover on areas that do not receive sufficient fresh sand.

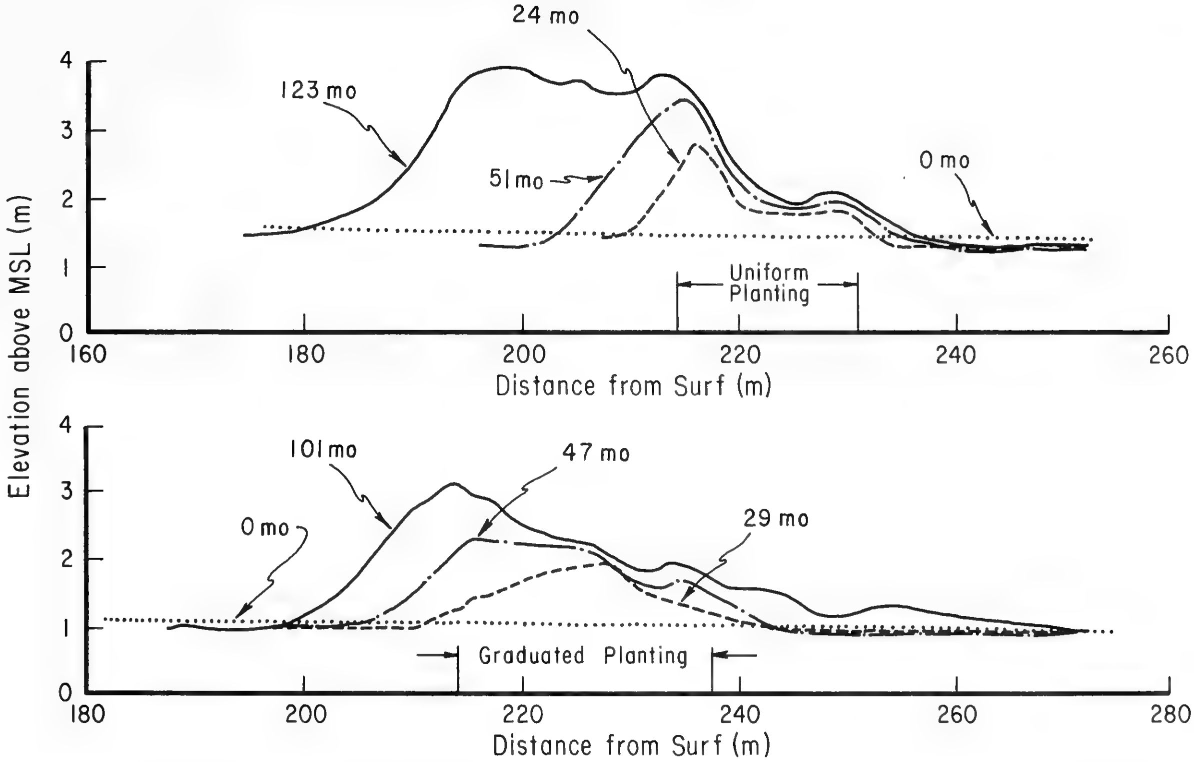

Figure 24. Dune profiles resulting from graduated and uniform planting patterns.

New stands will often benefit from the application of 100 to 150 kilograms of nitrogen per hectare and 30 to 50 kilograms of phosphate per hectare the first growing season. Application should begin as soon as new growth emerges and the total amount for the year should be divided into two or three applications, spaced 4 to 6 weeks apart. Fertilization after the first year should be adjusted to growth and appearance of the plants. It is usually not needed with substantial sand accumulation. Excessive fertilization is wasteful and can be harmful.

The same general principles apply to sand-starved stands. Poor stands will benefit from up to 150 kilograms of nitrogen and 30 to 50 kilograms of phosphate per hectare annually in two or three applications each year for 1 to 3 years. Stands that have not seriously declined may be maintained with an application of 30 to 50 kilograms of nitrogen per hectare applied in early spring, at intervals of 1 or more years. Fertilization practice should always be adjusted to the growth and appearance of the grass. Excessive growth may mat down and promote disease damage and plant loss.

Fertilizers containing nitrogen and phosphate in the suggested ratio are not widely available and, lacking these, the same effect can be obtained by alternating application of 10-10-10 or the equivalent with one or two applications of a straight nitrogen material such as ammonium nitrate, ammonium sulfate, or urea to approximate the desired ratio of nitrogen to phosphate. The added potassium is of no value but not harmful.

Fully established American beachgrass stands require protection from foot and vehicular traffic and prompt replanting of breaks that may lead to blowouts. The grass will tolerate moderate foot traffic but very little vehicular traffic. Suitable ramps and walkways should be provided where this traffic is expected. These structures should be elevated to permit growth under them. Accumulation of dead leaves and stems in established stands of American beachgrass can create a fire hazard during the winter and early spring. However, this grass will tolerate burning during this period. Controlled burning may be advisable in some cases to reduce the wildfire hazard or to control pests. American beachgrass will also tolerate occasional mowing. However, if repeated mowing is required, a different species should be planted.

In the North Atlantic region, American beachgrass may be killed by the soft scale, *Eriococcus carolinae*. This usually does not occur until stands are 2 or more years old. Losses are usually small where sand is accumulating. However, this pest can eliminate growth from sizable areas and may cause a serious loss of protective cover in a monospecific stand. In such cases, it is useless to replant affected areas with American beachgrass. Replant with bitter panicum, coastal panic grass (*Panicum amaralum*), or Bermuda grass (*Cynodon dactylon*).

(b) Bitter Panicum. Bitter panicum (dune panic grass in New England) offers promise as a companion to American beachgrass, particularly along the mid-Atlantic and perhaps extending into the North Atlantic region. It has been grown successfully as far north as Rhode Island (Jagschitz and Bell, 1966a) and is indigenous along the Atlantic coast from Connecticut southward (Palmer, 1975). Although a warm season grass, it is resistant to the common pests of American beachgrass. The plant should not be substituted for American beachgrass in this region but rather added as a safeguard against total loss in the case of insect or disease attack. Bitter panicum cannot withstand as high a sand accretion rate as American beachgrass but it has a better tolerance to sand starvation.

1 Planting Methods. Planting should be the same as for American beachgrass.

2 Depth. Plants should be set 20 to 25 centimeters deep in firm, moist sand, and 30 to 35 centimeters deep in loose, dry sand. Machine planting is preferable, where possible.

3 Planting Date. This plant can be planted the same as American beachgrass, and into late spring and early summer if moisture is favorable. However, since it is a summer grower, it probably should not be planted in this region before April to avoid long exposure to storm activity before the initiation of new growth.

4 Planting Stock. Bitter panicum has two types of stems (culms). Mature primary stems develop during the summer and are the only material available for transplanting in winter and in early through mid-spring. These tend to be hard and brittle, and may be 1 meter or more in length. Tillers are young, growing succulent stems with green leaves and are usually smaller than primary stems. Primary stems must be used during the late winter and spring until new tillers become available. Primary stems make satisfactory planting stock but behavior tends to be more erratic. Some plants remain dormant for some time after transplanting while others begin growing earlier. However, young tillers grow with little delay and are preferred when available.

The larger primary stems survive and grow better than small primary stems. Large stems are usually longer than needed and may be cut in half to form two transplants per stem with no consistent difference in survival between the top and bottom halves. Stems are usually harvested by hand pulling. Brittle, primary stems usually break off at the surface, but tillers will pull up with some roots and rhizomes attached. Presence or absence of roots on planting stock does not affect survival.

5 Spacing. Bitter panicum is not suitable for planting in pure stands in this region, except in spots where American beachgrass has been killed by insects or disease. In such cases, a spacing of 30 to 60 centimeters, depending on the degree of exposure, would be appropriate. Bitter panicum transplants should be substituted for a small proportion (10 to 20 percent) of American beachgrass plants and planted in the same planting pattern as the American beachgrass.

6 Fertilization and Management. Bitter panicum responds to increased nutrients and will benefit from the same fertilizer used for American beachgrass. Fertilizers may also be used to revive or maintain vigor of this species in areas that become sand-starved. No further management requirements for bitter panicum are known in this region.

(c) Other Species. There are a number of other plant species that occur on foredunes in this region and contribute to dune growth and stability. None of these have been widely used for planting in this zone except for certain specialized purposes.

Japanese sedge (*Carex kobomugi*) is useful as a stabilizer on heavy traffic areas in the pioneer zone (Hawk and Sharp, 1967). It resists foot traffic and the sharp-pointed leaves discourage pedestrian traffic; however, it is not very effective as a dune builder. It is propagated in the same manner as American beachgrass and responds the same to fertilizers.

The Bermuda grass (Tufcote) variety is a good turf-type plant for use on traffic areas near the sea in this region. Sprigs are planted in spring or early summer. It requires more frequent fertilization in the dune habitat than pioneer zone species (see Bermuda grass discussion in the South Atlantic region).

Coastal panic grass grows well in the pioneer zone. It is a heavy seed producer and can be seeded on the more protected sites, but it does not spread and fill in. It should be used as a secondary stabilizer.

Weeping lovegrass (*Eragrostus curvula*) can also be seeded in sands but it has about the same limitations as coastal panic grass, and it winterkills along the northern part of the region.

Other useful species are American dunegrass, Vancouver wildrye (*Elymus vancouverensis*) and Volga wildrye (*E. giganteus*).

Secondary plantings should supplement American beachgrass. Rugosa rose (*Rosa rugosa*) is used for this purpose. Switchgrass (*Panicum virgatum*) can be seeded and shows promise as an accessory.

(2) South Atlantic Region.

(a) American Beachgrass. This grass is widely used along the coasts of the Carolinas where it is the most effective initial stabilizer. However, it is usually short-lived in this region and should not be planted alone. Adding small amounts of bitter panicum or sea oats will ensure an orderly succession as the beachgrass stand deteriorates. American beachgrass has been grown as far south as northern Florida (Amelia Island) but it is of doubtful value there because of disease and pests.

1 Planting Methods. Planting is done by hand on small areas and rough or steep terrain, and by machine on large, smooth sites. In hand planting, plants are inserted in individual holes opened with a shovel, spade, or dibble. This is best done by two-man teams--one man opening the hole while the other inserts the plant and firms the sand around it. Machine planting is done with tractor-drawn transplanters designed to set crop plants such as tobacco, tomato, cabbage, etc. Most can be readily adapted to transplanting beachgrass by extending the openers or shoes to provide a deeper furrow in which to set the plant. Both one- and two-row machines are used. Wheel tractors are faster on smooth, relatively level sites; crawlers are needed on rougher sites.

2 Depth. American beachgrass should be planted 20 to 25 centimeters deep. The plants must be set deep enough for the basal parts to remain in moist sand until new roots and top growth develop. Also, the deeper into the moist sand the plants are placed, the less chance of blowout before becoming established. Shallow planting is the most common cause of failure.

It is difficult to open planting holes or furrows to the proper depth in hard-packed sand, and more difficult to keep them open long enough to insert the plants through a thick layer of dry, loose sand. This problem can usually be overcome by using more power, but in dry sand it may be necessary to irrigate or wait for rain.

Deeper plantings of 30 to 35 centimeters are necessary to stabilize large, mobile dunes to avoid early plant loss.

3 Planting Date. American beachgrass transplants well, and can be transplanted when dormant or active. The transplanting season is long. It can be transplanted successfully along the North Carolina coast from October to the end of May with the preferred period running from November to the end of March.

4 Planting Stock. Transplants should have one to several healthy, vigorous stems (culms). Multiple stems planted in the same hill need not be attached. First-year growth is related to the number of stems planted per unit area (Fig. 25). Consequently, on critical sites, where rapid stabilization may be essential, five or more stems per hill are suggested. However, normally spaced plantings of one stem per hill will cover well the first growing season and there will be little second-year difference in cover between these and multiple stems per hill plantings. As planting stock cost is a significant part of the total cost of a planting, one to three stems per hill are normally planted on all but the most critical sites. Critical sites are the windward slopes of large, mobile dunes areas that receive unusually large volumes of sand, blowouts in or between dunes, and areas vulnerable to storm waves.

5 Spacing. The spacing and planting pattern of American beachgrass is important in the design of a dune grass planting.

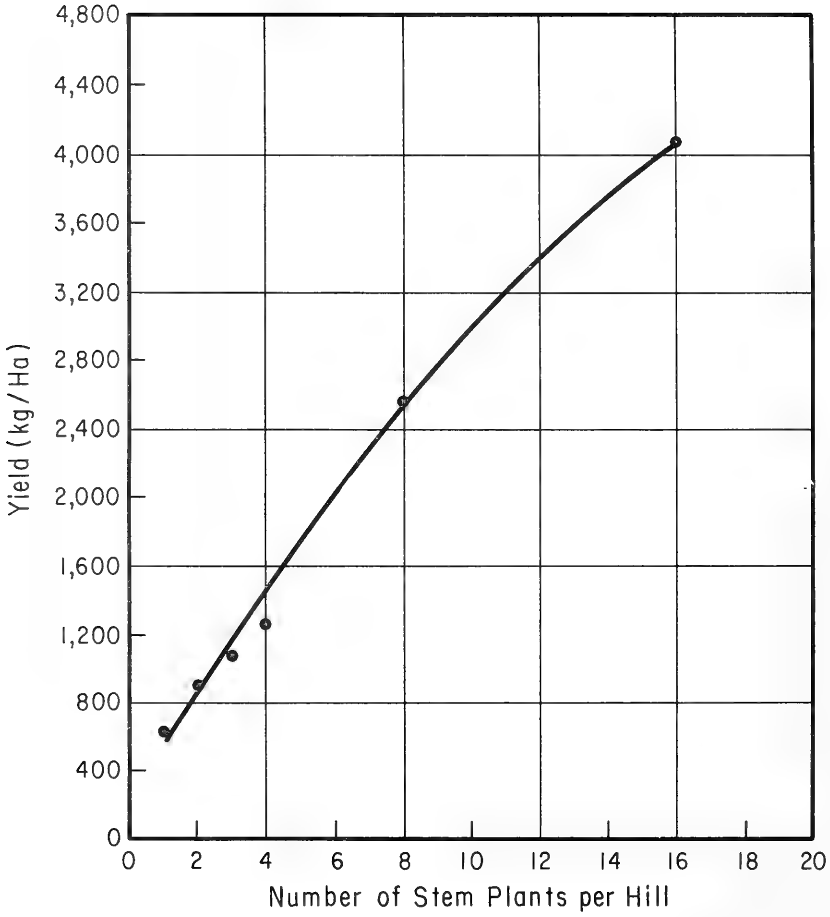

Figure 25. Effect of number of stems planted per hill on yield of plant tissue (stems) at end of first growing season.

Spacing that is too wide will result in partial or total failure; spacing that is too close is wasteful. Planting stock and costs are roughly proportional to the number of hills planted. A 30-centimeter spacing requires four times as many hills per unit area as a 60-centimeter spacing and costs about four times as much.

The spacing and pattern should be determined by the characteristics of the site and the objective of the planting. A strip of American beachgrass, 8 to 12 meters wide, planted 50 centimeters on centers will effectively stop windblown sand sometime in the latter half of the first growing season. Small blowout areas should be planted at a spacing of 50 centimeters or less. Stabilization of a large area of bare sand will require a spacing 50 to 60 centimeters. It also means that costs may be reduced in many instances by varying the planting pattern. For example, in building a barrier dune, it is essential that part of the strip be planted at a spacing that will stop sand movement sometime during the first year (about 50 centimeters). However, it is not necessary to plant the entire width of the planned dune at this density. Further, the use of a graduated spacing pattern will result in a dune with a more stable cross section and cost less (see Table 1).

Where sand movement is less (1.5 to 3 cubic meters per front meter), the following planting pattern on centers works well (front to back):

2 rows 1.00 meter
4 rows 0.75 meter
4 rows 0.45 meter
4 rows 0.75 meter
2 rows 1.00 meter

In both cases, the plantings are on equivalent spacing, obtained by varying row spacing and distance in the row when the planting machine cannot be adjusted to the exact row width desired.

With this type of planting pattern the dune grows, for the first 2 or 3 years, more rapidly near the center of the planted strip, and slopes gently to the outer edges. Sand accumulation increases near the edge as the plants fill in and develop trapping capacity. However, by that time the basic dune cross section has been broadened to a more stable form with gradual slopes (Fig. 24). The planting costs are less than half that of a uniform spacing.

6 Fertilization and Management. American beachgrass responds to fertilizers and the judicious use of fertilizers is useful in the management of this plant. Response varies widely, and is least under conditions of rapid sand accumulation, and greatest on old, leached sands in back dunes and deflation plains. Growth on sites lacking fresh sand may be increased tenfold by fertilization. Response is to nitrogen and occasionally to phosphorus. Fertilization is also used during establishment to speed up rate of spread and increase sand-trapping capacity.

New stands will often benefit from the application of 100 to 150 kilograms of nitrogen per hectare and 30 to 50 kilograms of phosphate per hectare the first growing season. Application should begin as soon as new growth emerges and the total for the year should be divided into two or three applications spaced 4 to 6 weeks apart. Fertilization after the first year should be adjusted to growth and appearance of the plants. It is not needed with substantial sand accumulation. Excessive fertilization is wasteful and may be harmful.

The same general principles apply to sand-starved stands. Poor stands will benefit from up to 150 kilograms of nitrogen per hectare and 30 to 50 kilograms of phosphate per hectare annually divided into two or three applications each year for 2 or 3 years. Stands that have not seriously declined may be maintained with an application of 30 to 50 kilograms of nitrogen applied in early spring, at intervals of 1 or more years. Fertilization practice should always be adjusted to the growth and appearance of the grass. Excessive growth may mat down and promote disease and plant loss.

Where fertilizers containing suitable ratios of nitrogen and phosphate are not available, complete fertilizers such as 10-10-10 may be used to supply all of the phosphate and part of the nitrogen and alternated with one or two applications of ammonium nitrate to supply the desired total nitrogen. The potassium in the 10-10-10 is of no value in the salt spray zone, but it will do no harm.

Fully established American beachgrass stands require protection from foot and vehicular traffic, and occasionally replanting of breaks that might lead to blowouts. This grass will tolerate moderate foot traffic but little vehicular traffic. Suitable ramps and walkways should be provided where this traffic is expected. These structures should be elevated to permit growth under them. Accumulation of dead leaves and stems in established stands of American beachgrass can create a fire hazard during the winter and early spring. However, this grass will tolerate burning during this period. Controlled burning may be advisable to reduce wildfire hazard or to control pests. American beachgrass will also tolerate occasional mowing. However, if repeated mowing is required, a different grass should be planted.

In this region, American beachgrass may be killed by Marasmius blight or by the soft scale, *Eriococcus carolinae*. This grass is most vulnerable when stands are 2 or more years old and active sand accumulation is light or absent. Given these conditions, these pests can effectively eliminate this grass from sizable areas and may cause a serious loss of protective cover in a monospecific stand. American beachgrass should not be replanted in affected areas. Replant with bitter panicum, sea oats, or Bermuda grass.

(b) Bitter Panicum. This plant is increasing along the South Atlantic coast. It seldom produces viable seeds, so to spread into new areas is slow and sporadic, and is readily propagated vegetatively.

It has promise as a companion to American beachgrass and sea oats along the Carolina coasts and an initial stabilizer farther south.

1 Planting Methods. Transplanting is the same as for American beachgrass. Stems (culms) are set upright by hand or by tractor-drawn mechanical transplanters.

The ease with which bitter panicum forms new tillers at buried nodes (joints) permits modifications in this planting procedure. Long stems may be planted horizontally in furrows, 10 to 15 centimeters deep, with the tip of the stem left exposed. This results in a new plant at nearly every node. This method has been successful in nurseries to increase planting stock supplies. The method results in a new plant for every 15 to 20 centimeters compared with one per 30 to 60 centimeters where stems are set upright in normal fashion. The method is difficult under beach and dune conditions where depth control is a problem.

An alternate method, which has been successful, requires mowing and raking top growth from the nursery, broadcasting this material on the sand surface, and covering it by discing or plowing. This approach is more mechanized and may result in denser stands than either type of row planting. It is also cheaper where planting stock is plentiful and close at hand. Again, the principal problem is control of planting depth. Shallow planting causes the new shoots to die during dry periods before becoming fully established; planting too deep will cause stored food reserves to become exhausted before new shoots can reach the surface.

Neither method is reliable where substantial sand movement, either erosion or accretion, occurs during the establishment period.

2 Depth. Planting depths for bitter panicum are similar to American beachgrass. Plants should be set 20 to 30 centimeters deep to prevent drying and subsequent loss that will lead to blowouts. This grass is more sensitive to sand burial than American beachgrass. Dahl, et al. (1975) reported low survival of bitter panicum when sand accumulation buried the uppermost living part of each transplant more than 15 centimeters deep. Survival of unburied plants was 68 percent; survival of plants buried 15 centimeters deep was 29 percent. This illustrates why control of planting depth is critical in furrow planting and plowing or discing of bitter panicum stems. It also explains the poor planting results near unfilled sand fences where sand accumulates rapidly. Care is required to avoid burying the grass too deep. This is another reason to plant sea oats, American beachgrass, or both with this grass.

3 Planting Date. Bitter panicum is similar to sea oats in response to planting dates and conditions. It can be transplanted with some success about anytime of the year, provided moisture conditions at and immediately following transplanting are favorable. Dahl, et al. (1975) obtained excellent survival in each month of the year in at least 1 out of 5 years in the gulf region. They found that

survival of plants transplanted in the summer was higher than those planted in winter. They considered fall the least desirable time to transplant panicum because transplants remained dormant over winter and did not resume growth until late spring. In the meantime, the planting was exposed to the hazards of winter weather--blowout, burial, and salt-water inundation. They concluded that as long as environmental conditions (principally moisture) were favorable, the best planting time for bitter panicum is in late winter or early summer. Experience along the South Atlantic coast agrees with this conclusion except a later (March) starting date is necessary in the northern half of the region.

4 Planting Stock. Two distinct types of bitter panicum stems (primary stems and tillers) are available in the fall and again in the spring and early summer. Primary stems represent mature growth from the previous year which has flowered and is generally dry and brittle. Such stems may be 1 meter or more in length and most of the lower leaves are dead with the terminal leaves still green. These are preferred for transplanting in fall and early spring. Tillers are young, growing succulent stems with green leaves and are usually smaller than primary stems (Fig. 26). Actively growing tillers are the best planting stock in late spring and summer when they become established and grow quickly. Consequently, planting stock should be according to the season.

Size of primary stems is important in selecting planting stock. Dahl, et al. (1975) obtained higher survival, threefold to tenfold, from large stems (60 centimeters long), as compared with small primary stems (30 centimeters long). Small primary stems are usually found in old, crowded, or starved stands; their poor performance is probably due to their limited reserves of stored food. Use of crowded nursery plants is not economical as it requires a high density planting to make up the higher mortality.

In upright planting, stems longer than 50 to 60 centimeters should not be used although primary stems from vigorous nursery stock are often 1 meter or more long. Long stems may be divided into two or more pieces for planting with little difference in survival between top and bottom segments (Dahl, et al. 1975). Consequently, where large primary stems are harvested, dividing them will double the number of usable transplants without reducing survival, and will decrease the cost.

5 Spacing. The spacing and planting pattern for bitter panicum is the same as outlined for American beachgrass. Excessively wide spacing invites failure; dense spacing is wasteful. The planting pattern should take into account the site and the objectives. In the more southerly part of this region, a planting of bitter panicum, 15 meters wide and 45 to 60 centimeters on centers, will effectively stop movement of windblown sand across the strip by the end of the first growing season. This spacing should also be used where a dense spacing is needed as on blowouts, diseased spots, or large bare dunes. However, a graduated pattern such as described for American beachgrass will build a better foredune at a lower cost.

Figure 26. Primary stems and tillers of bitter panicum.

The shorter growing season in the northern part of the region (coast of the Carolinas) would require closer spacing if this species was planted alone. However, it is usually cheaper and more effective to use it in a mixture with American beachgrass, with or without sea oats. In this case, spacing is the same as that used farther south, 45 to 60 centimeters on centers in uniformly spaced plantings or at appropriate spacings for graduated patterns.

One stem of bitter panicum is usually planted per hill. Spacing and planting pattern suggestions are based on this. Plantings of multiple stems per hill are not warranted except where planting stock is limited to very small tillers.

6 Fertilization and Management. Bitter panicum responds to fertilizers in the same general way as American beachgrass. Fertilizer will speed up plant establishment, help maintain a vigorous protective cover on areas receiving limited amounts of fresh sand, or revive and maintain vigor of old sand-starved stands. Rates of application are the same as for American beachgrass, ranging from two to three applications per year of 40 to 50 kilograms of nitrogen per hectare and 10 to 15 kilograms of phosphate per hectare to establish stands or reactivate old ones to a single similar application at intervals of 1 to several years to maintain vigor. Fertilization should be adjusted to the growth and appearance of the grass.

Fertilization suggestions are in terms of standard commercial nitrogen and phosphate fertilizer materials. The use of some of the recent types of slow-release materials is justified in some cases but care should be taken to be sure that the type is effective under dune conditions. Fertilizers that require fairly constant moisture or certain microorganisms to be available to plants are not effective in the dunes.

Management of bitter panicum stands after reaching full cover is similar to that for American beachgrass. The stand requires reasonable protection from foot and vehicular traffic, and replanting of breaks that might lead to blowouts. This grass is very palatable to livestock (Dahl, et al., 1975) and other grazing animals such as rabbits, and may require protection.

(c) Sea Oats. This grass dominates foredunes from Cape Hatteras south to Mexico. It is more persistent than other foredune species in the back-dune areas of this region, but it is not a good initial stabilizer. It grows slowly, is difficult to propagate, and is not widely available commercially. Consequently, it should not be planted in pure stands. Because sea oats is an excellent sand trapper, well adapted to this region, and very persistent, it is useful to include it as a minor part of a planting mixture. It can be mixed with either American beachgrass or bitter panicum along the coast of the Carolinas, and with bitter panicum farther south. Sea oats will spread as the other grasses die, thin out, or are overcome by excessive sand deposition.

1 Planting Methods. Planting is done with the same equipment as American beachgrass. Transplants tend to be more variable in size and are slightly more difficult to machine plant than American beachgrass plants.

2 Depth. Planting depth is the same as for American beachgrass, 20 to 30 centimeters. However, sea oats is a slow starter and it is essential that it be set to the full depth to prevent drying before establishment and to avoid blowouts.

3 Planting Date. Results of planting trials have been quite variable. Moisture conditions at and immediately following planting are more critical in the survival of sea oats than the season of the year or physiological condition of the plant. Transplanting is probably successful in any month of the year in the southern part of the region. Dahl, et al. (1975) obtained satisfactory survival in July and September during a wet summer. However, after 5 years they concluded that January and February were usually the best months. In the more severe climate of the South Atlantic coast, February to April appears to be the optimum time; later planting is feasible only under very favorable moisture conditions.

4 Planting Stock. The number of stems (culms) per transplant is not a factor in the survival and growth of sea oats. Dahl, et al. (1975) found little difference between one, three, and six stems per hill. Single-stem transplants survived well under favorable conditions; under poor conditions survival of three or six stems was slightly better. Multistem transplants do not appear to be justified.

The range in stem size is greater in sea oats than in American beachgrass (Fig. 27). Small plants survive poorly. Dahl, et al. (1975) obtained substantially better survival from medium to large stems (75 centimeters to 1.5 meters tall) as compared with very small to small (45 to 75 centimeters tall) stems. However, they concluded that the difficulty in digging and processing very large plants negates the survival advantage. Dahl, et al. concluded that there is an advantage in using 2-year-old nursery-grown sea oats as this will furnish a large proportion of intermediate-size plants.

5 Spacing. The slow starting of sea oats makes it necessary to use a denser spacing than is used with American beachgrass. However, sea oats is not usually planted in pure stands because of the high cost of the stock, and because sand-trapping capacity and stabilization can be developed quicker by including a high proportion of one or two less expensive species in the planting. Sea oats plants become unusually effective as sand trappers once they become well established. Dahl, et al. (1975) described a sea oats strip, spaced 60 by 120 centimeters, 15 meters wide, planted in April 1972, with only 36-percent survival, that effectively stopped sand moving across it by the end of the first growing season. The strip had built a dune over 2 meters high by March 1974. In view of this, it is doubtful that spacing closer than 60 centimeters on centers would be economically justified.

Figure 27. Small to large sea oats stems.

Sea oats is usually planted as a minor component of a dune grass mixture. One or two rows are generally included in barrier dune plantings or in every 10th to 20th row in very large plantings.

Direct seeding is not practical to establish sea oats on bare dunes. Seeds can be used to introduce the grass into new plantings of other species such as American beachgrass and bitter panicum. Seed heads can be gathered when mature (October in the Carolinas or September in Florida) and broadcast over the new planting where they will be trapped, covered by sand, and germinate later.

6 Fertilization and Management. Sea oats respond to the addition of nutrients in the same way as American beachgrass. A moderate application of nitrogen and phosphate can be used to speed establishment of new plantings, and to maintain growth and vigor in sand-starved areas. However, this plant is considerably more tolerant of low nutrient levels than American beachgrass and will persist in back dunes and deflation plains for long periods without the addition of nutrients or fresh sand.

Management requirements for established sea oats are essentially the same as for American beachgrass and bitter panicum. Protection from foot and vehicular traffic is essential and replanting of storm- or man-induced breaks in the cover is necessary. Seed heads need protection because they are in great demand for commercial and personal ornamental use. Harvesting the seed stalk does not harm the plant as the flowering stems die at maturity, but removal of the seed from the dune area can limit future dune development. The inclusion of sea oats in dune plantings provides a natural replacement of thinning stands of other species.

(d) Saltmeadow Cordgrass. This plant grows abundantly along the Atlantic coast. It has not been planted extensively for dune building and stabilization because it is not as effective a sand trapper as the other dune grasses. However, it frequently initiates and builds low dunes which may later be taken over by other plants (Fig. 21). It is more salt tolerant, but less drought tolerant than American beachgrass, bitter panicum, and sea oats. It is particularly well suited for planting on low, moist sites where periodic salt buildup occurs. It probably has greater utility for initial stabilization of this type of site than has been generally recognized.

1 Planting Methods. Saltmeadow cordgrass is planted the same way as the dune grasses. The finer, more pliable stems and the need for multiple-stem transplants make it more difficult to machine plant than the other grasses.

2 Depth. Planting depth on drier sites is the same as for American beachgrass, bitter panicum, and sea oats. Saltmeadow cordgrass should be set 15 to 20 centimeters deep to keep it in the moist zone. On low-lying moist sites, planting depth may be reduced to about 15 centimeters.

3 Planting Date. Little information is available on the planting date for saltmeadow cordgrass, but it appears to behave somewhat like bitter panicum. The best planting period is probably late winter and spring, and it can be transplanted into the summer if moisture conditions are favorable.

4 Planting Stock. The nature and condition of the planting stock appears to be a major factor in the survival of plantings of saltmeadow cordgrass. Stock must come from vigorous, uncrowded stands. As plants become crowded or starved, their value as transplants declines drastically. Suitable material is difficult to obtain from the wild; therefore, nursery production is necessary. The stems are small and multistem transplants are highly desirable. The number of stems to be used will vary with stem size and stored food content but generally there should be 5 to 10 stems per transplant. These plants are usually too long to machine plant without trimming. Also, due to the larger number of more pliant stems and leaves, more care in trimming is required to avoid problems in feeding through the planter.

5 Spacing. Spacing should be adjusted to the nature of the site and the objective of the planting. The plant is a less effective sand trapper than the grasses with larger, stiffer stems and leaves which suggests closer spacing. With vigorous plants, adequate nutrients, and favorable moisture, it is quick to establish and cover over. Consequently, spacing of 40 to 60 centimeters on centers is probably adequate for single-species plantings on suitable sites. Where a dune ridge is to be built, it should be planted on the same graduated planting pattern described for American beachgrass.

6 Fertilization and Management. This plant responds well to nutrient supply. Fertilization is probably the key factor in the success of healthy planting stock. Fertilization should be adjusted to growth and appearance of the grass, but it will usually benefit from 100 to 150 kilograms of nitrogen per hectare divided into two or three applications the first year. After that, fertilization can be reduced to a single application for 1 or 2 years, then discontinued until the stand appears to need additional nutrients.

Saltmeadow cordgrass requires protection from excessive traffic but vigorous stands are considerably more tolerant than most dune plants. It will also tolerate a moderate amount of mowing. This was the major salt-hay species harvested in the past in substantial quantities along the North Atlantic coast.

(e) Bermuda Grass. This is not a prominent dune species but occasionally occurs naturally in the dune habitat. It can be used very effectively for special purposes along the South Atlantic coast. The hay-type hybrid (Coastal) roots deep in sand, tolerates salt spray and sand accretion, and establishes rapidly on foredunes. It has been used to revegetate areas where American beachgrass had been killed by insects or disease (Fig. 28). This plant covers more rapidly in the spring and summer than others.

Figure 28. Coastal bermuda grass revegetating a Marasmius blight patch on an American beachgrass dune.

Bermuda grass is also the best species for traffic-resistant turf on dunes. The turf-type hybrids, Tifway and Tifgreen, perform well in the dune environment when properly managed. The three hybrids are suggested for grassed walks, driveways, and parking areas.

Sprigging of plants is the usual method of establishment. Spacing is determined by rate of spread desired. For stabilization on bare foredune areas, 45 to 60 centimeters on centers is usually adequate. Closer spacing of 30 centimeters or less on centers should be used for turf. Sprigs for use in sand should be 15 to 20 centimeters long and set upright or at a slight angle with the tip, including some leaves or a joint, protruding above the surface. Sprigging may be done from early spring into summer under favorable moisture conditions. Early planting is usually best on foredunes or where supplemental water is not available. Where turf-type cover is required in a hurry and water is available, "instant" turf can be established by placing strips of sod over the area.

Bermuda grass has a much higher nutrient requirement than the typical dune grasses. Fertilization is the key to its establishment and maintenance. Suggested fertilization to develop plant cover on the foredune is 30 to 50 kilograms of nitrogen per hectare at 4-week intervals as soon as new growth begins in the spring through late summer. To develop traffic-resistant turf, 500 to 1,000 kilograms of 10-10-10 fertilizer per hectare should be applied in early spring and followed by 50 to 75 kilograms of nitrogen per hectare at 4-week intervals through late summer.

The turf hybrids and Coastal variety will tolerate mowing but it should be infrequent and more top growth should be retained here than on inland sites to maintain trapping ability of sand.

(f) Knot Grass or Seashore Paspalum (*Paspalum vaginatum*). This grass is widely distributed along much of the South Atlantic coast where it forms a turf on moist areas along road shoulders, beside ditches, and near dunes. It serves the same purpose on moister sites that Bermuda grass does in drier situations, and it can be propagated and managed in the same way. It spreads naturally into suitable areas rather rapidly and does not usually require planting.

(g) Seashore Elder (*Iva imbricata*). This is the only broad-leaved plant with a potential for building and stabilizing foredunes in this region. It is widely distributed throughout the region, although not generally plentiful. It occurs on backshores, foredunes, swales, back dunes, and in the upper fringe of the salt marsh where it is mixed with marsh elder (*I. frutescens*). It is highly tolerant to saltwater, salt spray, sandblast, and sand accretion. Occasionally, this plant alone builds foredunes (Fig. 29) although it is usually mixed with one or more dune grasses. It spreads vegetatively and by seeds, and appears to be increasing.

Little was known about the ecological or propagation requirements of seashore elder until recently (Colosi and McCormick, 1978). Not enough

Figure 29. Young dune initiated by seashore elder.

is known to predict future use but the plant can be transplanted and contribute to attaining a more natural dune community. Community stability would be increased where it can be successfully introduced. It can grow throughout the pioneer and most of the intermediate zones.

Further research is needed for firm suggestions or recommendations. Three types of cuttings have been planted. Rooted stems taken from foredune plants have survived better than unrooted stems. Rooted cuttings in peat pots were more susceptible to wind erosion but those that survived grew faster than bare cutting. Woody stems were better transplants than soft (new growth) stems (Colosi, et al., in preparation, 1978).

Seedlings only establish in areas of little sand movement and favorable moisture. Transplanting is successful on sand flats with a high water table. Transplanting to high, dry sites is not recommended. Seashore elder does not invade established foredunes but continues to grow with them after earlier establishment at lower elevations.

(h) Pennywort (*Hydrocotyle* sp.). This is a very effective sand-stabilizing broad-leaf plant. It is widely distributed throughout the region. It is tolerant of dune conditions, responsive to fertilization, and can be planted easily by sprigging. It is primarily a stabilizer rather than a builder because the round, fleshy leaves grow very close to the sand surface and provide only a few centimeters of trapping capacity at any one time. When only stabilization is needed, it can be sprigged in the same manner as Bermuda grass and fertilized like bitter panicum and sea oats.

(i) St. Augustine Grass (*Stenotaphrum secundatum*). This is a turf grass similar in habit and requirements to the turf-type Bermuda grasses. It is adapted to coastal conditions from about the southern one-quarter of the North Carolina coast southward. It can be substituted for turf-type Bermuda grass.

(j) Others. Spanish bayonet (*Yucca aloifolia*) grows well throughout the region and is useful as a windbreak. Sea grape (*Coccoloba uvifera*) is widely planted in central and south Florida as an ornamental windbreak.

(3) Gulf Region.

(a) Bitter Panicum. Bitter panicum plays a similar role on the gulf coast to that of American beachgrass on the North and mid-Atlantic coasts. It is easy to propagate and multiply under nursery conditions and transplants readily into the beach and dune habitat. It is the best plant available for initial stabilization of windblown sand in this region.

Bitter panicum was nearly eliminated by grazing from much of the gulf coast long ago because it is highly palatable to livestock (Dahl, et al., 1975). However, this problem has been reduced and the plant has increased in recent years. It has no known serious pests but as its use expands, the probability of a buildup of a damaging insect or disease will increase. For this reason, other species such as sea oats should be incorporated in bitter panicum plantings.

1 Planting Methods. This grass may be planted in either an upright position or horizontally. It readily forms new shoots from buried nodes (joints) so horizontal planting, theoretically, results in more new plants per unit of planting stock. However, Dahl, et al. (1975) compared the two methods on Padre Island and found upright planting preferable where there was substantial sand movement. There was considerable risk of exposure by erosion or excessive burial of transplants by sand deposition with the horizontal method. Plants set upright, 20 to 30 centimeters deep, are less likely to be uncovered and blown out or buried too deep. The horizontal method may be used with very long stems in protected areas.

Bitter panicum plants are set by hand on sites that are too small, too rough or too steep for mechanized operations. Machine planting is done on larger, smoother sites with tractor-drawn transplanters of the type used to set crop plants such as tobacco, tomato, and cabbage.

Hand planting is done most efficiently by two-man teams. One man opens the hole with a shovel or dibble while the second inserts the plant and firms the sand around it. Both one- and two-row transplanters are used for machine planting. A one-row transplanter requires a four-man team; a two-row machine requires a six-man team for efficient operation.

2 Depth. Normal planting depth is 20 to 30 centimeters for plants set upright. This depth places the rooting zone of the plant where it will remain moist until fully established and anchors it against being blown out. Bitter panicum cannot withstand as much sand burial as some other dune grasses. Dahl, et al. (1975) obtained very low survival when the uppermost living part of the plant was buried more than 15 centimeters deep. Consequently, deep burial of plants during establishment should be avoided. Planting close to unfilled sand fences is also risky because the sand will accumulate too fast and bury the plant.

3 Planting Date. Survival of bitter panicum transplants depends more on moisture conditions at and following transplanting than on calendar date. Dahl, et al. (1975) transplanted this plant successfully at least once in each month of the year. However, the best planting period was from late winter to early summer. Fall and early winter plantings were inferior because the plants remained dormant until late spring. In the meantime, they were exposed to the hazards of winter weather, burial, blowout, and saltwater inundation.

4 Planting Stock. Two distinct types of stems of bitter panicum (primary stems and tillers) are available in the fall and again in the spring and early summer. Primary stems represent mature growth from the previous year which has flowered and is generally dry and brittle. Such stems are 1 meter or more long and most of the lower leaves are dead with the terminal leaves still green. These are preferred for transplanting from early winter through early summer.

Tillers are young, succulent growing stems with green leaves and are usually smaller than primary stems (Fig. 26). Tillers are best planted from late spring through summer because they become established and grow quickly. Consequently, planting stock should be according to the season.

The size of the primary stems is important in selecting planting stock. Small primary stems are usually found only in old, crowded, or starved stands; their poor performance is probably due to their limited reserves of stored food. Use of crowded nursery plants is not economical as the small stems must be planted at a much higher density to counter the high mortality.

In upright planting, stems longer than 50 to 60 centimeters should not be used. Primary stems from vigorous nursery stock are 1 meter or more long and may be cut into two or more pieces for planting with little difference in survival between top and bottom pieces (Dahl, et al., 1975). The number of usable transplants may be more than doubled by cutting the large primary stems. Survival will not be reduced and handling will be much easier.

5 Spacing. Planting density and pattern should be based on the nature of the site and the objective. A planting spaced 30 centimeters on centers, will cover over quicker than one spaced 60 centimeters on centers, but it will require four times as many hills and cost

about four times as much. Dahl, et al. (1975) found on Padre Island that bitter panicum spaced 60 centimeters on centers, planted in a strip 15 meters wide, effectively stopped windborne sand by the end of the first growing season. Closer spacing resulted in slightly more dune growth only in the season of establishment.

A graduated planting pattern, dense near the center and thinning toward the outer edges, has been found to be more effective and less costly than uniform spacing (Savage and Woodhouse, 1968; Seneca, Woodhouse, and Broome, 1976). The wider spacing on the outer edges allows sand to reach through to the center and build a ridge. This planting pattern produces a dune with a more stable cross section and at less cost.

A similar approach would be useful under conditions such as those at Padre Island. A planting pattern that will annually accumulate 8 to 12 cubic meters of sand per meter of length consists of a four- or five-row center strip with the plants spaced 45 centimeters on centers in a sequence of two rows spaced 80 centimeters apart, two rows 1 meter apart, and two rows 1.3 meters apart, from the front and sides of the center strip. This would result in a 15-meter-wide strip with fewer plants but more efficient than a 15-meter-wide strip with the plants uniformly spaced 60 centimeters on centers.

6 Fertilization and Management. Bitter panicum responds to fertilizer by speeding initial growth and early development of sand-trapping capacity. Dahl, et al. (1975) reported fourfold increases in growth of fertilized over unfertilized stands. However, fertilization after the first year is usually neither necessary nor desirable on active foredunes. Fertilization of a 15-month-old dune-width panicum plot produced growth and sand-trapping capacity far in excess of sand supply. This resulted in the retention of a high proportion of the sand near the front of the dune and a steeper, less stable dune (Dahl, et al., 1975).

Suggested rate of fertilization is 100 to 180 kilograms of nitrogen per hectare divided into two or three applications beginning in late April or May. The addition of small amounts of phosphate may be beneficial in some cases. Response to applied potassium is very unlikely in the salt spray zone.

(b) Sea Oats. This is the predominant foredune plant along most of the gulf coast and should be included with bitter panicum in all foredune plantings. It is too dificult and expensive to propagate to plant in a pure stand, but it will thrive under sand accumulations heavy enough to smother bitter panicum. The inclusion of sea oats in the mixture adds to stability of the planting as well as ensuring a seed supply for natural recolonization of bare areas. Also, sea oats will persist if conditions change and there is less sand movement, providing stabilization when other pioneer plants disappear.

1 Planting Methods. Sea oats is transplanted in the same way as bitter panicum. It is planted by hand on small, steep, or

rough areas and by machine on large smooth sites. Sea oats is more difficult to transplant than bitter panicum because of its form and the wide range in stem size.

2 Depth. Planting depth should be at least 15 centimeters on the moist backshore and 20 to 30 centimeters in loose dune sand. This plant is slow to start growth after transplanting and requires extra care to avoid excessive drying and to assure firm anchorage during the establishment period.

3 Planting Date. Dahl, et al. (1975) established successful plantings whenever moisture was favorable, including July and September, but concluded that January and February were usually the best months.

4 Planting Stock. Stem-size range is greater than that of bitter panicum (Fig. 26). Also, size is greatly affected by age; the larger plants are usually older. Dahl, et al. (1975) found larger stems survived best. However, the better survival of large stems did not compensate for the difficulty of digging and processing them, and there was no practical advantage in planting more than one stem per hill. Delaying harvest of nursery-grown plants until the second year resulted in a higher proportion of the more desirable, intermediate-size plants.

5 Spacing. Survival of transplanted sea oats is usually lower and regrowth slower than that of bitter panicum. Sea oats can be planted at a lower density than bitter panicum to trap sand under gulf coast conditions. There is no reason to space sea oats closer than 61 centimeters on centers. When included as a component of a bitter panicum planting, it should replace the appropriate number of rows, at the same spacing as the dominant species.

Direct seeding on bare dune sites is not feasible. However, this plant does invade other dune plant stands by seeds. Where transplants are not available, sea oats seeds should be introduced into bitter panicum plantings. Mature seed heads should be gathered in September or early October, and broadcast over the planting area where they may be trapped and buried.

6 Fertilization and Management. Response of sea oats to nutrients is similar to that of other dune plants. Fertilizer will promote rapid establishment and early development of sand-trapping capacity or revive or maintain growth and vigor in sand-deficient areas. This plant is probably the most tolerant of the pioneer species to low nutrient levels and persists in the intermediate zone for long periods without fertilizer or fresh sand adding nutrient.

Fertilization of mixed plantings with sea oats should be the same as that for bitter panicum. Where revival of sand-starved stands is required, 100 kilograms of nitrogen per hectare and 30 kilograms of phosphate (P_2O_5)

per hectare divided into two or three applications beginning in early spring should be used for a year or two. This should be reduced to a single application in early spring at intervals of 1 to several years as soon as growth permits. Vigor is usually maintained after sand supply is reduced or cut off entirely with a single application of 30 kilograms of nitrogen per hectare applied at 1- to 2-year intervals.

Management requirements for sea oats are very similar to those for bitter panicum. Protection from foot and vehicular traffic is very important and storm- or man-induced breaks must be repaired. Sea oats stems with seed heads need special protection from harvest in many areas due to the growing demand for them for ornamental purposes. This can have a significant effect on future dune development and stability by depleting the seed supply and consequently the potential for natural spread and replacement of vegetation. Harvesting of seed stalks does not harm the live plants as the flowering stems die and are replaced by new tillers from the basal nodes. Sea oats seeds represent the major natural vegetative repair mechanism in the foredune area in this region.

(c) Other Species. There are a number of other pioneer zone plants that commonly occur along the gulf coast and contribute to dune building and stabilization but are not ordinarily planted for this purpose.

Railroad vine (*Ipomoea pes-caprae*) is one of the more prominent plants. This is a robust vine that is capable of rapidly spreading over foredunes and back beach (Fig. 30). It is not planted because it is less effective in trapping sand than the dune grasses. There are also other smaller *Ipomoea* spp.

Figure 30. Railroad vine.

Saltmeadow cordgrass is more salt tolerant but less drought resistant than panicum and sea oats. It initiates dune growth on low-lying areas (see Sec. II,3,g,(1)), and can be planted along the gulf, particularly where salt concentration is a problem. It has been used very little along much of the gulf probably because of the drier climate.

Sea purslane (*Sesuvium portulacastrum*) occurs on the foredune and often invades the backshore where it forms embryonic dunes which may be eventually taken over by the dune grasses. Other fairly common plants, *Sporobolus*, *Hydrocotyle*, *Euphorbia*, *Erigeron*, *Croton*, and *Fimbristylis* sp. are seldom used.

Bermuda grasses and St. Augustine grass may be used for turf and traffic areas in this region. See discussion of these species in Section II,3,g,(2).

(4) North Pacific Region. Coastal dunes occur extensively in region and are usually associated with the larger streams. There was an estimated 20,000 hectares of dunes in Oregon and lesser but substantial areas in Washington and California in 1942 (McLaughlin and Brown, 1942). Much of the area consists of active or recently active dunes. Many of them are large and destructive. Due to the direction of the prevailing winds, northwesterly in the summer and southerly in the winter, sand movement is mostly landward, and unstable sand is soon moved inland out of the foredune zone. Consequently, the majority of the area to be stabilized is behind this zone.

(a) European Beachgrass. This is essentially the only species planted in this region since the 1930's for the initial stabilization of blowing sand. The ease with which this introduced beachgrass can be increased and transplanted is a great advantage in stabilizing large areas. No other plant is as inexpensive to use. In smaller plantings other species might possibly offer advantages that could outweigh their higher costs. European beachgrass is a very effective sand trapper (Fig. 31). Unfortunately, it forms dense stands but lateral spread is slow which results in dunes with steep windward slopes. Good initial stands and regular maintenance of this species are essential as it does not spread and fill-in as well as most dune grasses. European beachgrass is competitive in the active sand zone and excludes native species. This gives the dune a monotonous appearance and makes it difficult to establish mixed plantings. Behind the primary zone, the grass loses vigor and declines rapidly as its sand supply is cut off making it essential to introduce species that can take over and replace it.

1 Planting Method. Planting is done by hand on small areas and steep slopes and by machine on large, smoother sites. In hand planting, it is best to work in two-man teams with one man opening the hole with a spade, shovel, or dibble and the other inserting the plant

Figure 31. Growth habit of European beachgrass.

and firming the sand around it. Machine planting is done with tractor-drawn transplanters built or adapted for this purpose. With either method, sand must be firmed around the base of the plant to exclude air pockets.

Planting should not be done when the temperature exceeds 16° Celsius or is at or below freezing. Moist sand should be within 8 centimeters of the surface.

2 Depth. Suggested minimum planting depth on drifting sand is 30 centimeters. This depth may be impractical in the hard-packed sand of some foredune sites. It is essential that plants be set deep enough to remain in moist sand during establishment and to anchor them against strong winds during the planting season.

3 Planting Date. Suitable temperature and moisture conditions are more important to the survival of this grass than the planting date. These conditions are usually optimum in this region during the late fall, winter, and early spring months.

4 Planting Stock. Plants should be shaken free of sand, separated, cleaned of dead stems and trash, and pruned to an overall length of 50 centimeters. Stock may be temporarily stored by heeling-in in narrow trenches if soil is well drained. For long-term storage, clay-dip, bundle, and hold at about 1° Celsius. Three to five stems per hill are usually planted because dense stands are essential under the wind conditions in this region. Anything with less than a 90-percent survival rate should be replanted.

5 Spacing. This is a critical factor in determining both the probability of success and the cost of a planting. Planting costs are proportional to the number of hills planted. Spacing and planting pattern should be adapted to the site and the result desired. Generally, a 45- by 45-centimeter planting with three to five stems per hill is sufficient on all but the more critical sites such as steep windward slopes and the tops of foredunes. A graduated planting pattern (Savage and Woodhouse, 1968) is better for building a foredune by allowing the center ridge to develop rapidly and avoid the steep seaward slope typical of this species. A pattern of several rows with plants spaced 30 by 30 centimeters on centers and the other rows forward and backward of the center of the strip with plant spacing graduated from 45 by 45, 60 by 60, and 90 by 90 centimeters will build a more stable foredune at less cost than a uniformly spaced planting. Total width of the planted strip (20 to 40 meters) will depend largely upon the volume of moving sand anticipated.

6 Fertilization and Management. Fertilization is extremely important to the establishment of European beachgrass back of the foredune. It is probably less critical within the foredune but because of high-energy conditions there stimulation by fertilization is desirable. Response is limited to nitrogen, with 40 to 60 kilograms of

nitrogen per hectare applied in early April or when rapid spring growth begins. Ammonium sulfate is the customary nitrogen source because it is readily available. Other standard sources are probably as satisfactory (Woodhouse and Hanes, 1967).

A response to phosphorus could occur on some sites. Andriani and Terwindt (1974) found no benefit from phosphates applied on the well-washed sands of dikes built during the construction of Europoort. European beachgrass may be less sensitive to phosphorus supply than American beachgrass.

Management of this grass requires protection from traffic, prompt replanting of missing hills or breaks, and the introduction of other species able to take over and maintain stability in back-dune areas that are likely to become sand starved. Other grasses and legumes may be seeded in the intermediate zone for this purpose. Shrubs and trees are used farther inland (McLaughlin and Brown, 1942; Brown and Hafenrichter, 1962) but these do not tolerate foredune conditions.

(b) American Beachgrass. McLaughlin and Brown (1942) considered this plant equal or superior to European beachgrass for stabilization and preferable for maintenance, because of its spreading ability and resistance to weed competition. However, it is not popular in the region because it is more expensive to produce and European beachgrass works so well. It is widely distributed around and to the north of the mouth of the Columbia River (Barbour, DeJong, and Johnson, 1976) and occurs to a lesser extent throughout the northwest. The spread and persistence of American beachgrass, coupled with its apparent advantages such as the ability to fill-in patchy stands, repair storm damage, create dunes with more gentle windward slopes, and tolerate interplanting of other species and perhaps the invasion by native plants, indicate that it should receive further consideration for foredune plantings in this region. These apparent advantages may outweigh the lesser cost of European beachgrass. It may be superior on foredune plantings that usually represent small areas compared with the very large active dunes that have been stabilized in this region.

1 Planting Methods. These are the same as for European beachgrass. Plant by hand or machine 30 centimeters or more deep in moist sand and firm sand around the base of the plant to exclude air pockets. This plant is not as sensitive to temperature at planting as European beachgrass and can be planted during warmer periods than European beachgrass.

2 Planting Date. American beachgrass may be planted anytime during the European beachgrass planting season, November through March and perhaps through April into May. However, foredune planting should probably be limited to late winter and spring to avoid winter storm damages.

3 Planting Stock. Clumps should be shaken free of excess sand, divided into three- to five-stem transplants, cleaned of

dead stalks and trash, and trimmed to an overall length of about 50 centimeters. Transplants may be stored for a few weeks by heeling-in in narrow trenches in moist, well-drained soils. Clay-dipping and bundling is advisable when plants are to be moved over long distances or stored for substantial periods of time. Long-term storage should be at about 0° Celsius.

4 Spacing. A graduated planting pattern would be most effective for building a foredune. The suggested pattern may need to be modified to fit the particular situation. Plant four to six center rows with plants spaced 30 by 30 centimeters on centers where the dune ridge line forms, then plant in a graduated pattern forward and backward from the center rows. Space the plants 45 by 45 centimeters on center then 60 by 60 centimeters, 90 by 90 centimeters, and finally 1.2 by 1.2 meters. Number of rows and the total width of the planting depend on the nature of the site and the volume of sand anticipated. Generally, a width of 30 to 50 meters is sufficient for the initial development of a foredune. Plant spacings of 45 by 45 and 60 by 60 centimeters are suitable for stabilization of existing foredunes. For foredunes, three stems (culms) should be planted per hill. Use of American beachgrass for other than foredunes and repair purposes in this region appears to be impractical.

5 Fertilization and Management. Fertilization at the rate of 40 to 60 kilograms of nitrogen per hectare should be applied in early spring. Additional applications may be needed to maintain good color and vigor. Management is similar to that for European beachgrass. Plantings should be protected from traffic and breaks replanted. Little replanting of spotty stands should be required because American beachgrass spreads well.

(c) American Dunegrass. This plant (Fig. 32) is the only foredune grass native to the northwest and is widely distributed throughout the region (Barbour, DeJong, and Johnson, 1976). It is primarily a foredune species, thriving under foredune conditions and requiring considerable annual sand deposition for healthy growth (McLaughlin and Brown, 1942). It builds foredunes. It is more difficult and expensive to propagate than European and American beachgrasses and consequently has not been planted to any extent. Its culture has received little attention until recently (Barbour, 1976). While American dunegrass is not competitive with European beachgrass, it can be planted alone or in mixture with other native species to build foredunes. Due to its open spreading habit it produces low dunes with gentle slopes. This is often preferable to the high steep dunes formed by European beachgrass. A foredune in much of this region intercepts sand moving from the beach and prevents it from moving inland, rather than to bar storm tides. Here, there is no need for high, massive foredunes unless the space for sand storage is limited, then the type of dune from American dunegrass might be more appropriate. Use of this grass should be limited to the foredune zone because of high cost and plant requirements.

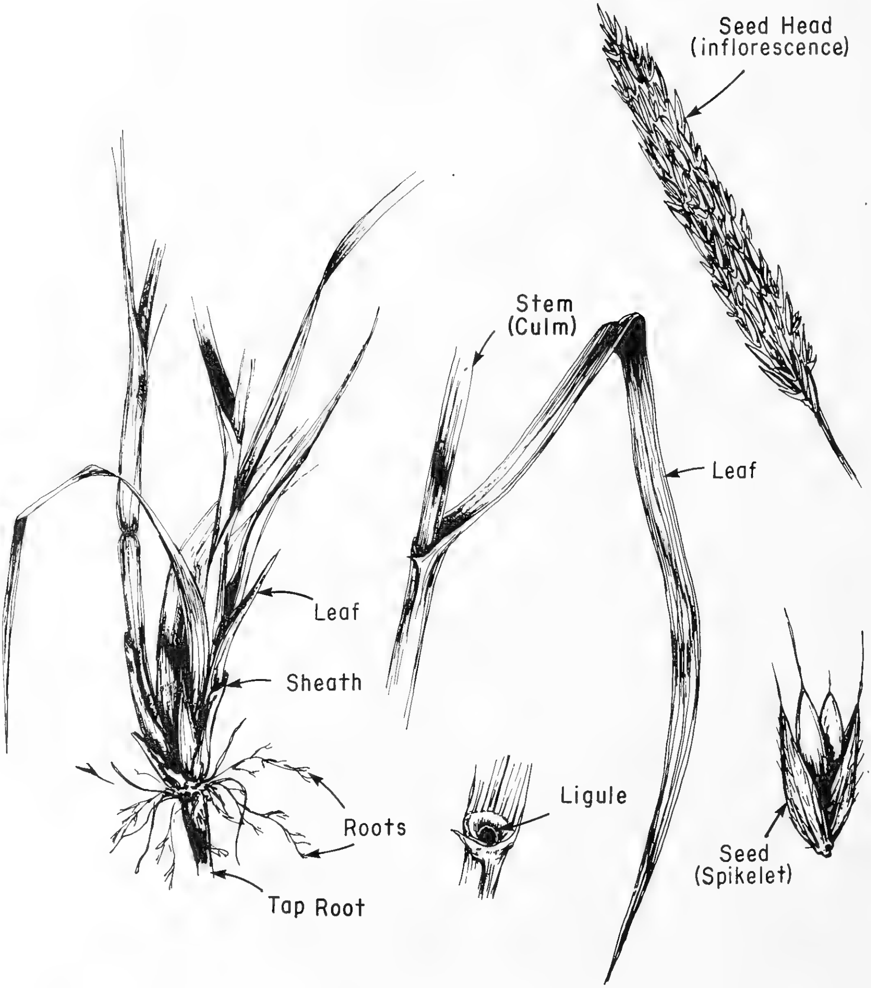

Figure 32. Morphological features of American dunegrass.

There is very little information available on the propagation and management of this species. The following suggestions are tentative and speculative.

1 Planting Methods. American dunegrass should be planted in the same way as the beachgrasses. It should be set 30 centimeters or more deep in moist sand and the sand firmed around the plant to exclude air pockets. Barbour (1976) found that adding peat moss to the planting hole improved survival. Dipping the plant bases in a clay slurry as is done with American beachgrass may be worthwhile. It is cheaper than peat moss and may serve the same purpose.

2 Planting Date. This grass has been transplanted satisfactorily on the Oregon coast only when dormant (late November through February). It does not become dormant in winter at Pt. Reyes, California, which may partially explain poor survival there (Ann L. Johnson, Botanist, University of California, Davis, personal communication, 1977). Temperature is also critical; planting is limited to temperatures below 13° Celsius.

3 Planting Stock. There is little information on plantings. Many stems grow from horizontal rhizomes or runners so more care should be taken with this species than with others. Because of the poor survival rate of this species, planting several stems per hill would be desired but may be too expensive. Closer spacing with one stem per hill makes better use of scarce planting stock.

4 Spacing. Barbour (1976) suggested planting at a density of 25 plants per square meter to attain comparability with natural stands. This would make planting too expensive for large-scale use. Other methods of thickening stands, such as the use of fertilizers, should be explored. Propagation techniques and more experience are needed to develop suitable planting patterns. However, the same general principles for spacing of other foredune grasses should apply with American dunegrass.

5 Fertilization and Management. There are no published reports of fertilizer response of American dunegrass from the northwest. However, the European version of this plant (a subspecies or variety), lyme grass (*Elmus arenarius*), thickens markedly when fertilized (Adriani and Terwindt, 1974). Fertilizer should equally benefit new plantings of American dunegrass in this region. Its response to fresh sand strongly suggests that it would benefit from fertilization. A suggested application rate is 40 kilograms of nitrogen per hectare from a soluble source applied as soon as new growth starts.

Protection of new plantings from rabbits may be essential in some areas. Both American dunegrass and lyme grass are attractive to rabbits; small plantings would be particularly vulnerable. Other management requirements are the same as those described for the beachgrasses.

(d) Ice Plant, Sea Fig, or Mesembryanthemum (*Carpobrotus* spp.). These plants are common in the region southward from about latitude 39° N. They are excellent stabilizers and easy to transplant, but are not very effective as dune builders and cannot tolerate rapid sand burial. The exotic and hybrid forms, which predominate in the region, are aggressive and tend to exclude most other plants. Ice plant is susceptible to low temperatures, risky where frost is possible, and vulnerable to traffic. It apparently requires fertilizer to remain healthy in the absence of fresh sand. Unsightly dead patches are common in the intermediate zone and these appear to be related to low nutrient supply. They do not appear to be desirable plants to use on dunes. Ice plants crowd out other plants, producing a rather monotonous, biologically uninteresting landscape.

(e) Other Plants. Other plants in this region invade bare sand near the sea and build foredunes (Wildemann, Dennis, and Smith, 1974). The most prominent of these are yellow sand verbena (*Abrona latifolia*) and beach-bur (*Ambrosia chamissonis*). Sand verbena is salt tolerant but difficult to propagate. Beach-bur is easier to propagate but less tolerant of salt spray and inundation by seawater. Practical procedures for field planting are under study (Barbour, 1976).

Most plants that are capable of growing near the foredune can only be introduced after stabilization of the sand by pioneer species. These species are essential for sand stabilization whenever the sand supply declines. Seaside lupine (*Lupinus littoralis*) may be seeded into grass stands and does well as a soil improver. As it dies down in winter it is not an effective stabilizer. The beach peas (*Lathyrus japonicus* and *L. littoralis*) grow well in this zone. Native grasses that can be seeded are seashore bluegrass (*Poa macrantha*), native creeping red fescue (*Festuca rubra*), sweet vernal (*Anthoxanthum odoratum*), and velvet grass (*Holcus lanatus*). Farther back from shore, shrubs and trees are effective as stabilizers (Brown and Hafenrichter, 1962; Wiedemann, Dennis, and Smith, 1974).

(5) South Pacific Region. Coastal dunes occur along this coast but are not as extensive as in the North Pacific region (Zeller, 1962). Sand activity declines sharply south of the Pt. Arguello, California, region. Wind direction and the location of dunes near stream mouths are similar to conditions in the North Pacific region. Because of lower windspeeds, bare sands are not as difficult to stabilize as in the Pacific Northwest. However, the climate becomes warmer and drier farther south and the perennial foredune grasses are not as well adapted to the climate. This increases establishment hazards for dune-building plants. Also, the coast is more heavily used by people so dune vegetation is generally in poorer condition.

(a) European Beachgrass. This grass has been planted successfully on dunes along much of this coast. The moderating effect of the sea apparently keeps pioneer zone temperatures within the tolerance range for this species south to the Mexican border. Extensive plantings were made in 1960 at Vandenberg Air Force Base, California, and these continue to be satisfactory (Clark L. Moore, Horticulturist, Arroyo Grande, California, personal communication, 1976). Although European beachgrass can be readily transplanted, Barbour (1976) believes it cannot establish naturally. It is the only available species that will trap and stabilize relatively large volumes of blowing sand near foredunes in this region.

1 Planting Methods. Planting specifications are the same as described for the North Pacific region. Plants are set 30 to 35 centimeters deep in moist sand and sand firmed around them to exclude air pockets. Transplanting is by hand on small areas and rough or steep terrain. Machine planting, using tractor-drawn transplanters to open furrows, and to place and cover plants, is preferable on large smooth sites. Planting should be limited to periods when the temperature is less than 16° Celsius for several days and the sand is moist to within 8 centimeters of the surface. Meeting temperature and moisture requirements is critical to the successful planting of European beachgrass. Planting to full depth of 30 to 35 centimeters is particularly essential in dry climate to keep the plant in the moist zone through its period of establishment.

2 Planting Date. Temperature and moisture conditions determine the planting date. These conditions are usually favorable after winter rains have wet the sand.

3 Planting Stock. Plants should be shaken free of sand, separated, cleaned of dead stems and trash, and pruned to an overall length of 50 centimeters. Stock may be stored for short periods by heeling-in in narrow trenches in well-drained soil. For long-term storage, clay-dip, bundle and hold at about 1° Celsius. Three to five stems per hill are usually planted because good stands are critical with this species under the wind conditions common to this region. A survival rate less than 90 percent will require replantings.

4 Spacing. This is a critical factor in determining the success and cost of a planting. Planting costs are roughly proportional to the number of hills planted. Stands that are too open may blowout. Spacing and planting pattern should be adapted to the site and the result desired. In general, a planting, 45 by 45 centimeters on center with three to five stems per hill, will suffice except on critical sites such as steep windward slopes and the tops of foredunes. A graduated planting pattern (Savage and Woodhouse, 1968) would probably be better for building a foredune by allowing the center ridge to develop rapidly and avoid the steep seaward dune slope that typically occurs with this species. A pattern of several center rows with plants spaced 30 by 30 centimeters on centers, with spacing increasing in rows forward and backward from the center will build a more stable foredune at less cost than a uniformly spaced planting. Suggested spacings from the center strip are 45 by 45, 60 by 60, and 90 by 90 centimeters. Total width of planting, which depends on volume of sand anticipated, is probably about 20 to 40 meters.

5 Fertilization and Management. Fertilizer response may be less pronounced in the dry climate of this region, but fertilization is essential for rapid establishment of European beachgrass on beach and dune sands. Suggested fertilization rate is 40 to 60 kilograms of nitrogen per hectare from a soluble source. Apply in early spring and repeat the application if needed to maintain healthy color and vigor of the grass.

Management requirements are protection from foot and vehicular traffic, prompt repair and replacement of dead plants, and replanting breaks in the stand.

(b) Sea Fig. Three forms of this plant occur in the South Pacific region. They are the introduced Hottentot fig (*Carpobrotus edulis*), the native sea fig (*C. aequilaterus*), and hybrids between the two species. Hottentot fig is dark green or often red with stiff, pointed leaves 8 centimeters or more long, with white to pale-lavender flowers up to 8 centimeters wide. Native sea fig has fleshy, bluish-green soft leaves about 4 centimeters long, somewhat rounded at the tip, and pink flowers no more than 4 to 5 centimeters wide. The hybrids are usually intermediate size, with pink flowers but with foliage resembling Hottentot fig (Cowan, 1975). Hottentot fig and the hybrids are very aggressive, covering dunes and many cliffs along this coast and excluding most other species. These types have usually been planted because of ease in planting and quick establishment.

Sea figs are effective sand stabilizers but not good dune builders. The growth above ground will not hold more than 10 to 15 centimeters of sand, usually less, at any one time and the plant cannot withstand much burial. It is only moderately tolerant to salt. Sea figs are the easiest plants to establish in the beach and dune zone. Cuttings 10 to 15 centimeters long should be set into moist sand about 45 to 60 centimeters apart to quickly take root and provide cover. Successful stands of Hottentot fig have been established by broadcasting plants over the bare sand surface without covering during cool, rainy periods (E.T. Crisp, Ranger, Bodega Bay State Park, California, personal communication, 1976).

Sea figs become nutrient-deficient on dune sands. The red color often exhibited by the exotic form is probably a response to low nitrogen levels. Occasional applications of nitrogen at the rate of 30 to 40 kilograms per hectare are required to maintain vigor and good color. Applications should be adjusted to growth and appearance of the plants. Native sea fig may be readily transplanted to beach and dune areas. It is much slower growing and less vigorous than its exotic relatives and is not available commercially.

(c) Other Plants. A number of other plants in this region invade the foredune area and contribute in varying degrees to the building and stabilization of dunes. American dunegrass occurs sporadically but because of the difficulty of propagating this species in cooler climates, it should be used as a mixture with native plants (see North Pacific region). Beach sagewort (*Artemisia pyenocphala*) is a pioneer species as far south as Monterey Bay. It can be readily transplanted, or seeded in less exposed areas. Divisions with roots and cuttings may be set in the moist sand (Cowan, 1975). Red sand verbena and beach-bur and, to a lesser extent, yellow sand verbena are common throughout the northern part of the region and are capable of invading bare sands near the beach. Yellow sand verbena is replaced entirely by red sand verbena south of Pt. Conception where the latter becomes the major foredune builder from there into Mexico (Ann L. Johnson, personal communication, 1977). Due to their growth habit, the sand verbenas never develop much capacity to trap sand but they do build dunes. These plants have tap roots; suitable field planting techniques for them have not yet been developed (Barbour, 1976). All of these species respond to moderate fertilization, particularly where fresh sand supply is meager or erratic.

Perennial veldt grass (*Ehrharta calycina*) was seeded at Vandenburg Air Force Base on a large disturbed area immediately behind the dunes. A variety of temporary stabilization techniques was used. Straw mulch was anchored by discing, the surface was sprayed with bituminous materials, or the sand was irrigated by a sprinkler. The veldt grass was successful and the gradual reinvasion of native plants has occurred (Clark L. Moore, personal communication, 1976). This grass appears to be very useful for initial sand stabilization.

(d) Native Plant Restoration. There is considerable interest in this region in the restoration of native sand dune plant communities as opposed to planting exotics to build and stabilize dunes. This approach has more promise in this region than in several others. Barrier dunes are not often required for storm surge protection as they are on low-lying coasts but rather are needed for the interception and storage of sand that would otherwise blow inland. The development of large continuous barrier dunes is not critical here. Dune areas get very high recreational usage on this coast and native plants provide an aesthetically pleasing landscape. Protection from foot and vehicular traffic is required or restoration attempts are useless.

Cowan (1975) described a procedure used to reestablish native species on active dunes at Asilomar State Beach, Pacific Grove, California. This method and its modifications are feasible where water for temporary irrigation is available and affordable. Briefly, the procedure involved temporarily stabilizing the dunes by hydromulching with a light seeding of annual and perennial ryegrasses, plus fertilizer. This was followed by periodic sprinkler irrigation to hold the sand and germinate the ryegrass, enabling it to grow into protective cover. Seeds of native plants could have been included in the hydromulch to accelerate the process but were not. Irrigation was terminated after 1 year and the ryegrass gradually died but protected the area for a second year. During the decline of the ryegrass, sea fig and beach sagewort were transplanted into the dying sod, and seeds of sand verbena, sand-bur, beach sagewort, seaside paintedcup (*Castilleja latifolia*), beach pea, sea rocket (*Cakile maratima*), and mock heather (*Haplopappus ericoides*) were broadcast over it. This approach developed a protective cover with a good variety of native species on the dunes at Asilomar State Beach within 4 or 5 years. It has promise for use in areas of limited size elsewhere. The principal problems are availability and cost of water, collection of transplants and seeds of native plants, and protection from foot and vehicular traffic.

(6) Great Lakes. Sand dunes occur around the Great Lakes, primarily along shorelines exposed to the north and west, and are fairly extensive in parts of Indiana and Michigan (Cowles, 1899). Many dunes are on cliffs or escarpments well above the lake level. Major active dune areas are associated with river mouths.

The function of barrier dunes in this region is primarily to intercept and hold sand that would move inland. Their function as a storm barrier is of no practical importance. Most dunes are inland from the barrier dune zone and some of the most severe sand stabilization problems have been with large mobile dunes created by exposure and misuse of sandy soils (Sanford, 1916; Lehotsky, 1941). Most plantings in the region have been for stabilization rather than dune building. The same devices and procedures used to build dunes along seacoasts apply to the construction of dunes in the Great Lakes. The problem of initial stabilization along these shores is magnified by the strong winds in this area, especially the winter gales. However, long-term stabilization is simplified by the absence of salt spray and flooding by saltwater which permits the growth of a much larger variety of species than along most seashores.

The lakeshores also differ from those along seacoasts in their lack of astronomical tides; the occurence of cyclic fluctuations of lake levels affects sand supply.

(a) American Beachgrass. This grass is native to the Great Lakes and is a major builder of natural dunes. It is essentially the only species planted for the initial stabilization of bare sands in this region. It is easy to multiply in a nursery and to transplant. Early growth is rapid; it is an excellent sand trapper, and is commercially available in the region.

Potential hazards of monospecific plantings of this species are much less in this region than elsewhere. There is no evidence of serious stand losses because of pests such as occur on the Atlantic coast. Natural invasion by other adapted pioneer and intermediate species appears to be more rapid than along seashores.

1 Planting Methods. Planting is done by hand on small areas and on rough or steep terrain; machines are used on large, smooth sites. In hand planting, grass is inserted in individual holes opened with a shovel, spade, or dibble. This is best done by two-man teams, one man opening the hole while the other inserts the plant and firms the sand around it. Machine planting is done with tractor-drawn transplanters designed for crop plants such as tobacco, tomato, and cabbage. Most machines can be adapted to transplanting by extending the openers or

shoes to provide a deeper furrow in which to set the plant. Wheeled tractors are faster on smooth, relatively level sites but crawlers are needed on rougher terrain.

2 Depth. Transplants should be planted 20 to 25 centimeters deep and deeper (30 to 35 centimeters) in loose, drifted sand. They must be set deep enough for their basal parts to remain in moist sand until new roots develop to anchor them. The deeper into the moist sand, the less chance of being blown out before becoming established. Shallow planting is the most common cause of failure.

It is difficult to open planting holes or furrows to the proper depth in hard-packed sand, and it is even more difficult to keep them open long enough to insert plants through a thick layer of dry, loose sand. The packed sand problem can be taken care of by using more power but if the sand is dry, it may be necessary to irrigate or wait for rain before planting.

3 Planting Date. American beachgrass tolerates transplanting well and can be transplanted satisfactorily while either dormant or growing. It has a long transplanting season. It can be planted in the fall (October and November) but the preferred period is from March through April or May to avoid exposure to winter storms.

4 Planting Stock. Transplants should have one to several healthy, vigorous stems (culms): Multiple stems to be planted in the same hill need not be attached. Larger plants are preferred because first-year growth is related to the number of stems planted per unit area. On critical sites where rapid stabilization is essential, five or more stems per hill are often warranted. However, with normal spacing plantings of one stem per hill will cover over the first growing season. There is little difference in cover between these and multiple stems per hill at the same spacing in the second year. As planting stock represents a significant part of the total cost of planting, one to three stems per hill are usually used on all but the most critical sites. The critical sites are the windward slopes and crests of large, mobile dunes; areas receiving unusually large volumes of sand, blowouts through or between dunes; and areas likely to be subjected to wave overtopping during storm surges.

5 Spacing. The correct spacing and pattern is of critical importance in the design of a dunegrass planting. Spacing that is too wide usually results in partial and often total failure; spacing too close is wasteful. Planting stock and transplanting costs are roughly proportional to the number of hills planted. A 30-centimeter spacing requires four times as many hills per unit area as a 60-centimeter spacing and costs roughly four times as much.

The spacing and pattern should be determined by the characteristics of the particular site and the objective of the planting. A strip of American beachgrass, 12 to 18 meters wide, planted 45 centimeters on centers will effectively stop the movement of sand across it sometime in the latter half of the first growing season. Small blowout areas should be planted solid at a 45-centimeter spacing or less; the stabilization of a large area of bare sand requires a spacing of 45 to 60 centimeters. Costs may be reduced by varying the planting pattern. For example, in building a barrier dune, it is essential that a part of the strip be planted at a spacing of 45 centimeters to stop sand movement sometime during the first year. However, since sand supply usually limits dune growth, it is not necessary to plant the entire width of the planned dune to this density. The use of a graduated pattern can result in a dune with a more stable cross section as well as a saving in planting expense (Savage and Woodhouse, 1968).

When the graduated planting pattern is used (Table 1), the dune grows more rapidly near the center of the planted strip, sloping gently to the outer edges. After 2 or 3 years, sand accumulation increases near the edge as the wide-spaced plants fill in and develop trapping capacity. By that time, the base of the dune has been broadened to a more stable form (Fig. 24). The planting cost is less than half that of a uniform spacing dense enough to trap the available sand.

6 Fertilization and Management. American beachgrass usually responds to fertilizers. The judicious use of fertilizers can be useful in the management of this plant. Response varies widely. It is least under the rapid accumulation of sand and greatest on old, leached sands in back-dune and deflation plain areas. Growth on sites lacking fresh sand may be increased as much as tenfold by fertilization. Response is to nitrogen and to a lesser degree to phosphorus and potassium. Fertilization is used during establishment to increase rate of spread and increase sand-trapping capacity, and to revive old, starved stands.

New stands often benefit from the application of 100 to 150 kilograms of nitrogen and 30 to 50 kilograms of phosphate per hectare the first growing season. Application should begin as soon as new growth is seen; the dosage should be divided into two or three applications, spaced 4 to 6 weeks apart. Fertilization after the first year should be adjusted to growth and appearance of the plants.

The same general principles apply to old stands. Deficient stands may benefit from up to 150 kilograms of nitrogen and 30 to 50 kilograms of phosphate per hectare in two or three applications a year over 1 to 3 years. Healthy stands may be maintained with an application of 30 to 50 kilograms of nitrogen per hectare in early spring, at intervals of 1 or more years. Fertilization should be adjusted to the growth and appearance of the grass. Excessive growth promotes disease damage and plant loss.

Fertilizers containing nitrogen and phosphate in the suggested ratio are not widely available. The same effect can be obtained by alternating application of 10-10-10 or the equivalent with one or two applications of a straight nitrogen material such as ammonium nitrate, ammonium sulfate, or urea to approximate the desired ratio of nitrogen to phosphate.

Management requirements are primarily protection from foot and vehicular traffic, and prompt replanting of breaks that may lead to blowouts. This grass will tolerate moderate amounts of foot traffic but very little vehicular traffic. Suitable ramps and walkways should be provided for passage over barrier dunes. These structures should be elevated to permit growth under them. Accumulation of dead leaves and stems in established stands of American beachgrass sometimes creates a fire hazard. This grass will tolerate burning in winter or early spring. Controlled burning may be advisable to reduce the hazard of wildfire or to control pests.

American beachgrass will also tolerate occasional mowing. However, where repeated mowing may be required, a different grass should be planted.

(b) Wild Rye, *Elymus mollis* (*E. arenarius*). This grass is widely distributed in the pioneer zone throughout the region (Hall and Ludwig, 1975). It is capable of building barrier dunes but more difficult to propagate and transplant, and is not as efficient a sand trapper as American beachgrass. It is more susceptible to rabbit damage than most other grasses in this zone. It is not commercially available in the region. Another wild rye, *E. canidensis*, also occurs along the Great Lakes shores (Cowles, 1899; Hall and Ludwig, 1975) but is apparently less of a dune builder than *E. mollis*.

(c) Other Plants. There is a wide variety of native plants that occur in the pioneer zone in this region; some are true pioneers, others are secondary or tertiary invaders.

Several species such as blue joint (*Calamagrostis canadensis*), prairie sandreed (*Calamovilfa longifolia*), tansy (*Tanacetom huronense*), European beachgrass (*Ammophila arenaria*), false heather (*Hudsonia tomentosa*), and scouring rush (*Equisetum hyemale*) invade as pioneers and contribute to dune growth and stability. Sand cherry (*Prunus pumila*), creeping cedar (*Juniperus horizontalis*), forest grape (*Vitus riparia*), beach pea (*Lathyrus maritimus*), and willow (*Salix* sp.) are frequently secondary stabilizers.

Balsm popular (*Populus balsamifera*) is the most frequent tertiary species.

Most Great Lakes dunes can be converted to forest once they have been stabilized with herbeceous plants as trees can grow much closer to the shore because of the absence of salt. Fully established forests usually form the most durable, maintenance-free cover for Great Lakes dunes. Coniferous species have generally been the most successful on dune sands (Lehotsky, 1941; 1972); other trees and shrubs may be used to stabilize for special uses (Brown and Hafenrichter, 1962).

4. Sand Accumulation.

The rate and volume of sand accumulated by a properly designed and maintained sand fence installation, vegetative planting, or combination of these is largely a function of sand supply. All windblown sand available at a site can be trapped by these devices. Vegetation does a more complete job since it stabilizes as well as traps. Sand is seldom lost unless the vegetative cover is damaged or destroyed; sand is often lost from fences.

Average annual rates of sand accumulation vary from less than 3 cubic meters per front meter on a shelly beach to 10 cubic meters per front meter on a wide sandy beach, for fences and American beachgrass plantings in North Carolina (Savage and Woodhouse, 1968). European beachgrass caught an average of 13.7 cubic meters per front meter a year for a 30-year period on the Clatsop Plains of Oregon (Meyer and Chester, 1977). The rate was probably higher than this the first few years. None of these approach the rate of 40 cubic meters per front meter in the first 15 months recorded on a 30-meter square of American beachgrass on an exposed site which received sand from all sides (Savage and Woodhouse, 1968). Thus, the trapping capacity of vegetative plantings usually greatly exceeds the sand supply. The capacity of a single 1.2-meter-high sand fence is about 5 to 7 cubic meters per front meter.

Ultimate dune height and rate of growth varies widely. Ocracoke Island dunes, initiated with American beachgrass, increased in height by about 18 centimeters per year in a 10-year period. However, upward dune growth slowed drastically and almost ceased during the last half of the period (Woodhouse, Seneca, and Broome, 1976); most of the growth became lateral, toward the sea. Increase in height of a sea oats dune on Padre Island averaged 60 centimeters per year and a similar bitter panicum dune increased 46 centimeters per year over a 5-year period (Dahl, et al., 1975). The Clatsop Plains dune crest increased an average of 27 centimeters per year over a 30-year period. These differences reflect variations due to climate and sand supply as well as species characteristics. Sea oats, bitter panicum, and European beachgrass build high steep dunes when sand is plentiful because they expand laterally at a slow rate. American beachgrass builds broader more gently sloping dunes with lower crests since it can expand toward the sand source at rates as high as 3 or 4 meters per year.

5. Costs.

Sand fence, when bought in quantity, costs about $1.25 to $1.50 per meter (free on board) factory. Cost of posts and braces varies widely with material and locality but should be less than $0.50 per meter of fence. The installation of standard 1.2-meter slat-type sand fence with all materials on site requires 1 man-hour for 9 to 14 meters. Fabric fences are usually competitive in price, but have a slightly higher labor cost.

Planting costs vary with species, availability of planting stock, planting method, and nature of site. American beachgrass is available in quantity on the Atlantic coast at about $15 to $20 per thousand stems. Planting rate is about 400 to 600 hills per man-hour by machine and 130 to 200 hills per man-hour by hand.

Dahl, et al. (1975) estimated harvesting, processing, and machine planting of bitter panicum at the rate of 230 plants per man-hour and 130 plants per man-hour for sea oats.

The cost of European beachgrass planting stock is not available but since this is the easiest of the beachgrasses to propagate, planting stock should be about the same or cheaper than American beachgrass. McLaughlin and Brown (1942) estimated a production rate of 136 to 156 hills per man-hour for hand planting. This is slightly lower than east coast estimates for planting American beachgrass. Machine planting of European beachgrass should be at the same rate as American beachgrass.

Fertilization costs (materials, rates, and application methods) vary considerably from site to site and region to region. In 1977, enough nitrogen (40 kilograms) to fertilize a hectare could be purchased as ammonium nitrate for $20 to $25.

III. STABILIZATION OF DUNES

Dune stabilization, as opposed to dune building, is required where dunes are constructed mechanically by dredge, bulldozer, or fence, or where existing dunes become unstable because of damage to vegetation by fire, lumbering, grazing, and overuse. Foot and vehicular traffic as well as grazing has caused extensive damage at Cape Cod (Westgate, 1904) and in other parts of the country, such as along the shores of Lake Michigan (Lehotsky, 1941) and in the Pacific Northwest (McLaughlin and Brown, 1942).

The principles and practices involved in planting grasses to build dunes generally apply equally to stabilizing bare or unstable dunes. However, there are other methods that are sometimes used to stabilize bare sands that collect little sand and have little or no value in dune building. Where stabilization is the primary purpose, some modifications in the planting techniques may be required.

1. Mats, Netting, Brush, Mulches, and Stone.

Bare sand surfaces can be quickly protected by matting and nets. Dahl, et al. (1975) found a coarse netting useful in protecting fence-built dunes while transplanted dune grasses were establishing. There are a number of commercially available mats and nets that may be used for this purpose. They protect the sand surface but collect little sand. Some are applied directly to the surface but the more open nets are used to hold a layer of mulch in place. Probably, the best use for nets is to protect new seedings as transplants tend to lift rather than grow through it. All nets and matting are subject to traffic damage and require careful protection of edges to prevent rollup by wind action.

Brush is an effective temporary stabilizer (Stratton and Hollowell, 1940; Lehotsky, 1941). It is laid over bare sand in a shingle arrangement with the tops of each successive layer overlapping the butts of the preceding layer. This method has a high labor requirement, and it interferes with subsequent planting. Use probably should be limited to small blowout areas.

Conventional mulches of straw, wood fiber, and Fiberglass are difficult to anchor to dune surfaces and require careful protection of edges to prevent rollup by wind action.

A cover of crushed stone or clay will provide immediate protection to a dune surface and this is probably the most practical remedy, short of paving, in traffic areas. It is expensive and usually can be confined to small parts of the dune. Unless the surrounding areas are stabilized, the material may become buried and lost.

2. Asphalt, Latex, and Chemicals.

Another method for rapid stabilization of sand is to apply binding agents to the surface layer. Asphalt emulsion and latex compounds are commonly used. Asphalt is often used to tack mulches to exposed surfaces. This is useful as a temporary stabilizer during the establishment of vegetation. As with netting and mulches, the edges must be protected from undermining, and the surface protected from traffic.

Adriani and Terwindt (1974) tested sand binders when establishing vegetation on the Europoort sand dikes. Three emulsions were tested. Two had a bituminous base and the third a base of rubber. All three emulsions were detrimental to the development of transplanted dune grasses. They concluded that this method was of little value under these conditions.

Zak and Bredakis (1963) tested asphalt emulsion, asphalt cutback, and elastomeric polymer emulsion in water, a polyvinyl polymer emulsion in alcohol, and a solution of sodium silicone following an ammonium sulfate and gelatin spray to stabilize the sand surface after sowing seeds at Cape Cod. The asphalt compounds stabilized the surface over the winter, but seedling growth was poor. None of the other compounds held the sand through the winter and seedling establishment was no better than in the control plot.

3. Fences.

A system of sand fences may effectively stabilize an area of blowing sand for 1 or 2 years, but dune protection with fences usually becomes a continuing process. Most fences tend to deteriorate because of corrosion or decay as well as from damages from storms and man. Without continuing maintenance and repair, the fences eventually fail and release the accumulated sand. However, fences are more durable than most netting and mats. Once a fence system is filled, it stops catching sand; the installation of additional fence is required. Consequently, a sand fence is a temporary dune stabilizer which must be supplemented or followed by longer term protection such as planted vegetation, or using a sand-binding agent where vegetation is not feasible, as in deserts (Kerr and Nigra, 1951).

Fences have two distinct advantages over planting. Sand fences may be installed at any season, and are fully effective as soon as installed. There is no waiting period for trapping capacity to develop.

The volume of sand moved by strong winds may be too large to permit the establishment of vegetation. Temporary protection with low fences is a possible solution.

The design of fence systems to stabilize areas of blowing sand should consider the characteristics of the particular site, including wind pattern and the ultimate configuration desired. Is the dune or dune field migrating because there is net movement in the same direction every year? If so, the first requirement is to stop movement from the upwind or sand source side. Stabilization may then proceed as necessary.

Field and laboratory studies have been made of the factors affecting the performance of sand fences (Bagnold, 1942; Savage, 1963; Savage and Woodhouse, 1968; Manohar and Bruun, 1970). The following summarizes this work and provides some guidance in the use of sand fence for this type of application.

a. A fence porosity of 40 to 50 percent is the most efficient in stopping sand movement and encouraging the deposition of sand. The standard wooden fence made of slats, 3.8 centimeters wide by 1 centimeter thick, is the most practical and cost-effective, and is readily available in the United States.

b. Double rows of fences are more effective than single rows when windspeeds are high. Manohar and Bruun (1970) stated that a single fence ceases to trap sand at windspeeds above 58 kilometers per hour while a double fence continues to be effective above that speed.

c. The most efficient spacing for multiple fences is about four times the fence height (4h) apart or about 5 meters for a standard 1.2-meter slat fence.

d. Trapping efficiency increases as the number of fence rows increase while scour and secondary deposition decrease. The practical number of rows in a set is limited to about four.

A multiple installation three or four rows deep spaced 4h apart and placed near the base of the windward slope of a bare dune will effectively catch sand from that edge until the fences are filled. However, on large areas of blowing sand, this design will need to be repeated downwind at short intervals to keep scouring between installations under control. The exact spacing for any given site is best determined through observation after the initial installation.

Since the direction of winds is not constant on most sites, a grid system of fences arranged in squares or rectangles may be preferred to a series of fences. In a Michigan project (Lehotsky, 1941), 2.5-centimeter-diameter wooden stakes were driven 5 centimeters apart into the sand leaving 30 centimeters protruding above the surface. The stakes formed 4-meter squares. On critical slopes, they were reinforced by a row of pickets placed diagonally across the center of each square. This arrangement effectively resisted winds of 105 kilometers per hour from the southeast on 1 day and 92 kilometers per hour from the southwest the next. Similar designs formed with stems of the common reed (phragmites) are used on the Dutch coast.

A square-to-rectangular pattern tried on a limited scale on large dunes in northern Florida consisted of a 60-centimeter slat fence (standard 1.2-meter fence, cut in half) arranged in squares 3 to 5 meters on a side. This approach uses half of the fencing, about two-thirds the amount of posts, and much less labor compared with a similar design using 1.2-meter fence. It requires less labor than driving individual pickets into the sand. It should be just as effective if a high enough proportion of the bare area is included. The 60-centimeter height is preferred with planting as it limits sand accumulation to a depth more likely to be tolerated by the developing vegetation.

It is generally necessary to treat a large proportion of the area (80 to 90 percent) for full control with any of the above methods.

4. Vegetation.

Vegetation is the only long-term stabilizer suitable for general use on sand dunes. It is the only stabilization with self-healing capability and the ability to grow and change with the dune. Plant selections, planting procedures, and maintenance for vegetative stabilization of bare sand in the barrier dune zone are the same as for dune building in the same region. The difference is in plant spacing and planting pattern.

A uniform planting pattern is usually appropriate for stabilizing the sand mass in place.

Spacing requirements vary with plant species and site exposure. In general, American beachgrass, bitter panicum, and sea oats should be spaced 60 by 60 centimeters on center, and European beachgrass, 45 by 45 centimeters on center. Plant spacing should be less on exposed sites such as dune crests--30 centimeters apart for European beachgrass, 45 centimeters apart for the others. Planting should begin on the sand source side near the windward edge of the site and extend over the entire sand mass. Partial planting is seldom effective because scouring of the unplanted surfaces usually undermines the planted strips or blocks, ultimately requiring the whole job to be done over.

Establishment of vegetative cover on large areas of mobile sand is difficult, particularly under high-energy conditions. Success is not always possible on the first attempt, and it may be necessary to supplement plantings with fences, nets, or other devices. However, closer spacing of plants and attention to the important details of plant quality and planting procedure will generally be the most economical and satisfactory method.

Fertilization may be more critical to the success of planting for stabilization than for dune building. The sand to be planted may be more highly leached of its nutrients and it is not likely that fresh sand will be entering the planting. If this is the case, fertilizer is essential to the establishment of vegetative cover, and periodic applications may be required for maintenance.

5. Stability.

The stability of fence-built dunes is usually short-lived without continued maintenance. Deterioration of the fences will start the release of sand within 1 to 3 years. This usually results in the eventual disintegration of the dune unless natural revegetation has stabilized it. The extent to which natural revegetation of fence-built dunes occurs varies widely. Revegetation usually begins on the back slope and crest, and is slow to cover the front of the dune. More often, fence-built dunes disappear after some years leaving, at most, a few vegetated dunelets located around some of the remaining posts (Woodhouse, Seneca, and Broome, 1976). Consequently, fence-built dunes should be planted early in their development.

Unvegetated, fence-built dunes offer little resistance to storm surge and wave action, and are easily eroded when overtopped.

Vegetated dunes are stable against wind as long as their cover is intact. Sand movement out of a good vegetative canopy is insignificant even under extremely high winds. Stable foredunes such as those on North Padre Island are periodically subject to hurricanes. The foredunes on the Clatsop Plains of Oregon were planted in the 1930's and continue to grow, withstanding the strong winds for over 40 years.

Vegetated dunes are moderately resistant to storm surges and waves. They cannot withstand undermining by persistent beach recession, but well-vegetated dunes are surprisingly tolerant to short-term wave attack and brief periods of overtopping by storm surges. This was evident on Ocracoke Island following Hurricane Ginger in October 1971 (Woodhouse, Seneca, and Broome, 1976). Substantial amounts of water flowed over the experimental dune during the storm and began serious undermining at the rear without breaking through the cover on the crest or upper three-fourths of the seaward slope. Instead, the grass cover caught sand on the crest and seaward slope (Figs. 33 and 34). Wave action created a low scarp on the seaward edge of the dune, but wind action filled this within 48 hours Within less than a week new shoots of the dune grasses emerged and the self-healing process was in operation.

Figure 33. A dune 2 days after overtopping by a storm surge and waves.

Figure 34. Rear of same dune showing scouring by water flowing down back slope.

IV. SUMMARY

Barrier dunes which are usually formed by vegetation accumulating windblown sand, serve as flexible barriers to storm tides and as sand stockpiles, nourishing the beach during storm attack. When windblown sand is available, they may be built by planted vegetation, sand fences, or a combination of the two.

Wood or fabric fences should have 40 to 50 percent porosity and be 60 centimeters to 1.2 meters high, with multiple fences spaced 4h apart.

Planting in the barrier dune zone is primarily done with perennial grasses. In the North and mid-Atlantic region, the first choice is American beachgrass planted in fall, winter, or early spring. Plant one to five stems per hill, 20 to 35 centimeters deep, in moist sand. Space the plants 45 to 60 centimeters apart or in a graduated pattern, dense in the center and thinning toward the edges. Apply 100 to 150 kilograms of nitrogen and 30 to 50 kilograms of phosphate per hectare in two to three applications, the first season. In the mid-Atlantic, add 10 to 25 percent bitter panicum to American beachgrass to form a mixture more resistant to disease and insect damage. In the South Atlantic region, plant American beachgrass with small amounts of bitter panicum or sea oats on the coasts of the Carolinas, and bitter panicum with a small amount of sea oats farther south. Plant American beachgrass in the winter or spring. Plant one to five stems per hill, one stem per hill with other grasses, 20 to 35 centimeters deep in moist sand. Space plants 45 to 60 centimeters apart or on a graduated pattern thick in the center, thinning toward the edges. Apply 100 to 150 kilograms of nitrogen and 30 to 40 kilograms of phosphate per hectare divided into two to three applications the first year. In the gulf region, plant bitter panicum with a small amount of sea oats in late winter, early spring, or during wet periods in late spring and early summer. Set one stem per hill, 20 to 35 centimeters deep. Space plants 60 centimeters apart or in a graduated pattern, thick in the center, sparser toward the edges. Apply 100 to 180 kilograms of nitrogen per hectare the first year in two to three applications beginning in late April or May. In the North Pacific region, set European beachgrass three to five stems per hill, 30 to 35 centimeters deep. Space 45 centimeters apart or in a graduated planting pattern, dense in the center, thinning toward the edges. Plant only when temperature is below 16° Celsius and when moist sand extends to within 8 centimeters of the surface. Apply 40 to 60 kilograms of nitrogen per hectare in the first half of April in the first growing season. In the South Pacific region European beachgrass should be planted three to five stems per hill, 30 centimeters deep, 45 centimeters apart, or on a graduated planting pattern, dense in the center, thinning toward the edges. Plant only when temperature is below 16° Celsius and when moist sand is within 8 centimeters of the surface. Where emphasis is on stabilization, sea fig may be used. Set the sea fig cuttings 10 to 15 centimeters long into moist sand. Space 45 to 60 centimeters apart or broadcast cuttings during cool, rainy periods. Apply 40 to 60 kilograms of nitrogen per hectare in spring of first growing season to either beachgrass or sea fig. Adjust later fertilization to growth and appearance of vegetation. In the Great Lakes region, plant American beachgrass during fall or early spring, at one to five stems per hill, 20 to 35 centimeters deep in moist sand. Space plants 45 to 60 centimeters apart or in a graduated pattern, dense in the center, thinning toward the edges. Apply 100 to 150 kilograms of nitrogen and 30 to 50 kilograms of phosphate per hectare in two to three applications the first growing season.

Stabilization is feasible with mats, netting, fences, etc., but vegetation is the only satisfactory long-term method. Species and practices are essentially the same as for dune building.

A tabular summary of adapted plants is presented in Table 2; a planting and fertilization summary is presented in Table 3.

Table 2. Regional adaption of foredune plants.

Major species	North Atlantic	South Atlantic	Gulf	North Pacific	South Pacific	Great Lakes
American beachgrass	1	1, 2		4		1
European beachgrass				1	1	4
Sea oats		3	3			
Bitter panicum	3	1, 3	1			
Saltmeadow cordgrass	4	4	4			
American dunegrass				4, 6	4, 6	
Secondary or regional species						
Seashore elder		6	6, 2			
Bermuda grass	7	7	7			
Knotgrass or seashore paspalum		4	4			
Ice plant				5, 2	5	
Sand verbena				6	6	
Beach bur				6		
Wildrye						4
St. Augustine grass		7	7			
Prairie sandreed				4		
Beach morningglory		4	4			

1. Dominant planted species
2. Part of region only
3. Valuable in mixture
4. Widely distributed, seldom planted
5. Stabilization only
6. Valuable, planting methods undeveloped
7. Specialized uses

Table 3. Planting and fertilization summary by regions.

Species	Planting: Date	Planting: Depth (cm)	Planting: Stems per hill	Planting: Spacing	Fertilization: First year	Fertilization: Maintenance
North Atlantic						
American beachgrass	Feb. to Apr.	20 to 35	1 to 5	45 to 60 cm or graduated	100-150 K/h N 30-50 K/h P_2O_5	1/3 1st year to none
Bitter panicum	Mar. to May	20 to 35	1	In mixture	100-150 K/h N 30-50 K/h P_2O_5	1/3 1st year to none
South Atlantic						
American beachgrass[1]	Nov. to Mar.	20 to 30	1 to 3	45 to 60 cm or graduated	100-150 K/h N 30-50 K/h P_2O_5	30-50 Kg/h N 1- to 3-yr intervals
Bitter panicum	Mar. to June	20 to 35	1	45 to 60 cm or graduated	100-150 K/h N 30-50 K/h P_2O_5	30-50 Kg/h N 1- to 3-yr intervals
Sea oats	Feb. to Apr.	25 to 35	1	In mixture	100-150 K/h N 30-50 K/h P_2O_5	30-50 Kg/h N 1- to 3-yr intervals
Saltmeadow cordgrass	Feb. to May	15 to 30	5 to 10	45 to 60 cm or graduated	100-150 K/h N 30-50 K/h P_2O_5	30-50 Kg/h N 1- to 3-yr intervals
Gulf						
Bitter panicum	Feb. to June	20 to 30	1	60 to 90 cm or graduated	100 Kg/h N 30 Kg/h P_2O_5	According to growth
Sea oats	Jan. to Feb.	20 to 35	1	60 to 90 cm or graduated	100 Kg/h N 30 Kg/h P_2O_5	According to growth
North Pacific						
European beachgrass	Below 15° C	25 to 35	3 to 5	45 cm or graduated	40-60 Kg/h N Early April	According to growth
American beachgrass	Jan. to Apr.	25 to 35	1 to 3	45 cm or graduated	40-60 Kg/h N Early April	According to growth
South Pacific						
European beachgrass	Below 15° C	25 to 35	3 to 5	45 cm or graduated	40-60 Kg/h N Spring	According to growth
Ice plant (stabilization only)	Cool Wet	10 to 15	1	60 cm or broadcast	40-60 Kg/h N Spring	According to growth
Great Lakes						
American beachgrass	Feb. to May	20 to 35	1 to 3	45 to 60 cm or graduated	100-150 Kg/h N 30-50 Kg/h P_2O_5 and K_2O	According to growth

[1]Carolinas coast only.

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