Historical evolution of coastal sand dunes on Currituck Spit, Virginia/North Carolina

Harold F. Hennigar

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HISTORICAL EVOLUTION OF COASTAL SAND DUNES ON
CURRITUCK SPIT, VIRGINIA/NORTH CAROLINA

A Thesis
Presented to
The Faculty of the School of Marine Science
The College of William and Mary in Virginia

In Partial Fulfillment
Of the Requirements for the Degree of
Master of Arts

by
Harold F. Hennigar, Jr.
1979
This thesis is submitted in partial fulfillment of the requirements for the degree of MASTER OF ARTS.

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ABSTRACT

Since colonial times, and especially since the 1930's, Currituck Spit, Virginia/North Carolina has undergone significant changes in vegetation and concomitant dune morphology, as revealed by a review of the primary literature. Well-vegetated before the nineteenth century, much of the vegetation was removed by logging and overgrazing. Originally, maritime forest existed as isolated tracts, each tract separated from the next by areas of sand sheets, medanos, inlets and former inlets. Maritime forest gradually succumbed to burial by sand due to the effects of logging, grazing and storms on adjacent areas. By 1900, much of the Spit was covered by a sand sheet. The dune building program begun in the late 1930's, and maintained locally in some areas by residents, resulted in the re-establishment of vegetation and a subsequent dune evolutionary sequence.

Vegetation maps were prepared for three compartments from existing aerial photography in order to document vegetation succession and its role in dune evolution. These maps revealed that the only major difference between medano, transverse and parabolic dune information was the growth of vegetation.

The actual mechanism of parabolic dune formation was delineated on the aerial photography and also on the prepared vegetation maps. Topographic maps of one dune were made as it metamorphosed from a medano into a parabolic dune. Topographic information was extracted from existing aerial photography (1955, 1961, and 1975) using simple parallax measurements. In the initial stage, the local polymodal wind regime results in the formation of high (~25 m), steep conical dunes called medanos, with each medano containing over 300,000 m³ of sand. As vegetation becomes established, either naturally or through plantings, these medanos metamorphize into lower (~12 m) transverse dunes or parabolic dunes. Transverse dunes form when a polymodal wind regime is transformed into a unimodal wind regime due to the sheltering effect of a maritime forest on the lagoon side of the Spit, in the presence of an upwind sediment supply. Parabolic dunes form in the unimodal wind regime when the sediment supply is diminished by the growth of vegetation on all sides. If vegetation is absent (i.e., due to storms and/or effects of man), medanos will persist on the sand sheet. Transverse dunes will form from the original sand sheet in 20-30 years; parabolic dunes require a total of 30-40 years. These rates are shown to be directly related to vegetation succession rates. The presence of medanos and transverse dunes vs parabolic dunes is directly related to the absence or presence, respectively, of a vegetated foredune which inhibits sediment supply via eolian transport or overwash.
The observed sequence of parabolic dune formation is different from that originally proposed by Landsberg (1956) in that more than one wind direction is involved in forming the dune and also because there is a flux of sediment between the arms of the parabolic dune.

Since the only major difference between the three dune types was the growth of vegetation, it can be concluded that vegetation is the main factor responsible for dune evolution. However, the growth of vegetation is regulated by overwash frequency. On Currituck Spit, sand fencing was used to create a protective foredune in some areas which allowed vegetation to colonize the interior by reducing overwash. In those areas where foredune sand fencing was maintained, vegetation has expanded to a much greater extent than in those areas which were not sand fenced, resulting in the observed evolutionary sequence of:

sand sheet → medano → transverse or parabolic dunes
HISTORICAL EVOLUTION OF COASTAL SAND DUNES ON
CURRITUCK SPIT, VIRGINIA/NORTH CAROLINA
INTRODUCTION

Purpose of Study

Coastal dunes have often been considered as stable geomorphic features which undergo major changes only during storms. However, this study shows that coastal dunes evolve through time in response to local winds, sediment supply and vegetation.

Preliminary observations of aerial photography of Currituck Spit, Virginia/North Carolina revealed an evolutionary sequence extant over the entire Spit. This thesis quantifies these observations.

Specifically, my objectives were:
1) To document the evolution of coastal dunes on Currituck Spit, Virginia-North Carolina
2) To develop a conceptual model of dune evolution
3) To quantify the interaction between vegetation and wind climate, and the resulting dune evolution and morphology.

A 60 km reach of Currituck Spit between Back Bay, Virginia, and Duck, North Carolina (Figure 1), was chosen as the location for this study because this reach remained relatively undeveloped, which allowed the assumption to be made that dune evolution in the study area was largely the product of natural processes.

Contemporary Land Use

Contemporary land use along Currituck Spit encompasses the spectrum of fully developed (i.e., Sandbridge, Virginia) to Wildlife
Figure 1. Regional Location Map,
Refuge (i.e., Back Bay National Wildlife Refuge, Virginia).

The southernmost portion of the Spit lies within the Cape Hatteras National Seashore while immediately north of the National Seashore are the summer resort communities of Nags Head, Kitty Hawk, and Duck, North Carolina. North of Duck the Spit remains nearly undeveloped. However, development pressures are rapidly increasing as a result of the increased demand for recreational areas caused by the rapid increase in population of the Hampton Roads, Virginia area. Proceeding north to the Virginia border, this area of scattered development has undergone only slow growth due to a lack of hard surface access roads. Furthermore, access from the north has been restricted by the Federal Government at Back Bay National Wildlife Refuge. In Virginia, the southernmost 18 km of the Spit remain undeveloped, as part of False Cape State Park and Back Bay National Wildlife Refuge. North of Back Bay, the Spit is fully developed at Sandbridge, Virginia.
Currituck Spit, in fact, has exhibited growth by spit elongation at Oregon Inlet, N. C. and mainland detachment at Back Bay, Virginia (Swift, 1975).

Zellmer (1977) analyzed 35 cores taken on the shelf immediately seaward of Dam Neck, Virginia and found a vertical sequence indicative of a former back barrier deposit. This suggests that Currituck Spit migrated landward to its present position under the influence of a rising sea level, as has also been suggested by Field and Duane (1976).

Gutman (1977a) investigated wave seasonality and found that wave seasonality (i.e., winter storms and summer calm) is present to a minor extent. Wave climate has been delineated by Goldsmith et al. (1974), and an attempt to relate wave refraction computations to shoreline erosion in the Cape Hatteras National Seashore (Fisher et al., 1975) indicated a significant correlation, wherein areas of wave ray convergence had significantly higher erosion rates than did areas of wave ray divergence.

Frisch (1977) investigated the seasonality of shoreline erosion between Cape Henry, Virginia and the Virginia/North Carolina line and concluded that, in general, most erosion of the foreshore and backshore occurred during fall storms and that accretion could occur throughout the remainder of the year. However, periods of erosion and accretion varied widely both spatially and temporally.

Goldsmith et al. (1977a) obtained beach profile data for 18 locations from Cape Henry, Virginia to the Virginia – North Carolina line over a three to eight year period. Their data show that shoreline erosion is extremely variable as beaches only a few kilo-
meters apart can concomitantly erode and accrete. Sutton et al. (1977) examined long term trends (i.e., over 125 years), and obtained similar results for the same area. Swift (1972) investigated a series of offshore ridges near False Cape, Virginia and measured their movement through time series analysis. These offshore ridges affect the refraction of waves passing over them, which may account for the location of some of the eroding and accreting beaches behind them, as measured by Goldsmith et al. (1977a).

Langfelder et al. (1968) and El Ashry and Wanless (1968) used aerial photography to document erosion along the Atlantic Coast of North Carolina. Langfelder et al. (1968) concluded that although the Outer Banks are eroding, the rate of erosion is extremely variable. Boc and Langfelder (1977) documented overwash along the coast of North Carolina and found that little or no overwash has occurred since 1962 on Currituck Spit. Prior to the Ash Wednesday storm of 1962, Currituck Spit had been partially overwashed in some areas and completely overwashed near the center of Currituck county. Since development had not occurred in the county, they concluded that development had no effect on the susceptibility of the area to overwash.

The mean tidal range for the area is 1.1 m, a near minimum value for the East Coast north of Florida (Redfield, 1958). No storm surge records exist for this portion of Currituck Spit, however, the maximum surge ever recorded at nearby Hampton Roads, Virginia inside Chesapeake Bay was 1.9 m above mean high water (MHW) in August 1933 (Pore and Richardson, 1977). The last major storm to affect this area was the Ash Wednesday storm of March 7, 1962, which had a surge of 1.72 m above MHW as recorded at Hampton Roads, Virginia. Since that time, storms have been infrequent.
Dunes

Dunes are nearly ubiquitous in their distribution along the Atlantic Coast of the United States and have been classified by many investigators (Goldsmith, 1978). Goldsmith et al. (1977b) devised a classification system for Currituck Spit which differentiates dunes as to whether they are vegetated, unvegetated, natural, or man-induced. Coastal dunes differ from desert dunes by the presence of vegetation, due to a large supply of moisture in the form of rain on Currituck Spit and dew along the Gaza Coast of Israel. As a result, coastal dune morphology is directly related to the quantity of vegetation. Parabolic dunes, for example, form primarily because of the influence of vegetation, and are common in coastal areas whereas they are relatively rare in desert regions.

Large parabolic dunes along Currituck Spit have been investigated by Gutman (1978), who hypothesized that their orientation was due to the influence of vegetation on the local wind regime. Upon attempting to correlate the local wind resultant, based upon one year of wind data, with parabolic dune orientation he found no apparent relationship. He proposed that a 15-meter high maritime forest on the inland side of the Spit effectively negated the offshore wind component and, following a method proposed by Jennings (1957), correlated only onshore winds with dune axis orientation. In this case, the onshore wind resultant was aligned within 10° azimuth of the parabolic dune axes. Thus, he concluded that vegetation played a significant role in the formation and orientation of these parabolic dunes.
Rosen *et al.* (1977) measured foredune cross bedding from Cape Henry, Virginia to Ocracoke Island, North Carolina and found that the strike of the beds was parallel to the shoreline, and that the beds dipped bimodally in the offshore and onshore directions at low angles. This result was surprising in that it differed from measurements made of coastal dunes around the world (Goldsmith, 1978). In other areas the strike and dip of the beds was directly related to the local wind climate while on Currituck Spit, there was less of a relation to the local wind climate. They hypothesized that this was due to the emplacement of sand fencing for promoting a shore-parallel dune ridge along most of the coastline.

Rosen *et al.* (1977) also studied the cross bedding of a large parabolic dune in the study area and found that most beds have low angle dips (mean = 12.2°) and that there was a wide scatter of dip direction. Most beds dip approximately 90° counterclockwise from the surface orientation of the dune (N10°E) and they attributed this to the importance of the northwest wind.

Gutman (1978) also measured the migration rates of two large sand hills in the area, which were 6 m per year and less than 1 m per year. He showed that this variation was directly related to the variation in density of vegetation in the immediate vicinity of the two dunes.

Since the 1930's, management strategies have been concerned with protecting the interior of the Spit. In an attempt to reduce storm effects, sand fencing has been used to create a protective foredune along most of the coast. This is particularly true of the Cape Hatteras National Seashore where a single, continuous, well-vegetated foredune has been created and maintained. Recent studies,
though, have warned that the creation of such an impermeable barrier may affect the long term stability of the barrier island by limiting overwash and inlet formation (Dolan, 1972; 1973; Godfrey and Godfrey, 1972). More recent studies by Leatherman et al. (1976) have shown that overwash may not furnish significant quantities of sediment to the interior of the island, and Godfrey (1976, 1978) has stated that the importance of overwash as a mechanism for the landward migration of barrier islands may be overestimated. No studies have attempted to explain the reduction in the number of observed inlets along this area since the early 1800's. However, this may be related to large scale climatic changes which have resulted in a diminished storm frequency (Fisher, 1962), or to sediment in-filling of the bays behind the barrier spit.

As an adjunct to the importance of overwash and inlet formation in barrier island migration, Jones and Cameron (1977) have recently hypothesized that eolian transport may aid the landward migration of a barrier island under conditions of a stable sea level. Sand is blown across the island where it is trapped by marsh vegetation (Hobbs, in press) and over a long period of time, eolian transport may account for a significant portion of the sediment transported landward over the barrier. Of course, this theory is only applicable in those areas where onshore winds are significant.

Vegetation

Coastal vegetation is subjected to severe physical stresses due to its proximity to the ocean. Many studies have attempted to delineate these stresses and their effects on such processes as
succession and zonation. Wells (1939) described a pine-oak association as the climax community for this region and concluded that wind-borne salt spray was responsible. Oosting and Billings (1942) expanded on this theory and quantified the effects of wind and salt spray. Au (1970) also concluded that salt spray and wind pruning were significant factors, though he added water table depth, extreme temperature variations, and grazing as additional factors in vegetational zonation. Boule (1976) studied succession on Fisherman's Island Virginia and found that dune morphology and vegetation are interrelated. Storms also affect vegetation as overwash causes burial by sand. Some species, such as Ammophila breviligulata, may require burial by sand to maintain vigorous growth (Goldsmith, 1978). Other species are unable to survive burial by sand, thus, burial also plays a role in vegetation zonation. Sand burial may be due to either overwash or eolian processes, thus vegetation zonation and succession may also be related to the available eolian sediment supply.

Other studies have described vegetation distribution on the Outer Banks. Brown (1959) and Levy (1976) identified vegetation communities and listed the plant species found in each community. Boule (1976) also described the species he found on Fisherman's Island. Early studies by Kearney (1900) and Johnson (1900) also quantified the extent of various species. Wells (1939), Au (1970), Boule (1976), and Schroeder et al. (1977) all described successional trends in the study area and concluded that a pine-oak maritime forest is the climax community. Schroeder et al. (1977) attempted to relate this to the recent emplacement of sand fencing in the area, which, they suggested, alleviated physical stresses and resulted in a climax community that is inherently unstable.
Sincock et al. (1965) mapped marsh vegetation in Back Bay, Virginia and Currituck Sound, North Carolina, and the Wetlands Section at VIMS is currently taking an inventory of the marshes in Back Bay. The marshes in the area are represented by typical fresh/brackish marsh vegetation (Walter Priest, Department of Wetlands Research at VIMS, personal communication), with the predominant plants being grasses, sedges, rushes, and cattails. Remnants of salt marsh exist, probably due to the historical occurrence of overwash and inlets, which raised the salinity of the lagoon. At the present time, salt water is pumped into Back Bay at Sandbridge, VA in order to maintain a salinity of 1-4 °/oo. It is believed that this reduces turbidity by inducing flocculation of suspended sediments which results in rapid deposition. Because turbidity has been reduced, subaquous vegetation covers nearly the entire bottom of Back Bay and Currituck Sound. Furthermore, plant succession within the marshes has been complicated by the changes between fresh and saline water, and also by man's effects (Silberhorn, 1977).

Marsh vegetation also plays a significant role in the local abundance of waterfowl. It is estimated that more than 15% of the waterfowl using the Atlantic Flyway winter in the area, thus any significant alterations of marsh communities can have deleterious effects on the waterfowl population (Howard et al., 1975). Unfortunately, long term data upon which to base management decisions are lacking.

Eurasian Milfoil has recently been recognized as a problem in Back Bay and Currituck Sound. Extensive growth has occurred due to the increased use of fertilizer on adjacent farmland, and this
has resulted in a significant decrease in the formerly extensive fresh water fishing industry (Howard, et al., 1975).
THE EARLY HISTORY OF CURRITUCK SPIT (1585-1940)

Introduction

In order to properly evaluate the evolution of dunes on Currituck Spit, an extensive literature search was undertaken to delineate the original (pre-European settlement) condition of the Spit. The purpose of the literature survey was to determine whether the present condition of the Spit is anomalous with its past condition, and also to determine whether or not the present growth of vegetation was abnormal. A synopsis of the early history, drawn from the primary literature, is presented as Appendix A.

Summary of the Early History

The early history of Currituck Spit, as delineated in Appendix A, strongly suggests that the Outer Banks were originally well vegetated and that devegetation was due to the activities of man and his animals. However, this conclusion has been debated (Dunbar, 1958). The theory of a formerly well vegetated Outer Banks may result from a failure on the part of early observers to understand the truly dynamic nature of the Outer Banks (Dunbar, 1958). Dunbar (1958) observed that early maps and charts do not show large areas of vegetation and concluded that the Outer Banks were originally sparsely vegetated. Dolan (1971), Godfrey (1973), and Shroeder et al. (1977) argue against a well vegetated Outer Banks, and have warned that the present increase in vegetation may have deleterious
long term effects on the ability of the Banks to maintain themselves against an ever rising sea level.

The earliest scientific observations of the Outer Banks date only from the late nineteenth century and, at that time, extensive areas of bare sand and migrating sand hills (i.e., medanos) existed on the Banks. Large scale grazing was also in evidence. Thus, early observers concluded that grazing, in large part, was responsible for the generally unstable condition of the Outer Banks (Spears, 1890; Cobb, 1906). Assuming that the Banks were originally forested, as were a few areas, they concluded that logging had occurred, which resulted in a release of the migrating sand sheets. Grazing further destroyed vegetation and helped make a bad situation worse. These were logical conclusions based on the available evidence. However, in lacking baseline data upon which to draw conclusions, their observations are tenuous. If the Outer Banks were not originally forested, what then was their original state?

Figures 2 to 5 are copies of topographic maps, all dating from the 1850's, which show contemporary land use on Currituck Spit. The only large area of forest is at False Cape (Figure 3), and even here, the forest does not extend to within 200 m of the ocean. Scattered within the forest at False Cape are nearly 20 houses, and many of them adjoin cultivated land. The average size of the cultivated plots is approximately 2 hectares, and all are found within the forest. The implication is that shifting sands seaward of the forest made agriculture an unprofitable occupation there. Furthermore, food crops generally require a rich soil, so the forest was the logical place to site a field as a layer of humus
Figure 2. 1850 Topographic Map of Back Bay Area,
Figure 3. 1850 Topographic Map of False Cape Compartment.

(A - Maritime Forest)
Figure 4. 1850 Topographic Map of Pennys Hill Compartment.
Figure 5. 1850 Topographic Map of Corolla Compartment.
overlies the sand. Commercial fertilizers were unavailable, so it is doubtful whether large areas of barren sand were reclaimed for agricultural use.

The description of the "Great Storms of 1846" by Ansel (1905) described damage which occurred at False Cape and his description of the area agrees very well with data on the topographic map. However, in writing about his Uncle Johnny Beasley and the War of 1812, he states that the forest extended seaward at least as far as the foredune, and describes the excavation of a large thicket of cedars on the beach during the storm. These cedar trees were subsequently cut up and sold for ship timbers. As of 1978, a large stump field is exposed at the same low tide location described by Ansell. It appears that they are the same trees as most of them have been cut down and the scars of saws and axes are still visible on many of the stumps. If this description by Ansell is correct, then sometime between 1812 and 1846 much of the forest was buried by sand. Whether this was due to storms, logging, or grazing is not clear, but it may have been a consequence of all three, plus the rise in sea level and subsequent landward migration of dunes.

Most early settlements along the Outer Banks were on the Sound side, usually within a stand of forest. Early settlers understood the power of storms and built their homes in those areas afforded protection from blowing sand and storm tides. Small areas within the forest were cleared to provide fields, and grazing animals were left to forage in the marsh or wherever food was available. Since forest is not conducive to grazing, the assumption that most grazing occurred on marshes or dunes is a valid one; and in fact, the only
existing ranch on Currituck Spit allows its animals to roam free, and most animals can be found in either the marsh or the adjoining dunes.

Pinchot and Ashe (1897) state that some of the islands produce "a limited number of cedar posts....", which indicates that some logging occurred as late as 1897, a time when most other observers state that the extent of the maritime forest was rapidly diminishing and needed protection. Most observers also state that forest was being buried by sand rather than being cut down. However, logging may have helped initiate the migration of sand sheets across the Spit, as described by Spears (1890) and Cobb (1906).

Based upon the early history, and the available topographic maps, vegetation cover seems to have originally been varied. Areas of dense maritime forest existed as isolated tracts along the Spit, separated from each other by areas of sand sheets, medanos, inlets and former inlets. This hypothesis is borne out by noting the locations of the original settlements on the Banks. They were located on the Sound side, within the forest belt, and their density was low, which suggests that the forest belt was discontinuous. Each village was probably separated from the next by areas of unstable dunes or inlets. Villages were established, grazing and logging were initiated, and gradually the areas surrounding the villages and forests become unstable. Eolian sand waves began migrating inland near the villages, with the result that, in time, existing forest was buried by sand, as were some of the villages within the forest.

Logging was initiated along the borders of the forest, or in isolated, uninhabited sections of the forest. This resulted in
destabilization through loss of sand-binding vegetation. Sand sheets formed and began migrating inland under the influence of the onshore wind; grazing animals compounded the situation by destroying new vegetation and further increasing areas of sand susceptible to the wind. This trend was well underway at the time of the earliest scientific observations, thus it becomes clear why these observers arrived at their conclusions. They believed they saw remnants of the original maritime forest, when in fact they observed nearly all of the maritime forest which had ever existed on the Spit. These observations were accepted as factual when they actually comprised only a limited view of the Outer Banks. This scenario does not contradict the geologic history of the Spit and may shed some light on the current debate over whether or not the recent increase in vegetation density is abnormal (Dolan, 1973; Schroeder et al., 1977).

It appears that there were large areas of maritime forest on the Outer Banks. However, they were isolated tracts which gradually succumbed to burial by sand, which was initiated by logging, grazing, and storm effect on adjacent areas. Evidently, the early settlers realized the dangers of storms and migrating sand dunes, which is why they established villages within the forest belt. Unfortunately, they did not realize that destruction of vegetation on surrounding areas would incur the same results as removing vegetation adjacent to their villages. Had they possessed a clearer understanding of the interaction of wind, sand, vegetation, and sea, the Banks could have remained a paradise (Epler, 1933) for them.
Conclusions about the Early History

1. Two inlets were open along this portion of Currituck Spit. Old Currituck Inlet, which opened before 1587, closed in 1728-1730. New Currituck Inlet opened 5 miles to the south in 1713 and closed in 1828. Since that time, no inlets have been open along Currituck Spit (Figure 6).

2. Currituck Spit was well stabilized by vegetation prior to European settlement. Areas of dense maritime forest existed as isolated tracts along the Spit, separated from each other by areas of sand sheets, medanos, inlets and former inlets. Grasslands and marshes provided free grazing land for the early settlers, consequently, grazing had an early start on Currituck Spit.

3. Forest which existed on Currituck Spit had some commercial value; hence, some areas of forest succumbed to the axe. This occurred during the early nineteenth century and resulted in the enlargement of existing open spaces. These open spaces were used for grazing, which resulted in a further reduction of vegetation.

4. After most of the vegetation was removed, sand sheets and sand hills (medanos) formed under the influence of the wind. This release of migrating sand also allowed increased storm damage through overwash, so natural revegetation could not occur. With gradual devegetation, these unstable areas grew in size until they extended over nearly the entire Currituck Spit.
Figure 6. Historical Map of Currituck Spit.
DUNE EVOLUTION (1937 - 1975)

Introduction

The previous chapter dealt with the early history of Currituck Spit; unfortunately, quantitative data are lacking, as much of the early history is based upon written descriptions which contain little information specific enough to be quantitatively analyzed. By the 1930's, the technique of photography became more sophisticated, and vertical aerial photography of coastal areas became an important tool. The quality of the early imagery is sufficient to allow the extraction of data pertaining to dune type, vegetation, and topography. This chapter deals with the post 1937 history of Currituck Spit as delineated on available historical aerial photography.

Method of Study

A complete list of the aerial photography used in this study is included in Appendix B. Stereo photographic coverage was obtained for all available dates so that dune topography could be measured.

In order to assess the reliability of the earlier written descriptions, the available imagery of Currituck Spit was examined and compared to the early descriptions which stated that much of the Spit was a low, barren sand sheet, which was frequently overwashed during storms (e.g., Cobb, 1906, Stratton, 1943). Much of the original vegetation had disappeared, either through sand burial
or by exposure to salt water through overwash. This is verified in the early imagery (Figures 8, 12, 15), which revealed that in the late 1930's much of the Spit was covered by a barren sand sheet.

In subsequent imagery, several sequences of dune evolution are apparent. Since many areas have remained undeveloped, dune evolution in those undeveloped areas must be the result of natural processes. Development of other areas has occurred within the past ten years, and in these, natural changes have been obscured or even obliterated by construction activities.

In order to focus on the natural sequences of dune evolution, the study area was divided into three compartments. Only those areas which have remained undeveloped since the 1930's were chosen. The assumption is made that natural processes acting along this portion of Currituck Spit are nearly identical and that it is correct to conclude that the end product of dune evolution would be similar in each compartment. However, each compartment exhibits a different scheme of dune evolution. The parameters which might vary among these three compartments are limited: inlet frequency, vegetation, overwash frequency, and external factors such as sand fencing or other human activities. Other factors, such as wind regime, wave climate, sea level rise, storm frequency and sediment supply can be considered to be nearly identical for all three compartments, as all three compartments lie within a 45-km reach of Currituck Spit and have a similar background.

Of the variables which influence dune evolution; vegetation, overwash and human activities are all measurable quantities on the aerial photography. Vegetation can be mapped (Carter and Anderson,
overwash leaves visible scars which can usually be identified on the imagery (Boc and Langfelder, 1977; Hosier and McCleary, 1977); and sand fencing can be identified by characteristic foredune patterns. If these parameters can be measured, then the factors responsible for dune evolution on Currituck Spit can be isolated and quantified.

Description of the Total Reach

In selecting three compartments from the total reach for intensive study, several criteria were employed to eliminate as much variability as possible. First, all areas that were significantly developed in the twentieth century or had been bombing ranges were excluded in order that only natural processes be studied. Since most of Currituck Spit had been pierced by an inlet at one time or another (Fisher, 1962), compartments were chosen so that they were as close as possible to the site of a former inlet without containing developed areas. This eliminated the question of whether or not these apparent differences were due to proximity to a former inlet.

The three compartments possess nearly identical histories, at least until the 1930's so differences in dune evolution should be due to factors introduced since that time. If this assumption is correct, an analysis of the available historical aerial photography might delineate these factors.

Figure 7 is a map of Currituck Spit showing the various compartments. Proceeding from north to south, each compartment and inter-compartmental area is described.

A. False Cape State Park Compartment, Virginia

False Cape State Park is the northernmost compartment of the study area. It is 8 km long and the width of the Spit varies
Figure 7. Study Compartment Location Map.
from a minimum of 1.96 km to a maximum of 2.8 km. The average width is approximately 1.6 kilometers. Old Currituck Inlet (open pre 1585-1730) lies within the southern half of the compartment, and it is here that the maximum width is observed, due to the existence of the large, relic flood tidal delta.

Dune morphology is varied; in the northern section a nearly continuous series of multiple foredune ridges is present, due to an earlier sand fencing program. In the southern section, the foredune is discontinuous, pierced at intervals by jeep trails leading to the interior. The principle inland dune type consists of large parabolic dunes, all of which have been stabilized by vegetation.

Extensive maritime forest extends nearly to the foredune in the northern section and forms a tract nearly 3 kilometres long and over 1.2 kilometres wide. Elsewhere, the forest forms a band approximately 250 metres wide on the lagoon side.

B. Corova Beach Development, North Carolina

This area is in the early stages of development. Although no hard surface roads exist, an extensive network of canals, which provide access into Currituck Sound, was dredged during the late 1960's, obliterating the natural dunes and vegetation in the area.

C. Penny's Hill Compartment, North Carolina

The Penny's Hill compartment is approximately 10 km long, and varies in width from 1.4 km to 3.6 km. This compartment was the site of New Currituck Inlet (open 1713-1830) and the deposits from the former inlet occupy nearly the entire compartment. Relic inlet channels penetrate to nearly the center of the Spit, and flooding of the interior is frequently caused by wind setup of Currituck Sound.
The northernmost portion supports a small cattle ranch (approximately 200 head), the only ranch still extant on the Outer Banks. The interior is undeveloped and is characterized by a barren sand sheet, with occasional medanos, or sand hills. Vegetation is, for the most part, limited to the sound side of the compartment.

D. Jones Hill, North Carolina

This area contains the town of Corolla, North Carolina, and a large former overwash area. One large transverse dune exists here; Jones Hill has migrated inland at an average rate of 11 m per year since 1940. The area served as a Naval strafing and bombing range until the mid-1960's.

E. Corolla Compartment, North Carolina

This compartment is approximately 8.8 km long and has a minimum width of .56 km and a maximum width of 3.6 km. The southern half of the compartment was the site of Caffey's Inlet (open 1770-1810) (Fisher, 1962) and contains a large relic flood tidal delta. This compartment contains a series of 14 en echelon transverse dunes which are migrating toward the southwest at a rate of 6 m per year (Gutman, 1978). Vegetation forms a belt of maritime forest approximately 200 metres wide on the sound side and there is little vegetation seaward of the transverse dunes.

Dune Evolution in the Three Study Compartments

A. False Cape Compartment

The earliest available imagery of the False Cape Compartment dates from 1937. This imagery (Figure 8) reveals that much of the compartment was covered by a sand sheet from ocean to sound-side marshes. Superimposed on this sand sheet are 12 medanos with an
Figure 8. 1937 Photomosaic of False Cape Compartment.
A - MEDANOS
B - MARITIME FOREST

1937 FALSE CAPE PHOTOMOSAIC
Figure 9. 1955 Photomosaic of False Cape Compartment.
A - INCIPIENT PARABOLIC DUNES
B - MARITIME FOREST

1955 FALSE CAPE PHOTOMOSAIC
average height of 6-7 metres and a basal diameter of 250 metres. Each medano is a distinct entity, separated from adjacent medanos by an area blown out to the fresh water table. Vegetation is absent from most of the compartment. The northern section of the compartment contains maritime forest; however, stereoscopic examination of tree and shrub height with a parallax bar indicates that the average height is less than $4.0 \pm 0.7$ m in 1937. Thus, the forest appears to be in a youthful stage. In the remainder of the compartment, vegetation is nearly absent. A foredune is nonexistent, although, in nearby Back Bay National Wildlife Refuge, sand fencing has been deployed and an incipient foredune is present. Thus, it appears that False Cape was initially sand fenced later than 1937.

By 1955 (Figure 9), many changes have taken place; a foredune was built up and numerous houses have been constructed along the ocean beach. The sand sheet is in the process of breaking up into discrete medanos, and many of the blowout areas have been colonized by grasses, thereby reducing the supply of sediment available to the medanos. Incipient parabolic dunes are present in the southernmost portion of the compartment. Maritime forest has developed as a continuous belt on the sound side between the original sand sheet and the marsh. The core of this forest is due to CCC and WPA plantings made during the initial dune stabilization program of the 1930's (Gary Soucie, Audubon Magazine, Personal Communication). This forest has exhibited growth along topographic highs which have been built out on to the marsh by eolian deposition.

In 1963, (Figure 10) the sand sheet has completely broken up and all of the medanos have evolved into incipient parabolic dunes
Figure 10. 1963 Photomosaic of False Cape Compartment.
Figure 11. 1975 Photomosaic of False Cape Compartment.
A - STABILIZED PARABOLIC DUNES

1975 FALSE CAPE PHOTOMOSAIC
that are migrating inland. Vegetation increased in both density and extent and a large area just landward of the nearly continuous foredune was colonized by grass and shrub vegetation. The maritime forest also increased in width and expanded seaward along the interdune swale areas. Parallax bar measurements revealed that the height of the maritime forest was \(7.0 \pm 0.5\) m in 1963.

Whereas in 1955, medanos were the dominant interior dune type, large parabolic dunes cover the interior of the compartment in 1975 (Figure 11). These parabolic dunes average more than 250 metres in length and have an upwind (i.e., NNE) opening of nearly 200 metres (Figure 11). The blowout areas have been colonized by grasses and shrubs and field observations reveal that these dunes are anchored by vegetation. Furthermore, measurements of dune cross bedding revealed the low angle (mean 12.2°) bedding dip characteristic of vegetated dunes (Rosen, et al., 1977). Immediately landward of the nearly continuous foredune, large areas have been colonized by grasses and shrubs. Height of the maritime forest is now \(12.0 \pm 0.7\) m and the forest has also increased in width.

In summary, dune evolution in the False Cape Compartment has been the following:

Sand Sheet \(\rightarrow\) Medanos \(\rightarrow\) Active Parabolic Dunes \(\rightarrow\) Stabilized Parabolic Dunes

B. Corolla Compartment

The Corolla Compartment exhibits a sequence of dune evolution much different from False Cape in that transverse dunes rather than parabolic dunes are the end product in 1975. In the 1940 imagery (Figure 12), this compartment was covered from ocean to sound by a
Figure 12. 1940 Photomosaic of Corolla Compartment.
A - MEDANÖS

1940 COROLLA PHOTOMOSAIC
sand sheet, with sand hills superimposed. These sand hills were as high as their contemporaries in the False Cape Compartment, i.e., six to seven metres. Low, interdunal areas blown out to the freshwater table are visible, although not distinctly, on the imagery between these medanos. Some vegetation is present, but is limited to the sound side of the compartment.

The 1955 imagery (Figure 13) shows that the sand sheet is in the process of breaking up to form distinct medanos, and a foredune has been created, although it is pierced at intervals by overwash sluice channels. Vegetation has expanded from the sound side toward the ocean side and some of the blowout areas have been colonized by grasses. All of the medanos exhibit net movement toward the southwest, even though the slipfaces are not on the southwest side of the medanos in the imagery. Slipface orientation of medanos responds quickly to local winds, thus, one can determine what the winds were prior to the aerial photography.

Although the evolutionary sequence in Corolla between 1940 and 1955 has been nearly identical to that which occurred in False Cape between 1937 and 1955, there are major differences between False Cape and Corolla between 1955 and 1975.

In 1975 (Figure 14), the Corolla compartment exhibited a series of 15 en echelon transverse dunes, all of which formed from medanos which existed in 1955. The transverse dunes present in 1975 are significantly different from their ancestral medanos in several respects. First, the average slipface height of the transverse dunes present in 1975 is much lower than that of the original medanos. For example, Lewark's Hill, a medano north of the Corolla Compartment, has
Figure 13. 1955 Photomosaic of Corolla Compartment.
Figure 14. 1975 Photomosaic of Corolla Compartment.
A - TRANSVERSE DUNES
B - EOLIAN FLAT

1975 COROLLA PHOTOMOSAIC
a slipface 15 metres high while Whalehead Hill, a transverse dune, has a slipface only 5.5 metres high (Gutman, 1978). Furthermore, transverse dunes possess a dense cover of maritime forest downwind of the slipface while medanos are completely surrounded by sparsely vegetated blowout areas. Medanos migrate slowly (e.g., Lewark's Hill has migrated toward the southwest at a rate of 4 m/yr since 1955) while transverse dunes migrate up to 12 m/yr (e.g., Jones Hill since 1940). Also, the slipface azimuth of a medano is variable while the slipface of a transverse dune always lies on the southwest side of the dune, which is the side of densest vegetation. It appears that the medano results from wind piling sand up from several directions. Once the vegetation alters the local wind regime, dune height decreases, and the rate of dune migration increases toward the vegetation.

Although these dunes are parabolic in planar view in Figure 14, the extensive growth of vegetation considered essential for parabolic dune formation is not present. Vegetation serves to bind the sand, resulting in a diminution of the sand supply and a reduction in the volume of the dune. Furthermore, sand can be blown back onto the beach during period of westerly winds as there is no dense cover of vegetation seaward of the medanos to inhibit eolian transport.

Within the compartment, the foredune is low and discontinuous, and during periods of onshore winds, sand is blown from the beach into the interior. Although these transverse dunes are located several hundred metres inland from the beach, there is a great deal of eolian interaction across the barrier (Gutman, 1978). Parabolic dunes form because they have been cut off from their sand supply by vegetation (Landsberg,
in this compartment a reduction in sediment supply has not occurred. However, as vegetation colonizes the eolian flat areas, conditions may become conducive for the formation of parabolic dunes. Thus, in the Corolla Compartment, dune evolution has been the following:

Sand Sheet → Medanos → Transverse Dunes → Early Stage Parabolic Dunes

C. Penny's Hill Compartment

Imagery of this compartment dates back only to 1955. Areas to the north and south possessed sand sheets as late as 1940, so it is logical to assume that a sand sheet also covered this compartment. This compartment was the site of New Currituck Inlet (open 1713–1828), and a large relic flood tidal delta remains in Currituck Sound. Relic inlet channels penetrate into the interior of this compartment from the sound side with the result that periodic flooding of the compartment occurs following strong westerly winds. This is visible in the 1955 imagery (A, Figure 15). Historical records, aerial photography, and conversations with residents revealed that this area is one of chronic overwash, both from the ocean and sound side. Noteworthy of mention is a large, linear sand ridge, parallel to the shoreline, located approximately 700 metres behind the low, discontinuous foredune (B, Figure 15). The interior dune ridge was probably created by sand fencing during the 1930's in order to limit overwash. Field measurements indicate that the ridge is two to three metres above the surrounding eolian flat.

Five medanos (Figure 15) are found in this compartment, but differ from their counterparts in the other compartments by being
Figure 15. 1955 Photomosaic of Pennys Hill Compartment.
A - FLOODED AREA
B - INTERIOR DUNE RIDGE
C - MEDANOS
D - PENNYS HILL
E - LEWARKS HILL

1955 PENNYS HILL PHOTOMOSAIC
widely separated from each other. Although they formed from the local sand sheet, it is possible that others were prevented from forming due to frequent flooding of the interior, which limited sand supply.

Most vegetation is found behind the interior dune ridge. Seaward of the ridge, vegetation is limited possibly due to the high frequency of overwash in the area.

By 1975, some stabilization by vegetation had occurred, but was limited to growth of the maritime forest inland of the interior dune ridge. Flooding is still in evidence (A, Figure 16), and a distinct foredune had not been created and maintained. The most notable change is the metamorphism of one dune, called Penny's Hill by local residents, from a medano into a parabolic dune (B, Figure 16). This dune has assumed its parabolic shape since 1955, which implies that dune evolution occurs in a remarkably short period of time. Over most of the compartment, a sand sheet is still present, and it appears that this is due to the effects of overwash in the area.

Lewark's Hill, in the southernmost portion of the compartment, is the largest medano in the study area (C, Figure 16). The height varies between 20 and 25 metres. A conservative estimate of volume, based upon a concic formula, is that more than 300,000 cubic metres of sand are contained in Lewark's Hill. Although this hill has a net southerwesterly movement of only 4 m per year, this represents only a small fraction of the actual movement, as the medano moves in response to local winds and can migrate as much as two to three metres seaward during periods of intense westerly winds (Gutman, 1978). Thus, net movement indicates a low net rate of eolian transport while actual gross transport is significantly greater.
Figure 16. 1975 Photomosaic of Pennys Hill Compartment.
A - FLOODING
B - PENNYS HILL
C - LEWARKS HILL

1975 PENNYS HILL PHOTOMOSAIC
In summary, dune evolution in this compartment since the 1930's has been limited, with the exception of one medano that has evolved into a parabolic dune.

The generalized sequence documented here is:

Sand Sheet → Sand Sheet

Source of Dune Sand

Dune evolution within the three compartments had proceeded along three different paths from the sand sheet present in the 1930's. In the False Cape Compartment, parabolic dunes are present, while in Corolla, transverse dunes presently exist. In the Penny's Hill Compartment, a sand sheet covers the Spit. The question now arises as to the cause of this divergent evolution, given that all three compartments had a similar starting point in the 1930's.

More than 300,000 cubic metres can be tied up in one hill and when all three compartments are considered, the estimate is approximately 8,000,000 cubic metres, for 27 kilometres of linear spit length. Estimates of the local annual longshore transport range from 50,000 to 500,000 cubic metres per year (Burch, 1969; Weinman, 1971). This suggests that another source of sediment other than sand deposited by littoral processes is required to supply the dunes. One possibility suggested is the reworking of relic beach ridges or dune ridges associated with former inlets.

Dolan and Hayden (University of Virginia, Personal Communication) have hypothesized that the source of sediment for Jockey Ridge, a large dune ridge located 20 kilometres south of the study area, has been the reworking of the sand in relic multiple dune ridges as
commonly form at the ends of southerly prograding spits. These were formed 2,000 to 4,000 years ago when the shoreline configuration was different (Dolan and Hayden, University of Virginia, Personal Communication). Relic dune ridges are today found immediately landward of Jockey Ridge, hence, erosion and recycling of sand in these dune ridges is supplying sediment to Jockey Ridge.

However, in the study compartments, relic dune ridges do not exist. Pierce and Colquohoun (1970) proposed that this portion of the Outer Banks is a secondary barrier, that is, the original Pleistocene barrier was overrun by a secondary barrier as it migrated landward during the Holocene rise in sea level. If such is the case, then no relic dune ridges would be found, as all evidence of the primary barrier would have been obliterated. Thus, it is still possible that the ultimate source of sand was the reworking of relic beach ridges even though the evidence has since been destroyed.

An analogous source of sediment for the dunes in the study area could be the reworking of dune ridges associated with inlets. Each of the compartments has been the site of an inlet during historical time and due to bad land use practices, vegetation was destroyed, which released large quantities of sand formerly contained in the dune ridges. Furthermore, a description of the False Cape Compartment in 1846 (Ansel, 1905) states that the compartment consisted of "lofty sand hills and high sand ridges . . .". It is possible that these sand ridges were associated with the former inlet and were reworked to form the presently occurring parabolic dunes. Due to subsequent land use practices, eolian erosion and overwash destroyed all vestiges of these dune ridges. Thus, reworking of relic dune ridges associated
with inlets may also serve as a source of sand. The speed at which these changes occur, a few tens of years, is shown by the aerial photos of False Cape since the 1940's.

The presence of the large dunes along the Outer Banks is probably due to both mechanisms. In areas where the primary barrier has coincided with the secondary barrier, erosion and reworking of relic dune ridges is the source of sand. In other areas, reworking of dune ridges associated with former inlets can serve the same purpose.

**Temporal Development of Parabolic Dunes**

False Cape State Park exhibits a sequence of parabolic dune formation similar to that previously described by Landsberg (1956, Figure 17). Gutman (1978) analyzed the orientation of these dunes and found that the dominant onshore wind (northeast) was responsible for their characteristic orientation. He plotted a wind rose based upon one year of wind data collected by an anemometer atop the Currituck Beach Lighthouse in Corolla, North Carolina and hypothesized that, although the total wind resultant was from the northwest, the growth of the maritime forest effectively blocked the westerly wind (180° to 360° AZ) and allowed onshore winds (0° to 180° AZ) to play a dominant role in the orientation of these dunes. Furthermore, the onshore wind passes over the original source of sediment (i.e., the sand sheet) and thus contributed to the growth of these dunes (Figure 18).

In order to test Landsberg's (1956) hypothesis and to quantify the process of parabolic dune formation, Penny's Hill, an isolated
Figure 17. Hypothetical Sequence of Parabolic Dune Formation.

(After Landsberg, 1956)
Figure 18. Corolla Station Wind Roses Including Total and Onshore Resultant. (From Gutman, 1978)
Corolla Station Wind Resultant

Excludes wind speeds < 5.0 m/s and all offshore winds.
parabolic dune in the Penny's Hill compartment, was selected for
intensive study. It remains isolated, thereby eliminating the effects
of other dunes on the local wind regime, as has been discussed by
Tsoar (1975).

Stereo photographic coverage of Penny's Hill was available
for three dates: 1955, 1961, and 1975. Within that time span the
dune metamorphosed from a medano into a parabolic dune. In order to
quantify the effects of wind, the dune was topographically contoured
from the aerial photography using a parallax bar. A discussion of
the parallax principle is not appropriate here, however, the Manual
of Photogrammetry (1966) discusses the technique in detail. A
discussion of specific methodology is contained in Appendix C.

Figure 19 is a graphic representation of the topography of
Penny's Hill as it has changed since 1955. The total wind resultant
and the onshore resultant, compiled by Gutman (1978), are included in
the diagram. Vegetation, mapped from the original photography, is
also shown.

Figure 19A show Penny's Hill in 1955. Note that the hill
has a medano-like morphology; no trailing arms stabilized by vegetation
can be distinguished. The maximum height of the dune can be seen as a
ridge, with an orientation of ENE - WSW, and an elevation of 11 m
above the base of the dune. The ridge lies almost normal to the
total wind resultant measured by Gutman (1978). This implies that,
in the medano stage of evolution, the offshore westerly winds are
significant in shaping the morphology of the dune. Vegetation inland
(SW) of the medano consists primarily of grasses and occasional low
(1 to 2 m) shrubs. At this stage vegetation exerts a minor influence on the local wind regime.

In 1961 (Figure 19B), the medano has assumed a parabolic outline; two trailing arms have formed and a blowout area exists between them. The bulk of the dune again forms a ridge that is almost perpendicular to the total wind resultant. However, the dune has decreased in height to 7 m, which agrees with Landsberg's (1956) dune evolution sequence. Inland vegetation is now more expansive; a low (2 to 4 m) maritime forest has succeeded the shrubs and grasses, indicating a vertical tree growth of 0.3 to 0.66 m per year.

By 1975 (Figure 19C), the dune assumed a completely parabolic morphology. The maritime forest increased in height to approximately 8 to 10 metres, and forest width also increased. Note that in 1975 the maximum dune height (6.8 m) is on the western flank, which is nearly normal to the onshore wind resultant. This is in contrast to the earlier topography where the maximum dune height was normal to the offshore wind resultant.

It should be noted that the slipface has advanced towards the SSW over 120 metres since 1955, for an average migration rate of 6 m per year.

Discussion of Parabolic Dune Development

The sequence of parabolic dune formation described here differs from that originally proposed by Landsberg (1956) in two respects. First, more than one wind direction is responsible for dune formation and second, there had been a transfer of sediment from the eastern flank of the dune to the western flank.
Figure 19. Temporal Evolution of Pennys Hill from a Medano to a Parabolic Dune.
1955
GRASS
GRASS/SHRUB (Height ≤ 2. M)

HEIGHT IN METRES ABOVE BASE OF DUNE

1) Contours based upon eleven measurements
2) Error of height measurements is ± 0.7 metre

*ONSHORE WIND RESULTANT

1961
MARITIME FOREST (Height ≤ 4. M)

SHORELINE ORIENTATION

1) Contours based upon 101 measurements
(Only 21 shown)
2) Error of height measurements is ± 0.2 metre

*TOTAL WIND RESULTANT

1975
MARITIME FOREST (Height ≤ 10. M)

SHORELINE ORIENTATION

1) Contours based upon ten measurements
2) Error of height measurements is ± 0.9 metre

*TOTAL WIND RESULTANT
Although it has been hypothesized that inland vegetation, i.e., maritime forest, has played a significant role in altering to local wind climate, there has been no discussion of a possible mechanism to account for this.

Stearn and Lettau (1963) conducted an experiment during which an artificial forest was constructed on a frozen lake and measurements of the resulting perturbation of the wind profile were made. They found that reattachment, that is, return to the original wind profile, occurred at a downwind distance of approximately 50X the height of the artificial forest. More recently, Willetts and Phillips (1978) have measured a ratio of approximately 40X the height of the obstruction. In this case, however, they used sand fencing in a wind tunnel; thus the results may not be completely analogous to Currituck Spit. However, if we choose an intermediate number, say, 45X the height of the obstruction as the distance to reattachment, we find that this can be used to explain the formation of the parabolic dune.

In 1955, the height of the forest was approximately 2 m, thus we would expect reattachment to occur 90 m downwind of the obstacle. Referring to Figure 19A, we find that the eastern flank is much higher than the western flank. This implies that vegetation at this point is exerting a relatively minor influence on the westerly winds.

In Figure 19B, the forest is now approximately 4 m high, thus reattachment would be expected within 170 m. Again, we find that the eastern flank is much higher than the western flank which indicates that the bulk of the dune lies within the normal wind regime.
In 1975, (Figure 19C) the forest averages 9 m in height and reattachment would occur nearly 405 m downwind of the forest. Here the dune is completely within the shadow zone of the northwest winds. As a result, the onshore winds have assumed dominance as they are not obstructed. Note that in 1975 the western flank is higher than the eastern flank. Another line of evidence which shows the domination of the westerly wind component are measurements of dune crossbedding made of a nearby parabolic dune by Rosen et al. (1977). They found that, in 1975, the azimuth of dip direction differed considerably between the western flank and the eastern flank. Dip direction of the western flank was primarily the result of the onshore winds whereas some of the beds on the eastern flank dipped offshore, in response to the westerly winds. This shows that the western flank of the parabolic dune lies within the shadow zone whereas the eastern flank, 300 m downwind of the forest, is not within the shadow zone.

In light of this corroborating data, it can be concluded that the growth of the maritime forest on the western side of the barrier island has resulted in the diminution of the westerly wind component. This resulted in the formation of parabolic dunes as the onshore winds gradually assumed dominance.
VEGETATION AS A FACTOR IN DUNE EVOLUTION

Introduction

The evolution of the various dune types has been documented in the previous chapter. However, in order to firmly resolve the question of divergent dune evolution between the compartments, the effects of vegetation must be taken into account. This chapter documents the changes in vegetation that have occurred concomitant with dune evolution and attempts to relate the quantity, height and type of vegetation to a specific dune type.

Method of Study

In order to measure changes in vegetation through time, vegetation maps were prepared from the aerial photography available for each compartment. The eight vegetation communities that were mapped represented the maximum number that could be accurately identified on the early black and white imagery. Also, since different vegetation communities exhibit different roughness characteristics, it is important to identify those areas which significantly alter the local wind regime, and also what wind directions would be affected. For example, a maritime forest would exert more drag than a lower grassy community (Bressollier and Thomas, 1977; Gutman, 1978), thus dune evolution is related to the quantity and type of adjacent vegetation.

Communities were selected on the basis of textural as well as areal differences. While marsh grass and dense stands of dune
grass can exhibit similar film densities, separation of the two communities can be accomplished. For example, marsh grass is found near water, usually on relic flood tidal deltas which are easily identified on the imagery, while *Ammophila breviligulata* occurs in dune areas. Also, black and white imagery can not usually distinguish between two species of dune grass, but dune grass can be differentiated from marsh grass. Communities were selected for ease of identification and to provide as much vegetation data as possible.

Mapping was accomplished using a Bausch and Lomb Zoom Transfer Scope. Tracings of community boundaries were made onto a base map. Areas were calculated for each community through time using a Numonics Corporation Electronic Digitizer. The original base map was planimetered to eliminate errors inherent in the reduction and drafting process.

Due to a lack of established control points in the compartments (i.e., shifting dunes, absence of roads and houses), maps were made by obtaining a best fit with the base map and tracing community boundaries. The errors inherent in this process are probably on the order of ±15 m, however, this error did not significantly alter the maps. In particularly complex areas, the boundary was generalized since the fine detail produced by accurately mapping a complex boundary did not provide much additional useful information, and overcomplicated the map.

For areas where vegetation succession rates were obtained, large scale (1:8,000) tracings were made on which the boundaries were accurately reproduced. Here, the error is on the order of ±5 m.
Since the boundaries of all communities were generalized to a certain extent, it is felt that the errors involved in the area measurements are not biased toward any one community. While some error is present in the area measurements, a similar error can be expected for each community. Since this study is concerned with gross changes through time, these errors are not significant enough to affect the conclusions.

Selection of Vegetation Communities

Using the criteria discussed previously, the following vegetation communities were mapped:

- Marsh: Typical brackish/fresh water marsh.
- Maritime Forest: Typical pine/oak association, generally less than 12 m high.
- Grass: A dense cover of grassy vegetation.
- Grass/Shrub: Scattered shrubs in a grassy area (less than 50% shrubs).
- Shrub/Grass: Dense shrubs with interspersed grassy areas (less than 50% grass).
- Stabilized Dunes: Low dunes covered by scattered shrubs and grasses (generally less than 50% of total area vegetated) not active.
- Eolian Flat: Area blown out to the fresh water table, water pools after rains or overwash, some vegetation.
- Active Area: Area of migrating dunes, sparse vegetation.

Table 1 is a generalized list of species found in each community, based upon other studies in similar coastal areas. With the exception of the Shrub/Grass and Grass/Shrub communities, all
Table 1. Generalized List of Plant Species found in Each Community.
GENERALIZED LIST OF PLANT SPECIES ON CURRITUCK SPIT

(From Brown, 1959; Levy, 1976; Boule, 1976)

**MARITIME FOREST**

<table>
<thead>
<tr>
<th>Species</th>
<th>Common Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pinus taeda</td>
<td>Loblolly Pine</td>
</tr>
<tr>
<td>Quercus nigra</td>
<td>Black Oak</td>
</tr>
<tr>
<td>Quercus virginiana</td>
<td>Live Oak</td>
</tr>
<tr>
<td>Acer rubrum</td>
<td>Red Maple</td>
</tr>
<tr>
<td>Prunus serotina</td>
<td>Black Cherry</td>
</tr>
<tr>
<td>Ilex opaca</td>
<td>American Holly</td>
</tr>
<tr>
<td>Juniperus virginiana</td>
<td>Red Cedar</td>
</tr>
<tr>
<td>Salix nigra</td>
<td>Black Willow</td>
</tr>
<tr>
<td>Sassafras albidum</td>
<td>Sassafras</td>
</tr>
<tr>
<td>Cornus florida</td>
<td>Flowering Dogwood</td>
</tr>
<tr>
<td>Diospyros virginiana</td>
<td>Persimmon</td>
</tr>
<tr>
<td>Persea borbonia</td>
<td>Red Bay</td>
</tr>
</tbody>
</table>

**SHRUBS**

<table>
<thead>
<tr>
<th>Species</th>
<th>Common Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Myrica pennsylvanica</td>
<td>Bayberry</td>
</tr>
<tr>
<td>Myrica cerifera</td>
<td>Wax Myrtle</td>
</tr>
<tr>
<td>Ilex vomitoria</td>
<td>Yaupon</td>
</tr>
<tr>
<td>Ilex imbricata</td>
<td>Seashore Elder</td>
</tr>
<tr>
<td>Baccharis halimifolia</td>
<td>Silverling</td>
</tr>
</tbody>
</table>

**GRASSES**

<table>
<thead>
<tr>
<th>Species</th>
<th>Common Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammophila breviligulata</td>
<td>American Beachgrass</td>
</tr>
<tr>
<td>Uniola paniculata</td>
<td>Sea Oats</td>
</tr>
<tr>
<td>Spartina patens</td>
<td>Saltmeadow Cordgrass</td>
</tr>
<tr>
<td>Cynodon dactylon</td>
<td>Bermuda Grass</td>
</tr>
<tr>
<td>Panicum amarum</td>
<td>Running Beachgrass</td>
</tr>
<tr>
<td>Triplasis purpurea</td>
<td>Purple Sandgrass</td>
</tr>
</tbody>
</table>

**MARSH**

<table>
<thead>
<tr>
<th>Species</th>
<th>Common Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spartina alterniflora</td>
<td>Smooth Cordgrass</td>
</tr>
<tr>
<td>Borrichia frutescens</td>
<td>Sea-Oxeye</td>
</tr>
<tr>
<td>Spartina cynosurondes</td>
<td>Big Cordgrass</td>
</tr>
<tr>
<td>Scientific Name</td>
<td>Common Name</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>------------------------------------</td>
</tr>
<tr>
<td><em>Salicornia virginica</em></td>
<td>Saltwort</td>
</tr>
<tr>
<td><em>Distichlis spicata</em></td>
<td>Saltmarsh Grass</td>
</tr>
<tr>
<td><em>Juncus roemelianus</em></td>
<td>Black Rush</td>
</tr>
<tr>
<td><em>Spartina patens</em></td>
<td>Saltmeadow Hay</td>
</tr>
<tr>
<td><em>Phragmites australis</em></td>
<td>Reed Grass</td>
</tr>
<tr>
<td><em>Typha spp.</em></td>
<td>Cattails</td>
</tr>
<tr>
<td><em>Scirpus olney</em></td>
<td>Olney Three Square</td>
</tr>
<tr>
<td><em>Iva frutescens</em></td>
<td>Marsh Elder</td>
</tr>
<tr>
<td><em>Baccharis halimifolia</em></td>
<td>Groundsel Tree</td>
</tr>
</tbody>
</table>
of the various communities exhibit significantly different effects on the local wind regime. These two communities were chosen in order to illustrate succession from grasses to forest, and provide data on how fast natural succession occurs on Currituck Spit.

Results

The data collected for this chapter are presented as a series of vegetation maps for each compartment (Figures 20-29).

In the False Cape Compartment, the most dramatic change between 1937 (Figure 21) and 1955 (Figure 22) has been the growth of a foredune, which can be distinguished as the band of stabilized sand immediately landward of the Atlantic Ocean (Figure 22). Concomitant with the growth of seaside vegetation was the growth and expansion of a maritime forest on the sound side. Each of the parabolic dunes in 1963 and 1975 (Figures 23 and 24) is characterized by vegetation on the upwind side. Downwind of the slipface, there is an area only sparsely colonized by vegetation (as indicated by the blank areas). Maritime forest on the sound side blocked the westerly winds as shown in the previous chapter. The seaside vegetation has not attained the height of the maritime forest, thus, it exerted a lesser role in changing the local wind climate. Nevertheless, the seaside grasses and shrubs stabilized the sand sheet, which isolated the dune from a sediment supply, and allowed the parabolic dune to form in a manner similar to that previously described.

In contrast, the Corolla compartment has been the site of the development of large transverse dunes (Figures 25, 26, 27). Here, vegetation growth has been limited to sound side expansion
Figure 20. Legend for Vegetation Maps.
<table>
<thead>
<tr>
<th>Vegetation Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MARSH</td>
<td>Typical brackish/fresh marsh associations</td>
</tr>
<tr>
<td>MARITIME FOREST</td>
<td>Typical pine/oak association generally less than 12 meters in height</td>
</tr>
<tr>
<td>GRASS</td>
<td>Dense cover of grassy vegetation</td>
</tr>
<tr>
<td>GRASS/SHRUB</td>
<td>Scattered shrubs in a grassy area (less than 30% shrubs)</td>
</tr>
<tr>
<td>SHRUB/GRASS</td>
<td>Dense shrubs with interspersed grassy areas (less than 30% grass)</td>
</tr>
<tr>
<td>STABILIZED SAND</td>
<td>Low dunes covered by scattered shrubs, grasses (less than 30% total vegetation, not active)</td>
</tr>
<tr>
<td>EOLIAN FLAT</td>
<td>Area blown out to the water table, pools water after heavy rains, some vegetation</td>
</tr>
<tr>
<td>WATER</td>
<td>Inland body of water, may be natural or dredged</td>
</tr>
<tr>
<td>ACTIVE AREA</td>
<td>Area of migrating dunes, sparse vegetation</td>
</tr>
<tr>
<td>SPOIL</td>
<td>Areas disrupted by construction activities</td>
</tr>
</tbody>
</table>

Legend for Vegetation Maps
Figure 21. 1937 False Cape Vegetation Map.
Figure 22. 1955 False Cape Vegetation Map.
Figure 23. 1963 False Cape Vegetation Map.
of the maritime forest. Vegetation on the oceanside is severely limited and is characterized by large eolian flat areas (Figure 27) in 1975. As a result of the paucity of seaside vegetation, there is still a significant interaction between the beach and the interior. This was discussed by Gutman (1978) who found that transport across an unvegetated eolian flat was much greater than in areas where vegetation had colonized an existing eolian flat. Thus, although there has been expansion of the maritime forest in the Corolla compartment, there has been no concomitant growth of seaside shrubs and grasses.

Vegetation growth in the Penny's Hill compartment has been limited to expansion onto former marsh areas. This is due to the increased elevation on the marsh resulting from eolian deposition. Overwash in this area appears to have been a minor contributor of sediment, since the inland dune ridge (Figure 28, 29) remains intact. Thus, eolian deposition is the major factor in the creation of new subaerial features. This has also been discussed by Jones and Cameron (1977) and Hobbs (in press). Seaward of the interior dune ridge, the compartment has remained nearly unvegetated, a possible result of overwash. No dune evolution has occurred in the compartment with the exception of Penny's Hill, which evolved from a medano into a parabolic dune (see Figure 19).

**Vegetation Expansion**

To quantify changes in vegetated area within each compartment, each vegetation community was planimetered. The results are presented in Table 2.
Figure 25. 1940 Corolla Vegetation Map.
Figure 28. 1955 Pennys Hill Vegetation Map.

A - Interior Dune Ridge
Figure 29. 1975 Pennys Hill Vegetation Map.

A - Interior Dune Ridge
By far, the greatest changes in vegetation areas have occurred in the False Cape Compartment. Here, vegetation has increased from 26.4% of the total area in 1937 to 72.8% in 1975 (excluding marsh). The increase in vegetation has occurred simultaneous with the sand fencing program. Thus, the effectiveness of sand fencing as an aid in dune stabilization appears clear. Although the core of some of the vegetation was due to plantings made in the late 1930's by the CCC, revegetation since that time has been a completely natural process. It appears that sand fencing gave the interior a respite from overwash which allowed for the growth of vegetation. This can be seen more clearly by comparing the changes in vegetation in False Cape to those which occurred in the Penny's Hill Compartment.

In the Penny's Hill Compartment, total vegetated area has increased slightly from 20.2% in 1955 to only 23.9% by 1975 (excluding marsh). However, this increase of 3.7% is deceptive since the increase occurred as vegetation colonized topographic highs created on the marsh by eolian deposition. Note that there has been an 8% decrease in marsh area; thus, there has actually been a 4% decrease in vegetation in the interior of this compartment. Since the "Active Zone" has actually increased in area, stabilization is not occurring. It is important to mention here that there is no foredune in this compartment and this may have resulted in frequent overwash.

The Corolla Compartment, has had an increase in total vegetated area from 15.1% in 1940 to 34.0% in 1975 (excluding marsh). This compartment has been sand fenced less than the False Cape Compartment, but has also been overwashed less frequently than has the Penny's Hill Compartment.
Table 2. Changes in the Areas of Vegetation Communities for Each Compartment through Time.
### % of Compartment Covered by Each Vegetative Community

<table>
<thead>
<tr>
<th>COMPARTMENT</th>
<th>ACTIVE AREA</th>
<th>FOREST</th>
<th>GRASS</th>
<th>GRASS-SHRUB</th>
<th>SHRUB-GRASS</th>
<th>EOLIAN FLAT</th>
<th>STABLE SAND</th>
<th>MARSH</th>
<th>SPOIL WATER</th>
</tr>
</thead>
<tbody>
<tr>
<td>COROLLA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1940 YEAR</td>
<td>65.4</td>
<td>0.5</td>
<td>4.7</td>
<td>5.6</td>
<td>5.0</td>
<td>2.5</td>
<td>0.4</td>
<td>15.8</td>
<td>-</td>
</tr>
<tr>
<td>1955</td>
<td>53.3</td>
<td>7.3</td>
<td>5.3</td>
<td>8.5</td>
<td>5.8</td>
<td>3.8</td>
<td>0.8</td>
<td>15.3</td>
<td>-</td>
</tr>
<tr>
<td>1975</td>
<td>41.4</td>
<td>15.6</td>
<td>1.5</td>
<td>4.6</td>
<td>6.0</td>
<td>15.8</td>
<td>0.5</td>
<td>14.5</td>
<td>-</td>
</tr>
<tr>
<td>FALSE CAPE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1937</td>
<td>49.7</td>
<td>16.2</td>
<td>4.0</td>
<td>4.5</td>
<td>0</td>
<td>0.6</td>
<td>1.1</td>
<td>24.0</td>
<td>-</td>
</tr>
<tr>
<td>1955</td>
<td>24.0</td>
<td>25.5</td>
<td>9.1</td>
<td>2.7</td>
<td>0</td>
<td>2.1</td>
<td>12.5</td>
<td>23.7</td>
<td>-</td>
</tr>
<tr>
<td>1963</td>
<td>20.4</td>
<td>27.1</td>
<td>7.2</td>
<td>2.5</td>
<td>6.6</td>
<td>0.4</td>
<td>12.3</td>
<td>23.6</td>
<td>-</td>
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<tr>
<td>1975</td>
<td>5.3</td>
<td>41.0</td>
<td>2.4</td>
<td>12.8</td>
<td>4.1</td>
<td>0</td>
<td>12.5</td>
<td>21.9</td>
<td>-</td>
</tr>
<tr>
<td>PENNY LS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1955</td>
<td>28.3</td>
<td>1.7</td>
<td>13.2</td>
<td>5.2</td>
<td>0</td>
<td>0.1</td>
<td>0</td>
<td>51.5</td>
<td>-</td>
</tr>
<tr>
<td>1975</td>
<td>26.7</td>
<td>9.7</td>
<td>2.1</td>
<td>3.2</td>
<td>2.9</td>
<td>2.3</td>
<td>3.7</td>
<td>43.5</td>
<td>5.7</td>
</tr>
</tbody>
</table>
The formation of a specific dune type is related not only to the quantity of vegetation present, but most important in dune evolution is the location of a specific type of vegetation through time, relative to the dunes. For example, while False Cape and Corolla both exhibit extensive growth of maritime forest on the sound side, only the False Cape Compartment has had a concomitant growth of grasses and shrubs landward of the foredune. Given the spatial and temporal differences in vegetation, the evolution of two different dune types has occurred. In Corolla, where the interior was free to interact with the sediment source, large transverse dunes have formed. This is due to the inability of vegetation to colonize an area subject to constant burial and exposure as sand was deposited or removed by the wind. No foredune was present here to block the supply of sediment from the beach, thus parabolic dunes could not form.

A continuous foredune was created in False Cape, which allowed vegetation to colonize much of the interior. Thus, it appears that vegetation had two functions in aiding parabolic dune evolution. First, the growth of the bayside maritime forest virtually eliminated the important westerly offshore wind component as a factor in dune evolution. As a result, dune formation and evolution was governed primarily by the onshore wind component. Also, the growth of grasses and shrubs immediately landward of the foredune served to eliminate the sand supply to the interior. Although the grasses and shrubs reduced the onshore wind velocities, the onshore wind is of sufficient magnitude to effect the evolution of the interior dunes.
(Gutman, 1978). Thus, vegetation served two purposes; it eliminated the offshore winds as a component in dune evolution and also cut off the interior from its source of sediment.

Therefore, as an essential requisite for parabolic dune formation, vegetation must perform two functions: it must cut off the sand supply, and reduce a normally polymodal wind regime to one that is unimodal. This has happened in the False Cape Compartment.

Discussion

A cursory review of the data presented in Table 2 reveals that the increase in vegetated area has proceeded in a irregular manner. For example, some communities have shown an increase in area since the 1930's while others have declined. However, total vegetated area has increased in the False Cape and Corolla Compartments. This variability in the expansion of individual vegetation communities is due to natural succession and vegetation plantings. However, the role of natural succession cannot be documented due to the limited amount of photography available. For example, grassy communities extant in the 1950's have been colonized by shrubs and trees, resulting in a decrease in the area of grassy communities and an increase in the shrub and forest communities. Furthermore, one cannot account for vegetation plantings. Brown (1959) states that indigenous species were used in the replanting program, thus it is impossible to distinguish planted areas from those that underwent natural colonization by vegetation. For example, Brown (1959) reports that a single plantation was responsible for the planting of 850,000 pine and cedar trees in the late 1940's and early 1950's near the Corolla Compartment.
In other areas, limited plantings were made by the North Carolina Highway Department (Gary Soucie, Audobon Magazine, Personal Communication) to check the migration of specific dunes. Due to the lack of records and poor photographic coverage, areas that were planted cannot easily be separated from those that underwent natural revegetation.

While the initial core of vegetation in some areas is due to plantings, the increase since that time is entirely due to natural processes. Once a foredune was built up and vegetation became established, natural colonization and succession became the dominant method of vegetation expansion.

If the total percent areas of the Grass, Grass/Shrub, Shrub/Grass, Forest, Stabilized Sand, and Eolian Flat Communities within each compartment are plotted against time (Figure 30), a trend for each compartment becomes apparent.

The vegetated area of the False Cape Compartment has consistently increased the fastest, while the Corolla Compartment has exhibited a smaller increase. Penny's Hill, on the other hand, shows a very small increase in vegetated area due to burial of the marsh by eolian deposition and subsequent colonization of the new substrate. This variability is hypothesized to be the result of sand fencing. False Cape, which has been sand fenced almost continuously since the 1930's and exhibited no overwash, has shown the greatest "natural" revegetation while Penny's Hill, overwashed to a much greater extent has exhibited a much smaller increase in vegetation.

Succession Rates

Since it has been shown here that the evolution of dunes on Currituck Spit is dependent on the growth and successful maintenance
of vegetation, it should be possible to assign a timetable to the proposed evolutionary sequence using vegetation succession rates. Unfortunately, few investigators have dealt with succession rates of coastal vegetation, primarily because of the difficulty in observing an area over long periods of time. In the study area, the availability of sequential aerial photography over a long time span (38 years) permitted on analysis of vegetation growth and succession based upon synoptic "snapshots" of the area.

The climax community observed in the study area has been documented by many investigators (Clements, 1928; Wells, 1938; Au, 1970; Boule, 1976; Schroeder et al., 1977) and all have concluded that the climax community is the maritime forest composed primarily of pine and oak. However, with the exception of Boule (1976), none have attempted to delineate the timetable for succession to the climax community.

Boule (1976) used sequential aerial photography to delineate the subaerial growth of Fisherman Island, Virginia, and its subsequent colonization by vegetation. Although he was primarily concerned with the interrelationship of dune morphology and vegetation, he did present a timetable of succession rates. This is presented in Table 3. He found that succession would proceed from a dune-marsh association to a maritime forest in 46 to 95 years, given that environmental factors, such as sediment supply, were consistent during that period of time. Several problems arise, though, when attempting to compare succession rates on Currituck Spit with those observed on Fisherman Island.
Figure 30. Graph of % area Vegetated vs. Time.
% of compartment vegetated (excluding marsh)

Year

1935 40 45 50 55 60 65 70 75

FALSE CAPE

COROLLA

PENNYS HILL
Although the two areas are within 150 kilometres of each other, there are several major differences. Fisherman Island has undergone almost continual accretion since it first formed during the early nineteenth century while Currituck Spit has been migrating landward since it formed several thousand years ago. Furthermore, Fisherman Island has never been sand fenced nor has it undergone any vegetation plantings (Mark Boulé, Shapiro and Associates; Seattle, Washington, Personal Communication). Also, Currituck Spit lies in the southern zone of coastal vegetation whereas Fisherman Island lies in the northern zone (Boule, 1976). This results in the climax community being somewhat different; in the case of Currituck Spit it is a pine-oak association whereas on Fisherman Island it is a pine-sassafras-cherry association. This may result in different succession rates.

In order to alleviate the problems caused by comparing two dissimilar areas, a small area within the False Cape Compartment was mapped to show vegetation changes. Since much of the area was originally planted, it was difficult to find an area which had been naturally colonized by vegetation. However, based upon field visits and analysis of the aerial photography, it was determined that a site approximately 5 km NW of the Virginia-North Carolina state line had not been planted since the late 1930's. Community boundaries at this site were accurately mapped (boundaries within ± 10 metres).

Since only four dates of imagery were available, succession rates measured here represent only approximations. Boule (1976) had nine sets of imagery upon which to base his succession rates; as a result he was better able to document the actual mechanism of succession.
In this study, the main emphasis was on imposing a timetable to the evolutionary sequence.

The maps are presented as Figures 31A, B, C, D and show the influence of sand fencing. Prior to sand fencing, much of the area was covered by a barren sand sheet (Figure 31A), with occasional medanos. At Site A in 1955 (Figure 31B), grasses had colonized the area immediately landward of the foredune. By 1963 (Figure 31C), shrubs had moved in and by 1975 (Figure 31D), the area had been stabilized by a dense cover of shrubs and grasses. Although the initial source of the grass was vegetation plantings made in the 1930's, no plantings have been undertaken since that time. This gives a time for succession from Grass to Shrubs of approximately 20 years.

At Site B (Figure 31A) in 1937, grass was already present. By 1955 (Figure 31B), this area was occupied by a Grass/Shrub community, giving a time of 18 years for succession from a Grass to Grass/Shrub community. Between 1955, 1963, and 1975 (Figures 31C and 31D), the area was colonized by a maritime forest whose present height is approximately 8 metres. Thus, succession from grass to maritime forest has occurred within 38 years. These data are also included in Table 3.

If one can assume that these rates are representative for the entire Currituck Spit, then it is possible to hypothesize that the evolution of parabolic dunes can occur at any site, given the necessary growth of vegetation, within 40 years.

Discussion

Although maritime forest became established at Site B within 40 years, the assumption that it will occur at all points along Currituck Spit is not supported here. For example, there is hori-
Figure 31. False Cape Compartment Vegetation Succession Map.
zontal and vertical zonation caused by a multitude of physical and biological factors (i.e., salt spray, wind pruning, sand burial, depth of the fresh water table, nutrient limitations, biological competition), as has been discussed by many investigators (Wells, 1938; Clements, 1929; Oosting and Billings, 1942; Oosting, 1954; Au, 1970; Boule, 1976; Levy, 1976). Therefore, it does not follow from the data that a maritime forest will necessarily invade and succeed at Site A. Vegetation communities at Site A may be subject to entirely different stresses than those at Site B, which is located 500 metres further inland. The only conclusion that can be drawn from the data presented here is that a maritime forest may succeed in an area within 40 years, given that environmental conditions are conducive to its growth and maintenance.

An implicit controlling factor of succession on Currituck Spit has been the presence or absence of a foredune. The foredune inhibits the transport of salt spray and sand into the interior. Thus, if there is no foredune, a maritime forest may not be present due to its inability to withstand large amounts of salt spray and sand burial. Moreover, local physiographic changes affect the successional relationships. In the Penny's Hill Compartment, maritime forest is not present seaward of the interior dune ridge, while there has been active expansion in the lee of the unbroken interior dune ridge. Yet, due to a local increase in vegetation caused by sand fencing, Penny's Hill was transformed from a medano into a parabolic dune.

The paucity of succession rate data is due to the inability to monitor an area over long periods of time. However, similarly obtained data for Fisherman Island, Virginia Boule (1976) agree
Table 3. Vegetation Succession Rates.
### VEGETATION SUCCESSION RATES

1. **Fisherman Island, Va. (Boulé, 1976)**

<table>
<thead>
<tr>
<th>Event</th>
<th>Time Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Establishment of Dune-Marsh Community</td>
<td>1-5 Years</td>
</tr>
<tr>
<td>Invasion of Dune-Marsh by Bayberry</td>
<td>5-10 &quot;</td>
</tr>
<tr>
<td>Maturity of Bayberry Thicket</td>
<td>10-20 &quot;</td>
</tr>
<tr>
<td>Invasion of Bayberry Thicket by Hardwoods</td>
<td>10-20 &quot;</td>
</tr>
<tr>
<td>Maturity of Woodland</td>
<td>20-40 &quot;</td>
</tr>
<tr>
<td>Dune-Marsh to Mature Woodland</td>
<td>46-95 Years</td>
</tr>
</tbody>
</table>

2. **Currituck Spit (This Study)**

<table>
<thead>
<tr>
<th>Event</th>
<th>Time Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grass to Shrubs</td>
<td>&lt;20 Years</td>
</tr>
<tr>
<td>Shrub to Forest</td>
<td>&lt;20 &quot;</td>
</tr>
<tr>
<td>Grass to Forest</td>
<td>&lt;38 &quot;</td>
</tr>
<tr>
<td>Sparse Grass to Maritime Forest</td>
<td>&lt;38 Years</td>
</tr>
</tbody>
</table>
reasonably well with the sparse data available for Currituck Spit. Since there were no vegetation plantings on Fisherman Island, Boule's (1976) data may be considered indicative of succession rates which might have occurred on Currituck Spit had there been no sand fencing program. As such, they probably represent a maximum for the study area. Thus, the formation of parabolic dunes as proposed earlier can be carried to completion in 30 to 50 years, if sand fencing and vegetation are used concomitantly to create a foredune.
DISCUSSION AND CONCLUSIONS

The evolution of a parabolic dune from a medano has been documented in previous chapters. However, a mechanism for the origin of a medano has not been discussed. This is due to the absence of aerial photography which showed the formation of a medano. Although data are lacking, one can hypothesize how a medano might form.

Given that a large supply of sediment was available on the original sand sheet, the polymodal wind regime would tend to pile sand up from many directions. The nucleus of the medano could be related to any surface roughness element, from the carcass of a dead animal to an isolated shrub which survived on the sand sheet. The formation of dunes around obstacles has been extensively discussed (Bagnold, 1942; Zenkovitch, 1967) and reviewed in Goldsmith (1978). Thus, in an area with a large supply of sand in all directions, a polymodal wind would pile sand into a somewhat circular mound. As the medano grew, it would create a wind shadow resulting in further deposition as sand was deposited in the lee side of the dune. This can be seen in the early imagery of False Cape, Corolla and Penny's Hill (Figures 3, 7, 10) where a blowout area surrounds each medano. There is a problem, though, when attempting to relate the height of a particular medano to a single parameter.

Tsoar (1978) has devised a theoretical model which states that desert dunes made up of fine sand will grow higher than dunes made of coarse sand. Thus, one might expect to relate dune height
to grain size. A problem arises, though, because dunes of the same grain size are not strictly comparable in height. For example, Lewark's Hill, a 25 m high medano, has nearly the same grain size distribution as Jockey Ridge, which is nearly 50 m high. Also, transverse dunes, which form from the medanos are much lower in height (~12 m) yet possess the same grain size distribution as the original medano. Furthermore, Wilson (1972, 1973) has found that desert dunes made of coarse sand are usually higher than fine grained dunes. Clearly, the regulation of dune height strictly by grain size does not apply here.

Since medano height was nearly uniform within the study area, it appears that there is some controlling factor at work. This factor may be depth of the fresh water table. Since water-saturated sand is difficult to erode, areas with a high water table may have lower medanos than areas with a low water table. In the 1937 imagery of False Cape (Figure 8) the medanos are surrounded by an area blown out to the water table. Ultimately, depth to the water table would regulate sediment supply. For example Jockey Ridge, which has a large sediment source area above the water table (i.e., relic dune ridges) is much higher than Lewark's Hill, which has a high water table. Undoubtedly, other factors also contribute to the regulation of medano height, but the solution of this problem is beyond the scope of this thesis.

Parabolic and transverse dunes form because of the effects of adjacent vegetation, which act not only to control sediment supply, but also to change the local wind climate. Parabolic dunes, as shown previously, form when vegetation transforms a normally polymodal wind regime into one that is unimodal. In the case of Penny's Hill,
it was shown that the maritime forest which grew up on the western side of Currituck Spit effectively negated the westerly winds and allowed the onshore winds to assume dominance. Concomitant with the growth of the maritime forest was an increase in grasses and shrubs seaward of the parabolic dune. This effectively cut off the sediment supply and allowed the dune to form similar to a sequence originally proposed by Landsberg (1956, Figure 17).

In the case of transverse dunes, maritime forest serves to diminish the westerly winds, and, as in the case of parabolic dunes, the onshore winds become dominant. However, seaward of the transverse dunes there has been no concomitant growth of grasses and shrubs. As a result, the transverse dunes remain attached to their source of sediment. In the Corolla Compartment, the transverse dunes have built up to the height of the downwind maritime forest, and are actively migrating over the forest at a rate of from 6 to 12 m per year. It appears that the onshore winds transport sand toward the forest where it forms an obstacle dune (i.e., this obstacle being the forest) which grows higher with time. Once the dune exceeds the height of the adjacent forest, the westerly winds blow sand back onto the eolian flat areas. Onshore winds blow sand onto the dune and over the slipface, thus, the height of a transverse dune is regulated by the height of the adjacent forest. Migration occurs as sand is transported over the slipface and deposited on the floor of the forest. Once sand has been transported over the slipface it cannot be blown back onto the dune, which results in the migration of the dune over the forest.

Since the only major difference between parabolic and transverse dune formation was the growth of vegetation seaward of
The dune, it can be concluded that vegetation is the main factor responsible for the evolution of a specific dune type.

The evolutionary sequence is summarized in Figure 32, which also shows the approximate time frame for dune evolution and the stage of each compartment in 1975.

The differences in vegetation and resulting dune evolution may be due to differing amounts of overwash and sand fencing. Overwash destroys vegetation either by burial or by exposure to salt water. Thus, in an area where there is no foredune to prevent overwash, dune evolution may be retarded.

Figure 33 is taken from Boc and Langfelder (1977) and summarizes the recent history of overwash along Currituck Spit. Note that the Penny's Hill compartment exhibits the highest frequency of overwash while the Corolla compartment has been overwashed to a lesser extent. Boc and Langfelder (1977) did not study the False Cape compartment. However, an analysis of available aerial photography revealed that virtually no overwash has occurred there since the initiation of the sand fencing program in the late 1930's.

Figure 34 summarizes the history of sand fencing in the study area, as delineated from the aerial photography. This shows that False Cape has had nearly continuous sand fencing since the late 1930's while the other compartments have been sand fenced to a lesser extent. Thus, there appears to be an inverse relationship between sand fencing and overwash. However, other factors may determine whether or not an area is subject to overwash. Nearshore submarine topography may influence wave refraction, resulting in convergence or divergence of wave rays (Fisher et al., 1975). While
Figure 32. Observed Dune Evolution Sequences on Currituck Spit.
PRESENT (1978) STAGE

PENNY'S HILL COMPARTMENT STAGE 1-2
COROLLA COMPARTMENT STAGE 3
FALSE CAPE COMPARTMENT STAGE 4

TEMPORAL DEVELOPMENT

STAGE 1 → STAGE 3 ~ 25 YEARS
STAGE 1 → STAGE 4 ~ 40 YEARS
Figure 33. Overwash History on Currituck Spit.  
(From Boc and Langfelder, 1977)
no attempt has been made to relate wave refraction to overwash in this area, the presence of a foredune does prevent overwash during minor storms (Hosier and Cleary, 1977; Schroeder et al., 1977). Since major storms have been rare for the past 16 years, sand fencing may have been the most important factor in reducing the frequency of overwash in the False Cape and Corolla compartments. Unfortunately, the exact relationship between overwash, sand fencing and vegetation cannot be quantified here.

Dune evolution on Currituck Spit has been the direct result of the growth and expansion of vegetation. Vegetation serves to regulate sediment supply and also to alter the local wind climate. Thus, it appears that vegetation is the most important factor in dune evolution. While vegetation is the most important factor in dune evolution, overwash frequency regulates the growth of vegetation. On Currituck Spit, sand fencing was used to create a protective foredune in some areas which allowed vegetation to colonize the interior by reducing overwash. Additionally, the low frequency of major storms over the last 15 years may have also been a factor in the growth and expansion of vegetation.

It appears that overwash on Currituck Spit was the result of devegetation rather than the cause. Early settlers removed forest and grazing animals removed the remaining vegetation. This resulted in the formation of a low, barren sand sheet which was susceptible to overwash even during minor storms. As a foredune was created in some areas, the frequency of overwash diminished. This allowed vegetation to recolonize and restabilize the interior of the Spit. The resulting differential growth of vegetation along Currituck
Spit has resulted in the formation of three different dune types. Medanos form when there is a complete lack of vegetation, in an area with a polymodal wind regime (which is common in coastal areas). Transverse dunes form when maritime forest increases sufficiently in height to allow wind from one quadrant to become dominant. Also, the dune remains attached to a source of sediment due to the absence of upwind vegetation.

Parabolic dunes also form when maritime forest increases in height and the local wind regime becomes unimodal. However, sediment supply is cut off by the growth of upwind vegetation.

Vegetation on Currituck Spit has also undergone many changes. As revealed in Appendix A, it appears that Currituck Spit was originally well vegetated. Vegetation was destroyed and this resulted in the creation of a barren sand sheet by the mid-nineteenth century. This condition persisted until the mid-1930's when sand fencing was used to create a foredune, and vegetation was planted on the Spit. Since that time, vegetation has rapidly increased in density and area. In those areas where sand fencing was maintained, vegetation has expanded to a much greater extent than in those areas which were not sand fenced. In light of the early history of Currituck Spit, it appears that the recent increase in vegetation is not abnormal and, indeed, represents a return to the original conditions which existed on Currituck Spit.
REFERENCES


THE EARLY HISTORY OF CURRITUCK SPIT (1585-1945)

References to the Outer Banks are as old as the European in North America. In fact, the first attempt at an English colony in North America was undertaken by Sir Walter Raleigh at Roanoke during the late 1580's. The colony was a failure, the only clue to its disappearance was the word "CROATAN" carved on a post (White, 1590). Subsequently, colonies were established along this area, and for the next one hundred and fifty years the Outer Banks played an important part in the history of Virginia and the Carolinas (Dunbar, 1958).

The boundary between Virginia and Carolina was long disputed and arose from the charter of King George II, dated March 24, 1663 (Boyd, 1967). A line was to be run, according to the charter, from the north side of Coratuck Inlet (known now as Old Currituck Inlet) west to Weyanoke Creek and thence through the Dismal Swamp. Unfortunately, no one at that time knew the exact location of Weyanoke Creek. Therefore, the governors of both colonies agreed to end the controversy by forming a joint commission to determine the true boundary line. Fortunately, the surveying of the boundary line was recorded by Col. William Byrd in "The History of the Dividing Line" written in 1728. The following is from Byrd:
... It was just Noon before we arrived at Coratuck Inlet, which is now so shallow that the Breakers fly over it with a horrible Sound, and at the same time afford a very wild Prospect. On the north side of the Inlet, the High Land terminated in a Bluff Point, from which a Spit of Sand Extended itself towards the South-East, full half a Mile. The Inlet lies between that Spit and another on the South of it, leaving an Opening of not quite a Mile, which at this day is not practicable for any Vessel whatsoever. And as shallow as it now is, it continues to fill up more and more, both the Wind and Waves rolling in the Sands from the Eastern Shoals.

However, that we who were punctual might not spend our precious time unprofitably, we took several bearings of the Coast. We also surveyed part of the Adjacent High Land, which had scarcely any Trees growing upon it, but Cedars. Among the Shrubs, we were shewed here and there a Bush of Carolina-Tea called Japon, which is one Species of the Phylarea. This is an Evergreen, the Leaves whereof have some resemblance to Tea, but differ very widely both in Tast and Flavour.

We also found some few Plants of the Spiked Leaf Silk grass, which is likewise an Evergreen, bearing on a lofty Stem a large Cluster of Flowers of a Pale Yellow. Of the Leaves of this Plant the People therabouts twist very strong Cordage. A virtuoso might divert himself here very well ...

... At Noon, having a Perfect Observation, we found the Latitude of Coratuck Inlet to be 36 Degrees and 31 Minutes.

Whilst we were busied about these Necessary Matters, our Skipper row'd to an Oyster Bank just by, and loaded his Periauga with Oysters as Savoury and well-tasted as those from Colchester of Walfleet, and had the advantage of them, too, by being much larger and flatter.

About 3 in the Afternoon the two lagg Commissioners arriv'd, and after a few decent excuses for making us wait, told us they were ready to enter upon Business as soon as we pleas'd. The first Step was to produce our respective Powers, and the Commission from each Governor was distinctly read, and Copies of them interchangeably deliver'd.

It was observ'd by our Carolina Friends, that the Latter Part of the Virginia Commission had something in it a little too lordly and Positive. In answer to which we told them twas necessary to make it thus peremptory, lest the present Commissioners might go upon as fruitless an Errand as their Predecessors. The former Commissioners were ty'd down to Act in Exact Conjunction with those of Carolina, and so could not advance one Step farther, or one Jot faster, than they were pleas'd to permit them.

1Note Byrd's reference to HEMP
The Memory of that disappointment, therefore, induc'd the Government of Virginia to give fuller Powers to the present Commissioners, by Authorizing them to go on with the Work by Themselves, in Case those of Carolina should prove unreasonable, and refuse to join with them in carrying the business to Execution. And all this was done lest His Majesty's gracious Intention should be frustrated a Second time.

After both Commissions were considered, the first Question was, where the Dividing Line was to begin. This begat a Warm debate; the Virginia Commissioners contending, with a great deal of Reason, to begin at the End of the Spitt of Sand, which was undoubtedly the North Shore of Coratuck Inlet. But those of Carolina insisted Strenuously, that the Point of High Land ought rather to be the Place of Beginning, because that was fixt and certain, whereas the Spitt of Sand was ever Shifting, and did actually run out farther now than formerly. The Contest lasted some Hours, with great Vehemence, neither Party receding from their Opinion that Night. But next Morning, Mr. M. ......, to convince us he was not that Obstinate Person he had been represented, yielded to our Reasons, and found Means to bring over his Colleagues.

Here we began already to reap the Benefit of those Peremptory Words in our Commission, which in truth added some Weight to our Reasons. Nevertheless, because positive proof was made by the Oaths of two Credible Witnesses, that the Spitt of Sand had advanced 200 Yards towards the Inlet since the Controversy first began,\(^2\) we were willing for Peacesake to make them that allowance. Accordingly we fixed our Beginning about that Distance North of the Inlet, and there Ordered a Cedar-Post to be driven deep into the Sand for our beginning. While we continued here, we were told that on the South Shore, not far from the Inlet, dwelt a Marooner, that Modestly call'd himself a Hermit, tho' he forfeited that Name by Suffering a wanton Female to cohabit with Him.

His Habitation was a Bower, cover'd with Bark after the Indian Fashion, which in that mild Situation protected him pretty well from the Weather. Like the Ravens, he neither plow'd nor sow'd but Subsisted chiefly upon Oysters, which his Handmaid made a Shift to gather from the Adjacent Rocks. Sometimes, too, for Change of Dyet, he sent her to drive up the Neighbour's Cows, to moisten their Mouths with a little Milk. But as for raiment, he depended mostly upon his Length of Beard, and She

\(^2\)Note that the inlet had migrated 200 yards south in less than 16 years (Boyd, 1967). This southerly migration is typical of inlets in the area.
upon her Length of Hair, part of which she brought
decently forward, and the rest dangled behind quite down
to her Rump, like one of Herodotus's East Indian
Pigmies.

Thus did these Wretches live in a dirty State of
Nature, and were mere Adamites, Innocence only excepted.

This Morning the Surveyors began to run the
Dividing line from the Cedar-Post we had driven into
the Sand, allowing near 3 Degrees for the Variation.
Without making this Just allowance, we should not have
obeyed his Majesty's order in running a Due West Line.
It seems the former Commissioners had not been so exact,
which gave our Friends of Carolina but too just an
Exception to their Proceedings.

The Line cut Dosier's Island, consisting only of
a Flat Sand, with here and there an humble Shrub
growing upon it. From thence it cross over a narrow
Arm of the Sound into Knot's Island, and there Split
a Plantation belonging to William Harding.

We also saw a small New England Sloop riding in
the Sound, a little to the south of our course. She
had come in at the New Inlet as all other vessels
have done since the opening of it. The Navigation
is a little difficult and fit only for vessels that draw
no more than ten feet Water ...

Sharpe (1961) remarks that the port of Currituck was one
of the five original parts of the colony and discussed its' early
history. In 1726, the General Assembly appropriated funds to mark
the entrance to New Currituck Inlet. By 1731, the Inlet was shoaling
and in 1761 efforts were made to improve it. By the time of the
Revolutionary War, traffic to the Port of Currituck was faltering,
though even as late as 1786, 194 schooners, 43 sloops and 5 brigs
entered through the Inlet. The Inlet finally closed in 1828, possibly
buried in part by one of the medanos (i.e., sand hills) in the area,
as this excerpt from Fletcher and Guild (1947) suggests:

"... Many years ago there was an inlet to the north,
of Corolla and the water of the sound was salt. Then a
great dune, probably Lewark Hill itself, had a part in
closing the inlet, and the water turned fresh ..."

3 New Currituck Inlet. Note that it too was wide and
shallow.
The completion of the Dismal Swamp Canal in 1805 may have also played a role in the closing of New Currituck Inlet as this excerpt from Brown (1970) implies:

"... Apart from commercial jealously, the company also had its share of litigation over damaged mills, flooded lands, and so forth. The principle objection lodged against it, however, stemmed from the drastic change in the entire drainage pattern of the east side of the Dismal Swamp. Water which normally would have seeped through this area was diverted into the canal and found its way out at the ends. This caused a desiccation of the land on the east side and a corresponding impounding and flooding on the west. In 1828, the narrow 3 1/2-foot deep inlet from the Atlantic into Currituck Sound became bar-bound and it eventually closed entirely. This was said to be the direct result of the diversion of the water from the streams which had emptied into the sound and kept the inlet upon. With less water to discharge, ocean waves blocked the passage with sand and, once this arm to the sea was closed, Currituck Sound gradually became entirely fresh and so spoiled the once prosperous oyster beds and salt water fishing industry of the area and necessitated a complete reorientation of the commerce of the region. A plan was made immediately to reopen the inlet and improve it, but apparently nothing ever came of this ..."

After 1828, Currituck was no longer a port of entry into the Carolinas. The effects of this closure on determining the subsequent cultural history of Currituck County are still evident today (Massey, 1971). Farming, fishing and hunting support approximately 85% of the population (Sharpe, 1961) and in 300 years the county has not developed an incorporated town, or a community of more than 500 people. Population of the county is less than it was 150 years ago; in brief, it remains a depressed area, a testimony to the important role of inlets, and specifically to the importance of New Currituck Inlet in the early growth of Carolina.

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4This earlier eastward drainage of the Dismal Swamp has been verified by Lichtler and Walker (1974).

5New Currituck Inlet.
Our next glimpse of the Banks comes from Henry Beasley Ansel, who wrote "Recollections of My Boyhood on Knotts Island" (Unpublished) in the early 1900's. While dealing primarily with Knotts Island, one portion in particular described the Banks. The following is his eyewitness description of "The Great Storms of 1846";

"... Along the greater part of the North Carolina coast runs a narrow strip of land, beach, sand hills and marsh, that separates the ocean from the sounds and serves as a kind of breakwater between the ocean on one side and the beautiful sounds, the low lying islands in them, and the mainland on the other.

This narrow strip is commonly called The Banks, probably because of its enormous banks or lofty dunes of pure sand. Though sparsely inhabited, in places it contains a goodly number of people. Knotts Island is thus protected from the plunging Atlantic by a narrow bay and The Banks which are between the island and the ocean a mile or so to the eastward.

The people living on the mainland of the island did not know what had taken place on its water fronts, but the news flew that the Atlantic was now breaking on the island shores. I with others went down to the bay side. Such a sight had never been seen before. No marsh, no beach. The tops of a few mountainous sand hills were all that could be seen.

The great salt waves were beating, pounding and breaking at our feet. Nothing of land ocean-ward was visible except the tree tops of Wash Woods and Freshpond Island and the tops of the larger sand hills. The ocean ebbed and flowed on the island shore. High water must have been from eight to 10 feet higher than normal. Nearly everything was submerged.

It was not long before a score of people were gathered with us each lamenting the calamitous situation. Hogs, cattle and sheep on marshes, beach and low lands all gone, all fences blown flat, all water fences washed away. Everything, including the dead animals had been carried down the sound .... The seriousness of it all was apparent ....

.... Before this storm the beach opposite Knotts Island consisted of lofty sand hills and high sand ridges. These had in greater part accumulated since the War of 1812. This I learned from the following facts: The tides of these storms cut these hills and ridges away and in their stead, at a certain point on
the beach, appeared to the great wonder of the young, a large thicket of dead cedars whose gigantic arms stretched heavenward.

Uncle Johnny Beasley knew all about these cedars for he had boiled salt under these trees in the War of 1812 and their thick foliage had screened him and others from the view of the British as they passed up and down the coast. I believe the salt water from the sea was hauled to this place to make the salt—a slow process.

He said he had left three of his kettles there where they had sanded up with the trees and now he could get them. He got a crew, I with them, and went over. He pointed out the old stooped cedar under which he had once sat, and boiled salt underneath. He pointed out the place where he had left the kettles.

Digging down just below the surface they found two of them but the third one was never found. These kettles were three by six feet and about 10 inches deep. Uncle Johnny carried them home after they had been sanded over for 30 years. These cedars were dug up, cut and split for vessel timbers and for that purpose were sold to Wallis Bray and B. T. Simmons.6

.... But Nature had not wreaked full vengeance on the Island. In September of the same year another storm set in, I believe on the 8th day of that month. It blew harder than the previous March storm and it would have done the same damage if its predecessor had left anything to damage. The few cattle and hogs that the people had gotten together from elsewhere during the summer were away as before. This storm, it was said, blew with even greater force than the first one; but since the wind ranged farther north, the tide lacked two feet of being as high as in the former storm. Then, too, the former storm was at spring-tide, the latter neap tide. This September storm had the same staying quality as the former. The sound and bays, normally fresh, kept salt for many years ..."

Sometime during the period from 1800-1860, extensive logging of the maritime forest was undertaken. Large areas of forest adjacent to the beach were cut down, leaving bare sand which was susceptible to the winds. Shortly thereafter large sand waves began migrating across the island. While there has been some debate over whether the Outer Banks were originally forested, the extensive stumps present on the beach between False Cape and Corolla are ample evidence.

6Cedar stumps, cut by man, are now found in the surf zone.
Pinchot and Ashe (1897) also commented on the controversy:

"... The maritime forests extending northeast and southwest along the entire coast-line, rise from high-water mark, cover the narrow islands, the so-called banks skirting the coast, and on the mainland extend inland for a short distance ...

The growth of the original forest where it is yet preserved is from 40 to 60 feet in height, the trees short-boled, the crowns large and spreading, interlaced into a dense canopy. Water oak, laurel oak, live oak, red cedar, smooth sweet bay, holly, and mock-orange, in relative abundance about in the order named, constitute from one-half to over three-fourths of the growth. Where culling has been carried on occasional loblolly pines have gained a foot-hold, or abundant-seeding species like yaupon, red cedar and the laurel oak have greatly multiplied.

Beginning at the Virginia line and passing to the south, there is a constant increase in the number of species present, so that while only a few species are represented beyond the Albermarle sound the number reaches a maximum in this State at and around the mouth of the Cape Fear river, where at least two species find their northern limits. These enables the maritime forests to be roughly separated into two divisions: one lying to the north of Cape Hatteras, which point may be considered to mark the division between the two; and the other to the south of this cape. In the northern division, water oak and live oak, and red cedar form nearly the entire arborescent growth; ...

Probably not over one-half of the area is wooded; the remaining portion is naked, only a small part of it being under cultivation. In places along the coastal islands, and this is particularly true to the north of Cape Hatteras, there are great stretches destitute of all tree growth, the soil being a coarse beach-sand, the surface of which rises into parallel ridges which reach a height, in places, of 70 or more feet above sea level; and this sand, being fixed by no network of plant root-fibers, and containing no binding ingredient, is constantly shifting under the impact of the winds. Some such areas were originally forest-covered, but once cleared, and the humus, which was slightly cohesive, destroyed, the constant movement of the sand before the winds, which have piled it into shifting dunes, has prevented a general growth of any kind from securing a foothold. Fishermen's houses have been destroyed by these moving dunes and their sites obliterated, and others are manaced by them. Con-
siderable areas of forest have been destroyed by the roots of trees being deeply covered with sand or the entire forest buried, thus increasing the extent of the shifting dunes. Occasional clumps of prickly ash and devilwood, which put forth adventitious roots from the young twigs as they are partly covered by the sand, or thickets of shrubby live oak, plum, and shrubs which sucker freely, maintain themselves in some places for many years. All oaks, except the youngest, are killed by such moving dunes. Red cedar, holly, palmetto, mock-orange and myrtle, not rooting from the young wood are quickly destroyed by the covering of sand.

Commerically these forests are unimportant except where they produce, on some of the islands, a limited number of red cedar posts. Their protection is worthy of consideration, however, as they act as a safeguard in preventing the formation of inlets which would impair existing water ways ..."

The following excerpts from Cobb (1906) document the effect of logging:

"... This movement of the sand was started just after the Civil War by the cutting of trees next the shore for ship timbers, and the section is still known as The Great Woods, though not a stick of timber stands upon it today. Pamlico Sound for two miles from the Hatteras shore is growing steadily shallower from the deposit of blown sand ...

As already pointed out, the movement of these sands was in every case started by the deforesting of a strip of land next the shore... On Currituck below Coffey's Inlet Life Saving Station, the sand has advanced completely across the island, and one man, moving before the advancing sand has at last built his house on piles in the Sound ...

Another excerpt from Spears (1890) describes the same set of events:

"... As was said, the whole island was covered with a great forest years ago. It was in the thickest parts of woods, but nearly always near the Sound, that the people built their homes ....

... A distance of over forty miles, was almost completely covered with a prodigious growth of trees, among which live-oak and cedar were chief in size and number ...

The population was sparse then, but it has been increasing in such ratio as families of from nine to nineteen children may give. The people then, as now, were of simple habits, living on corn-meal, fish, oysters, pork, and tea made from the leaves of the yapon shrub: but they had to have a little money for clothing and tobacco. To obtain this they cut and sold the live-oak and the cedar.
Thus it happened that spaces along the seaside of the island were denuded by the axe, and then burned over by the fires the fishermen built when the bluefish and the mackerel came swarming into the beach. In time, and especially during the great demand for live-oak, for Yankee clippers, just before the war, these spaces were enlarged, until at last there was a permanent widening of the whole beach north of the cape.

It was then that the northeast wind, on a bright day, picked up the sand just beyond the edge of the surf, and tossed it back inland in a fine spray, when it fell down, at the feet of the laurel, and the young cedar, and the young live-oak and the pine, and the yapon. With each fine day the pile of sand in the shrubbery grew, until the shrubbery withered under the breath that fanned it, and finally died. Where the green trees had stood in a sandy loam, a sand-ridge arose, which receiving the breath of the northeast gale, started on a mission of death ..."

At about this time grazing took on major importance as this excerpt from Gibbs and Nash (1961) states:

"... Less than a hundred years ago the Outer Banks were covered with trees, shrubs, vines, grasses, and other types of vegetation from the sound almost to the edge of the ocean. Live oak, water oak, dogwood, pine, sycamore, pellitory, holly, persimmon, yaupon, and mulberry were the principal types of trees, growing so thick that one could go from tree to tree on the interlacing vines for a distance of one-half mile or more without touching the ground.

At that time the inhabitants were primarily engaged in fishing and stock raising; small horses known as banker ponies, cattle, sheep, goats, and hoggs were all raised in the area. Originally the stock was kept in fenced enclosures and marsh grass was harvested to feed them during the winter months. As the population increased, the stock increased, fences were abandoned and soon the grasses and other vegetation began to disappear, leaving vast areas barren of all types of vegetation (a familiar cycle that has been repeated in many other areas). First, horses, then cattle, then sheep, then goats, until grasses and shrubs were gone. Then followed the hogs that dug up the remaining roots. Can you imagine a more pitiful situation, especially in an area so fragile as the thin sand barrier of the Outer Banks?

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7The Civil War.
8Cape Hatteras.
As time went on, the accumulation of sand from the beaches was blown across the barren areas and the vegetation not destroyed by overgrazing was covered up with drifting sand. Since most of the people were engaged in fishing, trees were used in the construction of fishing vessels, others were used for constructing buildings, and many others for firewood. So that eventually all of the sturdy trees, with the exception of a few left around the homes, were used up or swallowed up by the moving sands. As a result, the storm tides began to wash across the barren beaches from the ocean to the sound ...

Stratton (1943) provides a similar description:

"... Overgrazing became one of the major causes in the transformation of the area. The grass and shrubs having been uprooted by hogs and the vegetation having been destroyed by woodsmen, or other lumber interests, or by the cattle and ponies, the sands became susceptible to every wind and tide. This condition, together with the occasional very dry seasons in eastern North Carolina, did much to change the physical condition of the area. The inlets to the salt water sounds became partially closed and in some instances were closed, resulting in serious damage to the salt water fishing industry. The blowing sand resulted in a decrease of elevation of the Banks, causing the ocean tides to flow over into the sounds. The salt water that flowed over into Currituck Sound which had always been a fresh water sound, destroyed not only the food for the millions of migratory water fowl that wintered there, but also ended the fresh water fishing industry, which was a lucrative business to the residents of that section. Thus, a one time haven of rest and beauty had been changed to a barren beach subject to the ravages of sand, water, and wind ..."

Engels (1942), in describing the vertebrate fauna of Ocracoke Island, had this to say about the effects of grazing:

"... It cannot be doubted, however, that human activity has contributed to and hastened the progress of this natural process of change. In a fenced area of several acres near the Knoll, protected from the ponies and the cattle, the thickets are notably denser than elsewhere, and here one frequently sees sapling red cedars, which are otherwise extremely uncommon on the island ...

---

9This is obviously wrong as Currituck Sound had been a body of salt water prior to the closure of New Currituck Inlet in 1828.
Oosting and Billings (1942), in concluding their work on vegetational zonation or coastal dunes summarized the history of vegetation in a succinct and straightforward manner:

"... The banks paralleling the North Carolina coast are elongate sandy islands once well stabilized by vegetation. Breaks in the cover resulted in blowouts which spread to form extensive dune areas ..."

The importance of overgrazing and logging as the causes of migrating dunes are also mentioned by Epler (1933), Cobb (1906), Spears (1890), Stick (1958).

During the late nineteenth and early twentieth centuries conditions became so bad that entire villages were abandoned due to their burial by moving sand dunes (Gibbs and Nash, 1961; Stratton, 1943). The banks became desolate, grazing diminished and due to the mass emigration from the Banks, the government took action (Stratton, 1943).

"... As far back as 1904, several of the large hunting clubs endeavored to protect their property by carrying out erosion control on a small scale. In 1907 the State of North Carolina called on the United States Forest Service to aid it in saving what little forested areas remained from the moving dunes.

Meanwhile, erosion was taking its toll. The situation had become so acute that in several places along the coast for a distance of three miles or more ordinary high tides were running over the Banks. Residents were fast deserting their homes and moving to other sections of the State ...

In 1934 the Federal Emergency Relief Administration undertook erosion control along several miles of the beach adjacent to Currituck Sound. Because of lack of proper study and methods, high tides in a few months destroyed the entire effort.

In 1935 The Works Progress Administration recruited some 1500 workers, transporting them to the area where operations were started over more than 125 miles of the coast line.

The first major undertaking was to eliminate the flow of ocean water over the Banks. To accomplish this, it was necessary to construct a barrier sand dune along the crown of the beach. If this could
be accomplished, in addition to stopping the overflow from the ocean, it would act as a windbreak to allow transplanting of vegetation in its lee on the sandy flats.

Experiments indicate that if certain types of barriers were placed along the crowns of the beach, nature would build the barrier dunes. Sand fences of all types from wood slats to jute bagging were tried. As there were no materials available along the coast and transportation extremely hazardous and difficult, the idea was conceived to prefabricate sand fences and transport them by trucks and barges to location.

It developed that an ordinary brush panel 8 feet long and 3 feet wide was the most successful type. These were prefabricated inland about 50 miles, where brush was available. It was found that the success of the panel depended on its height and the thickness of the brush. If the panel was too high and too thick, it acted as a windbreak, causing a scouring motion as the base of the panel, digging out the posts to which the panel was fastened, thereby causing it to collapse. If the panel was too low, winds of velocities of 25 miles would carry the sand completely over the fence and was of little value.

A sand fence of the proper height and thickness acted as a partial windbreak, stopping a percentage of the sand at the base of the fence, allowing the balance to go through the brush of the panel, and with the decreasing wind on the other side of the fence, the latter also was deposited on the ground.

When the panel was covered with sand, it resulted in a lineal dune with a very broad base, sloped very much like the natural ocean beach. Thus, the incoming waves during storm and moon tides would roll up on the base of the barrier dune and when their force was spent, rolled back to the ocean. A high fence also caused a slope so steep that the waves instead of rolling up the natural incline would pound at the base and destroy the dune. In some cases it was necessary to build the barrier dune as high as 25 feet above the crown of the beach; in other localities where erosion had not gained as much foothold, only 8 or 9 feet above normal high tide were necessary.

The base of the barrier dune, depending upon its height, was from 40 to 200 feet. The raising and location of the barrier dune could be accomplished by use of additional sand fences erected at the proper location and heights on the already started dune, adding various types of short laterals to hold the collected sand in place. Taking advantage of the prevailing winds and various sand conditions, in approximately 12 months from the beginning of the project, the tides had been stopped from washing over the Banks.
The study of the numerous huge sand dunes along the coast indicated the direction and rate per year of their movement. It was impossible to cover all of the dunes with vegetation and had it been possible, would have ruined their aesthetic value. Again, by experimental work, it was found if the source of supply of sand was cut off, the action of the dune was greatly retarded and in most instances stopped. This was accomplished by transplanting the bases of the dunes and the surrounding sand flats with grasses and shrubs. In several cases where necessary to protect buildings or natural resources, whole sand dunes were moved by drift fences to another location or were combined with another existing dune.

In some places along the coast were shallow inlets which had been cut through to the sounds by ocean tides but were not of value to the fishing industry, or for drainage purposes, and invariably caused transportation difficulties. These inlets were completely closed and the elevation of the beach raised to normal.

Results of the work were evident almost immediately. No longer do the ocean tides flow over the Banks to hinder traveling, wash away the beach, and kill out the vegetation.

The cost of the project ran well over a million dollars. There were many skeptics when the project was undertaken and there are still skeptics as to the ultimate value over a long period of time of the project. Time and time alone will give the answer...

Unfortunately, this condition did not last for long;

"... more details on the hurricane of September 14, 1944, about which I had been hearing all down the Coast. With the barometer falling to 27.97 and the onshore winds blowing, the Sea rose and passed completely across the reef, piling up water in Pamlico Sound and flooding the mainland.

Suddenly the wind decreased in velocity with approach of the storm center; then, increasing again, it blew violently from the opposite direction, and the piled up water from the sound surged back and washed across the reef, meeting the seas coming in from the ocean.

... Much of the extensive grass plantings made in the late '30's has been lost because during the war there was no money or labor for replacing the grass washed out by hurricanes..." (Guild and Fletcher, 1947).
This is reiterated by Gibbs and Nash (1961):

"... With the outbreak of World War II, the emergency dune stabilization program came to a close. During the next fifteen years, much of the fine work accomplished by the emergency works program of the 1930's was lost because of the lack of maintenance. Livestock was still running free on some of the area, and again large areas became barren sand flats where the waves washed across from sea to sound during storm ..."
APPENDIX B

INDEX OF AERIAL PHOTOGRAPHY USED IN THIS STUDY

DATE: August 15, 1937
SCALE: 1:20,000
AGENCY: U.S. Department of Agriculture
FORMAT: 9x9" Black and White Prints
PHOTO ID NOS.:
    FG 140 143 TO FG 140 162

DATE: October 21, 1940
SCALE: 1:24,000
AGENCY: Department of Defense
FORMAT: 9x9" Black and White Prints
PHOTO ID NOS.:
    V1 TO V23

DATE: March 29, 1955
SCALE: 1:20,000
AGENCY: Coast and Geodetic Survey
FORMAT: 9x9" Black and White Prints
PHOTO ID NOS.:
    W5726 TO W5744
    W5667 TO W5696

DATE: September 22, 1961
SCALE: 1:6,000
AGENCY: North Carolina Highway Department
          Raleigh, North Carolina
FORMAT: 9x9" Black and White Prints
PHOTO ID NOS.:
    311, 312, 313

DATE: February 16, 1963
SCALE: 1:16,800
AGENCY: Virginia Department of Highways
          Richmond, Virginia
FORMAT: 9x9" Black and White Prints
PHOTO ID NOS.:
    5-134-110-157 TO 5-134-110-185
DATE: April 17, 1975
SCALE: 1:24,000
AGENCY: NASA Wallops Station
        Wallops Island, Virginia
FORMAT: 9x9" Color Infrared Transparencies
        (Prints Available)
PHOTO ID NOS:
        Roll No. - W3220102
        Frame NOS. - 138-185
APPENDIX C

ACCURACY OF PARALLAX MEASUREMENTS

Since each set of imagery was at a different scale (1955: 1:20,000, 1961: 1:6,000, 1975: 1:24,000), and the final product was intended to be a diagram showing changes in topography through time, the data obtained from the different sets of imagery had to be normalized to a common scale. This was done by superimposing a grid system over the dune in each set of imagery, obtaining parallax measurements, and then drafting the results at a common scale.

The fact that the original imagery were at different scales also affected the accuracy of topographic measurements. In order to determine the accuracy of the measurements, one point on each set of imagery was measured with the parallax bar twenty times, on different occasions, in order to determine the repeatability and hence, the accuracy of the measurements. These results are presented in Table 4. Results indicate that repeatability is within ± .02 millimeter for all measurements. However, the actual error is different for each imagery set due to differences in scale. Each millimeter of differential parallax represents a different measurement of height depending on the scale (1 mm at 1:20,000 = 36.3 m; 1 mm at 1:6,000 = 10.2 m; 1 mm at 1:24,000 = 43.1 m). For example, at a scale of 1:6,000 the error of height measurement was ± 0.2 metre; at 1:20,000 the error was ± 0.7 metre and at 1:24,000 the error was ± 0.9 metre.
Another factor which influenced the accuracy of measurements was operator fatigue. Operator fatigue was recognized as a factor in the early stages of data collection, as repeatability of parallax measurements declined after approximately three hours of continuous data collection. This problem was identified by taking multiple readings of each data point. Each data point was measured at least five times and the average was used in computing height. After more than three hours, the accuracy of the parallax measurements was noticeably reduced, thus, data were collected in two-hour sessions.
Table 4. Accuracy of Parallax Measurements.
# Accuracy of Parallax Measurements

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<th>1975</th>
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VITA

Harold F. Hennigar, Jr.