A Guide to Sand Dune and Coastal Ecosystem Functional Relationships
Michigan State University Extension Service

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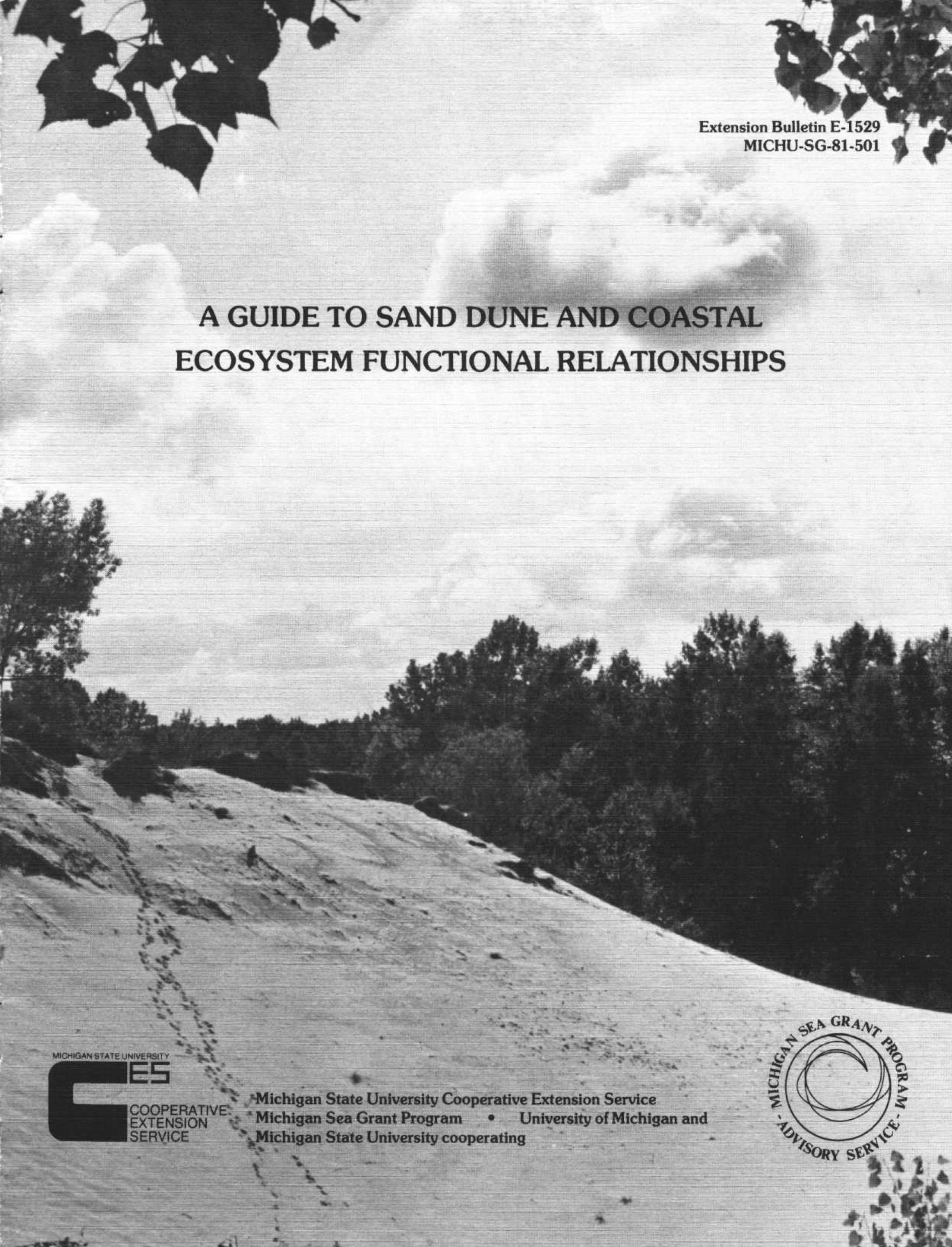

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A GUIDE TO SAND DUNE AND COASTAL ECOSYSTEM FUNCTIONAL RELATIONSHIPS

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A GUIDE TO SAND DUNE AND COASTAL ECOSYSTEM FUNCTIONAL RELATIONSHIPS

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Introduction

Sand dunes bordering Lake Michigan represent the largest assemblage of freshwater dunes in the world. In the state of Michigan alone, there are 269,760 acres of dunes within a zone extending for two miles inland from the lake. Formed during the last 13,000 years as a result of the retreat of glaciers, these dunes are among the youngest geomorphic structures in the state. The special climatic and geomorphic conditions responsible for the dune formations are no longer operative. These dune formations, therefore, are a unique and irreplaceable resource.

The dune environment remains a very dynamic system. A variety of factors such as wind, waves, currents and vegetation continually change the face of the dunes. Natural factors contribute both constructively and destructively to the maintenance of the sand storage capacity of dunes. Ultimately, a balance between the conflicting impacts of these natural forces is struck, and the dunes are able to continue their vital function of stabilizing and resupplying beachfronts with sand. However, intense use pressures threaten to disrupt the dynamics of this ecosystem by interrupting or accelerating the natural processes.

The berm-and-dune system characteristic of the Lake Michigan coastal area acts as a buffer against storm waves, protecting backlying areas from erosion and deposition. By providing a reservoir of sand, the berm-and-dune system is able to deposit sand in needed areas and moderate change. Maintenance of the sand supply of the berm-and-dune system is vital to the continued functioning of the coastal ecosystem. Greater storm resistance is offered by increased dune height. Consequently, all human activities that accelerate erosion and/or lower the dune, increase the potential storm damage to shorelands.

Continued existence of the dune ecosystem is important to the maintenance of the total ecosystem of Lake Michigan. Understanding the interrelationships between the factors responsible for dune formation provides public and private resource managers the ability to see opportunities for better planning and management of the interdependent coastal ecosystems. Ideally, a site-specific survey of dune ecosystem characteristics should be conducted and used as a basis for management.

Who is Responsible for Management of Sand Dunes?

Recognition of the importance of sand dunes by the State of Michigan prompted the enactment of the Sand Dune Protection and Management Act of 1976 (P.A. 222). The major thrust of the legislation is to provide a basis for management of sand mining activities in dune areas. Specifically, the act provides for the "study, protection, management and reclamation" of Great Lakes sand dunes. It is the intent of this act that the aesthetic, recreational, ecological and economic benefits which accrue from sand dune areas be preserved. The multiplicity of beneficial functions provided by sand dunes are made possible by their inherently dynamic nature. For this same reason sand dunes must be managed as an integral part of the coastal ecosystem.

Administration of the Sand Dune Protection and Management Act has been affected by the insufficient data base from which to formulate management plans. Although limited information is available on the ecology of Lake Michigan sand dunes, no systematic attempt has been made to identify the relationship between these dunes and the Lake Michigan coastal ecosystem.

Protection of coastal resources is mandated in the federal Coastal Zone Management Act of 1972. Although state governments develop their own coastal zone management plans based on federal guidelines, plan implementation is primarily the responsibility of local governments. Local units of government have the authority to adopt and implement land use controls designed to direct development to environmentally suitable areas. Interstate coordination of management plans is recommended in the Act. However, to date there has been little coordinated effort among Great Lakes states to protect shoreland resources.

Zoning ordinances provide one mechanism by which communities can control growth in environmentally sensitive areas such as shorelands. Shorelands may also be protected by designating them as conservation districts, open space districts, or low density residential districts. The content of an effective zoning ordinance would include a statement of purpose, permitted and conditional uses for each zoning district, regulations and performance standards.

What Constitutes a Sand Dune Area?

As legally defined by the Michigan legislature, a sand dune area includes "those geomorphic features composed primarily of sand, whether windblown or of other origin and which lie within 2 miles of the ordinary high water mark on a Great Lake." Additional criteria for the definition were developed by the Geological Survey Division of the Michigan Department of Natural Resources. They include the following (22):

1. "An area which contains geomorphic feature(s) of significant topographic relief as determined by a geologist as being composed of more than 50% of unconsolidated sand."
2. "Those areas identified as coastal dunes, inland dunes or coastal sand strips."
3. "Those shorelines classified as high sand dunes or low sand dunes by the Great Lakes Frame Work Study."
4. "An area which contains soil types as identified and qualified by the U.S. Department of Agriculture, Soil Conservation Service as sand dune types or sand dune associated soil types."
5. "An area which is identified as a transition or buffer zone bordering or adjoining dune areas."

Sand Dune and Coastal Ecosystems

An ecosystem is characterized by a series of energy flows which lead to species diversity, trophic structure, and material cycles (28). While this concept of ecosystem is useful for a functional understanding of a particular environment like sand dunes, an ecosystem should not be viewed as a separate and distinct entity. Energy flows are not confined to a particular ecosystem. They exist and are interactive with various designated ecosystems as well. In this way, the dune ecosystem is connected to the larger unit of the Great Lakes coastal ecosystems.

The coastal ecosystem includes a defined water basin, all marginal transition areas and all shoreland watersheds that drain into the coastal basin (6). Two types of areas of special significance to coastal ecosystems are found in shorelands. They include "retention and direct drainage systems of the coastal watersheds," and "special ecological areas at the lower edge of the shorelands, such as sand dunes" (6).

The relationship of the dunes to the rest of the coastal area is illustrated in Figure 1. The profile of the beach shifts with seasonal variations in wind and wave action. The plunge zone is an erosional zone which serves as the final breaking point of an incoming wave. The remaining forward motion of water which causes it to rush onto the beach engulfs the "swash zone" (39). Sand is transported by waves and deposited along the upper limit of the swash zone in ridges called berms. "The berm moderates change by providing a reservoir of sand available to either dunes or beach as needed" (6). Harsh winter storms erode this sand ridge while summer storms restore it. Thus, the berm-and-dune system plays an important role in protecting uplying areas from the destructive forces of storm waves.

How and When Were Lake Michigan's Dunes Formed?

The dunes along Lake Michigan formed primarily during the Algonquin and Nipissing lake stages 13,000 and 4,000 years ago respectively. Glacial debris in the form of moraines[1] were deposited when the ice melted and retreated. As the ice retreated, the depth of the lakes changed. At the Algonquin and Nipissing lake stages, a single lake formed with a depth of 605 feet, from the combined waters of the Lake Michigan and Lake Huron basins (13). With waters at this level (25 feet higher than present) considerable wave action occurred, eroding glacial debris along the shoreline (39).

An understanding of the geological processes important to the formation of dunes along Lake Michigan is necessary for identifying which assemblages are especially unique and deserving of protection. In addition, geological processes provide explanations for deposition or erosion of sand in fragile dune areas.

What Factors are Responsible for the Shape of Dunes?

The characteristic shape of a dune is determined by a variety of factors such as wind, waves, and vegetative growth. As a dune begins to form, it takes on a characteristic shape in relation to the prevailing wind. A prevalence of westerly winds led to the formation of the dunes on the eastern shore of Lake Michigan. Dunes formed are parallel or at right angles to the wind direction depending on wind strength. The windward slope is generally more gradual than the leeward slope. Dune

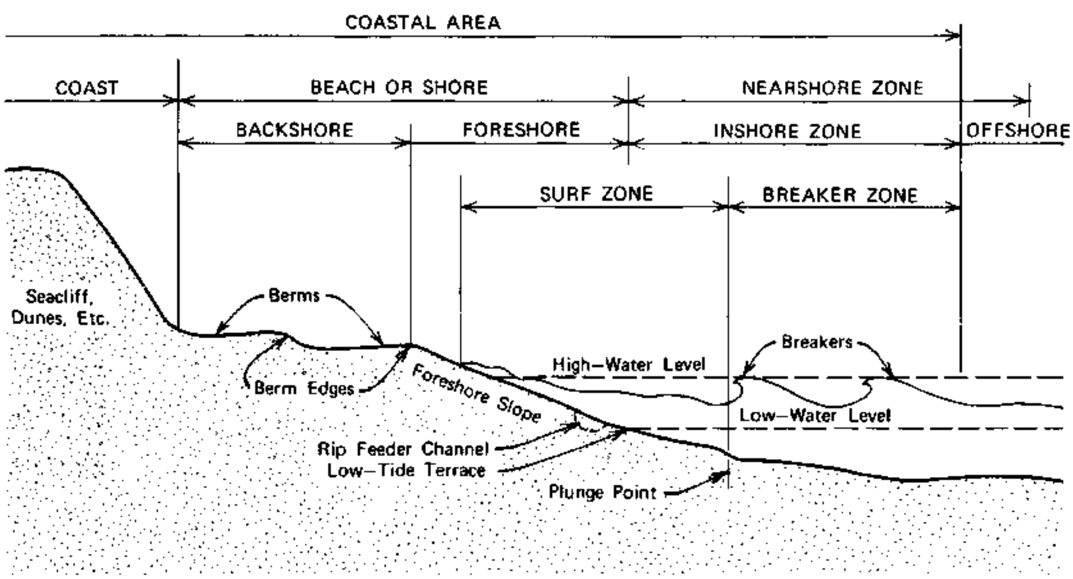


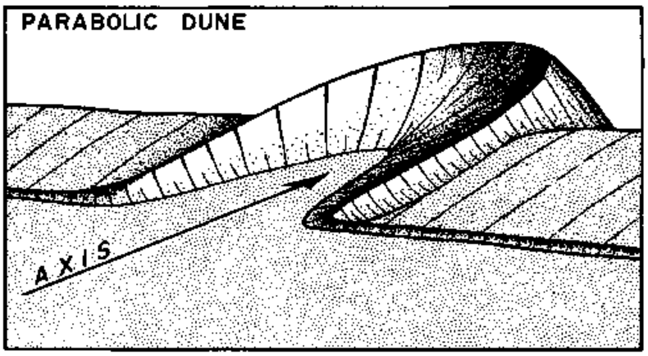
Figure 1. The anatomy of a typical beachfront.

From: U.S. Army Corps of Engineers, Division of Pacific Ocean Corps of Engineers, 1971.

1. A moraine is an accumulation of earth, stones, etc. carried and finally deposited by a glacier.

formations which result from the effect of wind are called parabolic dune units (Figure 2).

Dune formation is altered by the growth of vegetation and storm waves. Vegetative growth ultimately determines the shape of the dune (26). For example, marram grass typically builds long, low gently sloping dunes due to its vast network of underground stems. In contrast, cottonwood, which has no means of vegetative propagation, is responsible for the formation of the highest, steepest dunes. Figure 3 shows the formation of 'embryonic' dunes by one type of beach grass. Although the type of grass illustrated is more typically found on dunes in a marine environment, the principle of dune formation by plant colonization displayed is the same as would be observed from the growth of marram grass along Lake Michigan sand dunes. Vegetative growth slows sand movement and initiates dune growth. Undercutting by storm waves can cause the windward face of the dunes to be more vertical than would otherwise be expected.



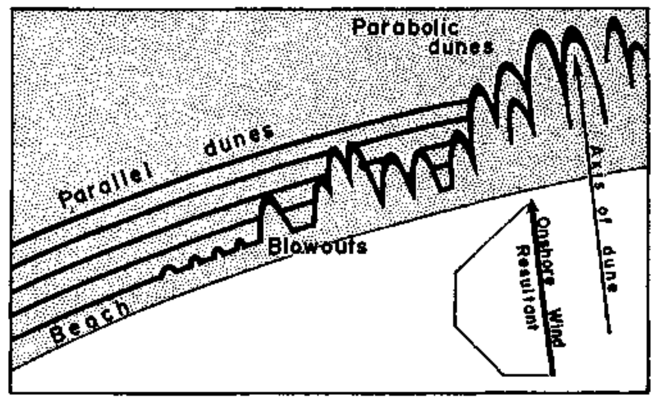


Figure 2. Above, diagram of a parabolic dune; below, blowouts and parabolic dunes interrupting parallel dunes on a coast, and showing axes aligned with the onshore wind resultant.

From: Bird, 1969, p. 139.

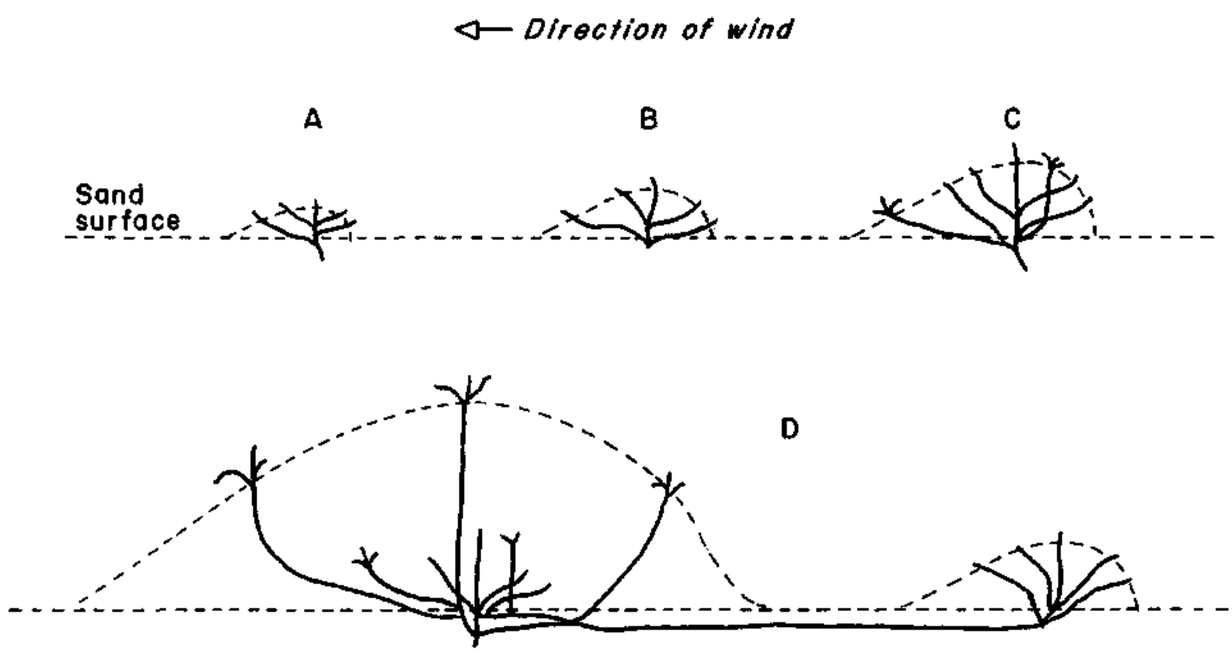


Figure 3. Stages in colony development and formation of 'embryonic dunes' by Agropyron junceiforme. The upper broken line represents the surface of the dune.

From: Nicholson, 1952.

Changes in the foredune into an irregular, "U"-shaped dune ridge known as a blowout, can result from disturbances of the sand-stabilizing vegetation by either natural or man induced causes. Sand has been known to accumulate in drifts up to 250 feet high and move inland for ½ mile or more (4, 16, 17). Historical records show that some forests, farmlands and at least one small town which existed at the beginning of this century, have since been buried by the moving sand (16). Blowouts will continue to move inland until vegetation once again becomes established and stabilizes the dune.

Sand dunes must be viewed as part of a continuous dune assemblage extending from the beach to the forested dune. Inland from the water's edge several different zones or assemblages (dune types) are represented. Nine dune types were named by Buckler in 1979 including: parabolic dunes, linear dune ridges, dune terraces, dune platforms, domal dunes, complex dune fields, dune flats, marginal sand aprons, and inter-dune lowlands. These dunes differ with relative relief of dune form, orientation of dune form with respect to present shoreline, and arrangement of dune form and underlying and/or associated landforms (Figure 4 and Table 1).

In addition to this classification scheme, Buckler includes a practical definition for the identification of the barrier dune formations. He defines it as "that first dune assemblage whose forms display the greatest relative relief within the officially designated 'sand dune area'; its inland boundary is at the base of the assemblage's landward limit" (3). The designated boundary of the barrier dune formation is illustrated in Figure 5. Use restrictions should be applied in the barrier dunes if they are to function in their protective capacity. They protect backlying areas from the destructive forces of wind and waves. The Sand Dune Protection and Management Act of 1976 requires a permit for removal of all or a portion of the barrier dune.

First Letter (Dune Form)

A	Marginal Sand Apron
C	Complex Dune Field
D	Domal Dune
F	Dune Flat
L	Inter-Dune Lowland
P	Parabolic Dune
PL	Dune Platform
R	Linear Dune Ridge
T	Dune Terrace

Second Letter (Relative Relief)

l	low (0-20')
m	moderate (20'-80')
h	high (80'+)

Third Letter (Orientation)

a	arcuate
i	irregular
n	normal (perpendicular)
p	parallel

Fourth Letter (Arrangement)

r	repetitive (multiple)
s	singular

Relation of dune form to substratum formation

Xxxx[a]	non-elevated
$\frac{\text{Xxxx}^{b}}{\#}$	perched
Xxxx/[c]	overriding

a Non-elevated dunes are represented by only the four (or less) code letters.

b Perched dunes are represented by the four (or less) letter code over a horizontal bar below which is the height above sea level of the surface of the underlying non-dune formation (the Lake Michigan surface is approximately 580' above mean sea level).

c Overriding dunes are represented by the four (or less) letter code followed by a slash.

Table 1. Code for the dune morphology classification of the Lake Michigan shore.

From: Buckler, 1979, p. 7.

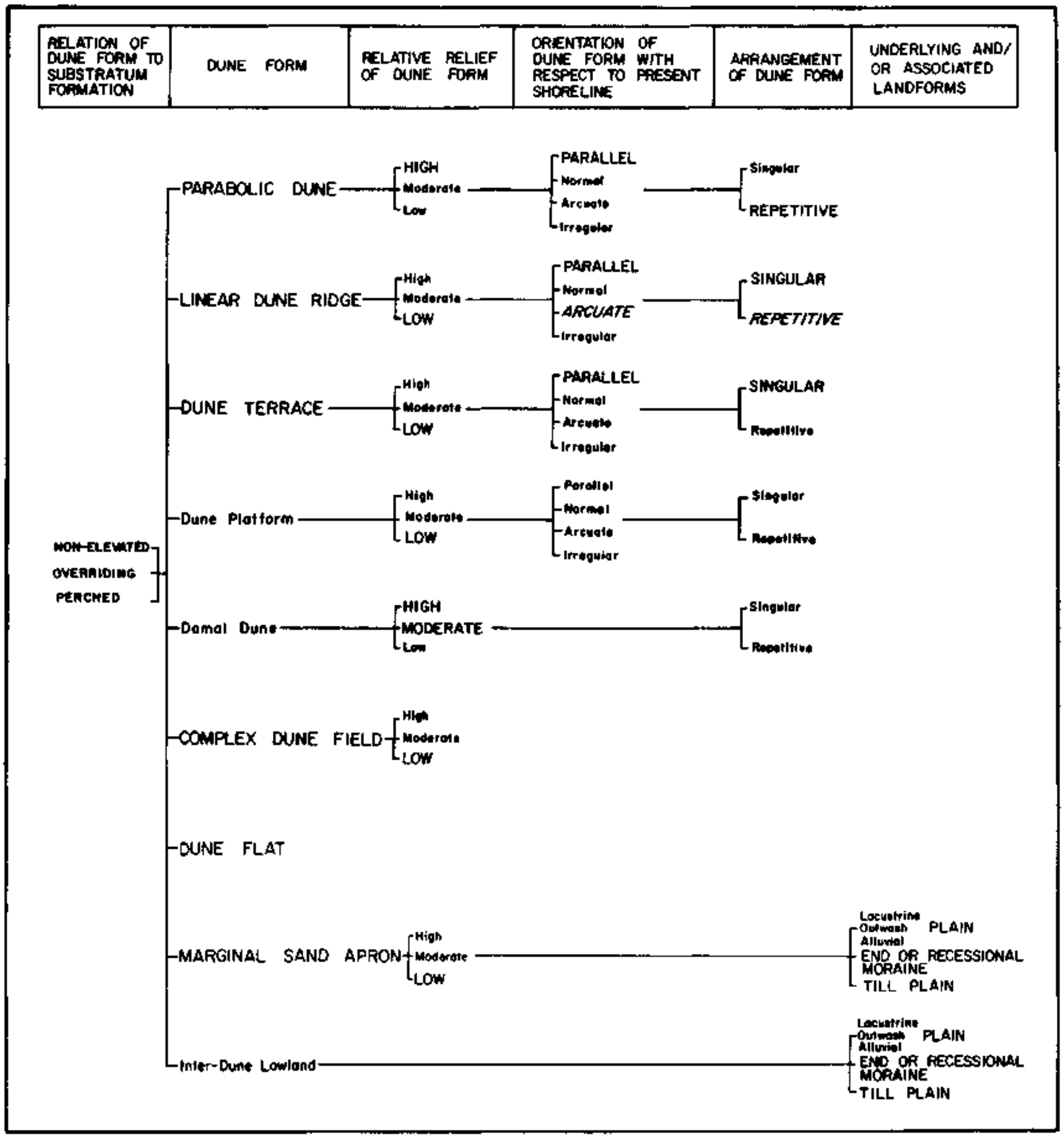


Figure 4. Dune morphology classification of the Lake Michigan shore. Dune forms and correlated characteristics which are more common or dominant are indicated by capitalization.

From: Buckler, 1979, p. 6.

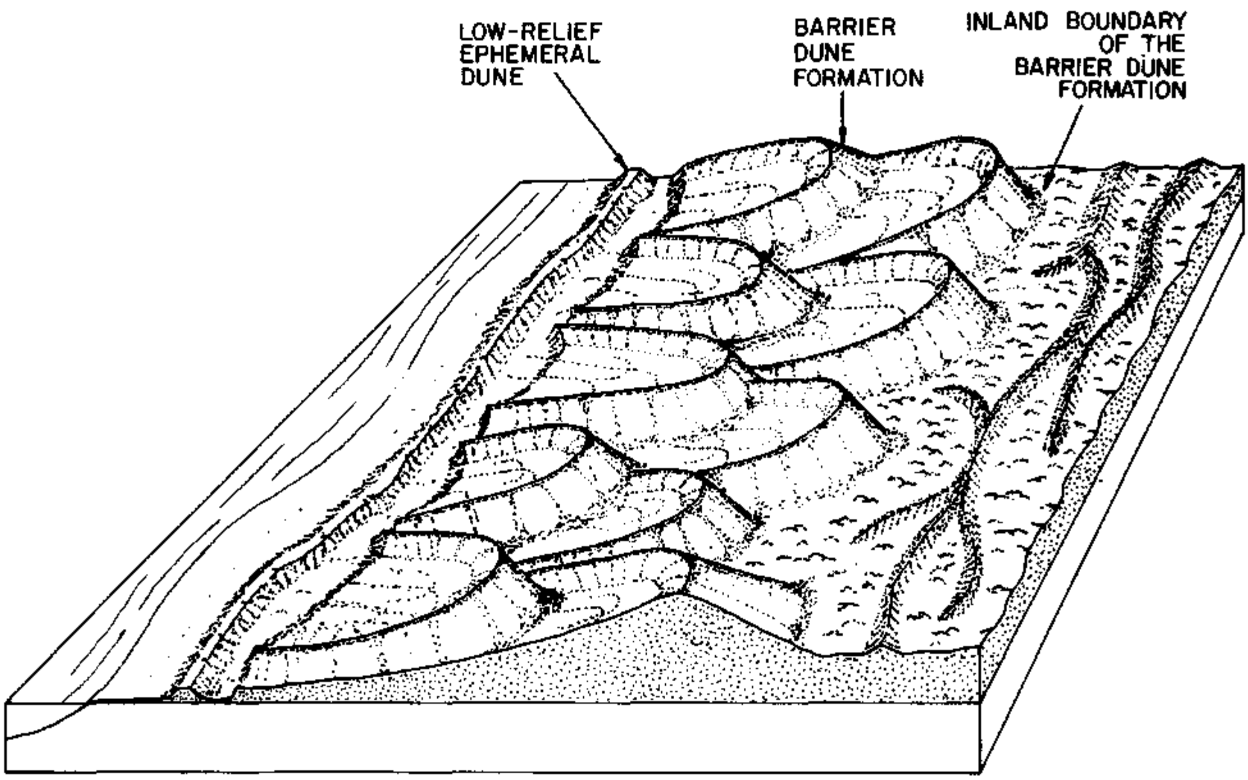


Figure 5. Designated boundary of the barrier dune formation.

From: Buckler, 1978, cover.

Dune Dynamics

Topography is an important factor in the dynamics of the sand dune ecosystem. The deposition and erosion of sand is influenced by topographical features such as the presence or absence of bars and troughs, the slope of the dune, the height of the dune, etc. An understanding of the relationships between sand movement, wind flow and dune vegetation is essential for determination of the effect topography will have on these factors.

Sand movement by wind is a result of two processes; surface creep and saltation. Surface creep occurs when wind rolls the sand along the ground. In the process of saltation, sand advances by a series of short jumps. Saltation begins when sand grains are swept up by the wind's motion then fall back to the surface due to the force of gravity (1). The impact of the fallen grains on the surface sets other sand grains in motion.

The extent of sand movement depends on factors such as wind velocity, grain size, and surface roughness. Grain size is significant in the sense that smaller grains are transported at higher velocities than are larger-sized grains (21). Generally speaking, the greater the wind velocity, the more sand that can be transported. Occasional strong winds which can overcome the effect of surface drag may be more effective in sand movement than the prevailing wind.

Surface roughness dictates the force needed to initiate sand movement. When the sand surface is relatively smooth, the friction slowing sand movement will be minimal. Increasing surface roughness interferes with the smooth flow of wind transporting sand. The consequence of increased surface roughness is decreased wind velocity. If the wind velocity drops below the threshold velocity, the minimal level needed to keep the sand in motion, then sand will be deposited.

The threshold velocity of sand movement is altered by surface characteristics such as dune relief, vegetation, and moisture content. Vegetation increases surface roughness, reduces wind velocities to below the threshold velocity for sand movement, and succeeds in trapping sand (29). Once the obstacle is covered, sand smoothness is restored and dune movement continues. Dune-building vegetation is able to maintain its impact on sand movement by continued growth which regenerates surface roughness. Shrubs and trees are more effective than grass at slowing wind and stabilizing sand(29).

Moisture levels of the sandy surface greatly affect the movement of sand particles. Water lying between sand particles serves as an adhesive force effective in holding sand at the surface. More wind energy is needed to set in motion wet sand than dry sand.

The dune formation or topography has a pronounced effect on the continued movement of dune assemblages. A greater wind velocity accelerates the rate of dune movement regardless of the dune size. An obstacle such as a mound or hillock will produce wind reductions for great distances to the lee of the obstacles and a short distance in front. Thus, some protection is offered by the topographic form which results from dune building. However, this same form is responsible for "crowding and accelerating the wind over the dune summit and thereby increases the risk of subsequent wind erosion on the most exposed parts of the dune" (29).

One of the most significant topographical factors facilitating or inhibiting beach erosion is the presence and location of sand bars. Offshore sand bars induce wave breaking, absorbing the energy of waves and currents and protecting the beach from destructive forces. Thus, large sandy beaches lead to sand deposition.

Along the shores of Lake Michigan there is a predictable movement of material in the coastal system determined not only by the direction of prevailing winds and currents, but by the existence of various topographic features. Sand is deposited in protected reaches such as the lowlands formed by outwash and ice gouging. Deposition of sand at the mouth of rivers has led to extensive areas of active dunes in certain locales (i.e., Holland and Ottawa Beach) (8).

Sand dunes along the southeastern shore of Lake Michigan range from 75-200 feet in elevation (29). Perched dunes which occur when windblown sand accumulates on a bluff may reach heights of approximately 300 feet (25). Removal of all or a part of a dune will restrict the types of plants able to reestablish on the dune. Reduction of dune height will result in lower humidity, higher winds, more sunlight, and greater temperature extremes. In effect, leveling a dune homogenizes the ecosystem allowing less diversity of plants and animals.

Data on topographic forms along the shoreline should be collected and utilized in formulating sand dune management plans. A survey of landforms will provide information on bars, points and troughs where sand deposition can be expected. Regional topographic maps, aerial photographs and Michigan Department of Natural Resource's classification of dunes into Series I, II, and III can provide a uniform basis for the designation and determination of dune types. A survey of backlying areas such as wetlands, farms, or chards, woods, towns, etc. can be useful to identification of areas protected by existing dune formations. Finally, data obtained by measurement of the slope and area of the dunes can be used to determine the rate and probability of dune movement.

How Do Hydrologic Factors Affect Dune Construction?

The transport of sediment by wind, generated waves and currents has been researched extensively. "As waves break, the up-rushing water on the beach carries with it a certain amount of sand and gravel. When the water does lose its momentum, it reaches the limit of advance and there is a momentary halt. Then the backwash occurs, and the water and its sand load flow down to the beach and back into the lake" (25). Wind and currents cause the waves to strike the shore obliquely (9). Consequently, sand and beach detritus are moved along the beach in this process known as long-shore or littoral drift. The direction of these currents will indicate where deposition and erosion will occur.

Sand transport at the lakeward limit is significant up to a depth in water of 60 feet. Past this point, larger storm waves do not agitate the bottom sediments to any appreciable degree. The sand is transported continually from the large reservoir of sand under the water to the beach, where it becomes available for the construction of dunes (31).

The transport of sediment by waves causes distinct changes to take place in the nature of this material. Beach sand is mostly a fine quartz sand. Coarse gravel known as beach shingle and composed of crystalline and sedimentary rocks is common. Wave action rounds the edges of these originally subangular pebbles.

Frost and ice action play a considerable role in the decomposition of larger rocks and pebbles. The abrasive action of ice loosens material while the wedging action of ice weakens the substrata. The result of all these forces acting on sediments is dune sand, which has unique qualities. The size, chemical purity, and uniformity of dune sand are special characteristics which make this sand a valuable resource for a number of industries.

Surface runoff may cause gullying and erosion of superficial materials on dunes. Additional waters will increase ground water.

It has been speculated that removal of considerable weight may decrease the compaction of the soils underneath and increase permeability. The result might be a localized change in water levels or direction of flow (23). Furthermore, removal of significant quantities of sand may expose the water table and increase the risk of pollutants entering the water supply system. The significance of these alterations has never been ascertained.

Mitigation of problems which may be caused by interference with the ground water system depends on proper identification of the following:

1. Ground water table maps
2. Permeability of bedrock material
3. Location, depth, static level and pump setting of wells in the area, and
4. Existing surface waters.

Microenvironment

Microenvironments are the small environments created by differences in temperature, moisture, and light intensity within the sand dune ecosystem. Examination of these small environments is essential to a clear understanding of the 'whole' ecosystem. The diversity of organisms in sand dune areas is made possible by the variety of habitats found in relatively small areas. Any alteration of the dune which homogenizes the ecosystem will allow less diversity of plants and animals.

"Organisms occupying the same general habitat may actually be living under very different conditions" (28). Depending on the orientation of the dune, variations will exist in the vegetative cover, sunlight intensity and winds. Microclimatic differences on the dune are evident on 1) dune plateau; 2) solar slopes; 3) shade slopes; 4) windward slopes; 5) leeward slopes; 6) intermediate slopes; and 7) dune hollows (33). In addition, various topographic differences among dunes, i.e. blowouts, hummocks, pathways, etc., lead to different conditions within the same general area of the dune environment.

This variety of microenvironments allows for a diversification of species that would not be expected in a more uniform environment. Among the earliest invaders of the beach area are the seaside spurge, tumbleweed and seâ rocket. These species are able to sink their roots to the water table and thus, survive the severe desiccation of the sun and the instability of the sand. The plants have developed various mechanisms by which they are able to withstand this harsh environment. For example, sea rocket is a succulent and is, therefore, able to store water in its leaves. Seaside spurge, found on the middle and upper beach and windward slopes of active dunes, is characterized by a supply of latex and by a prostrate habit, both of which are advantageous to survival in an arid environment.

Marram grass (Figure 6) is the primary stabilizer of sand in areas of rapid deposition due to its capacity for rhizomal propagation and internodal growth. Underground stems reach downward to the water table and upward to the surface to form new plants. The underground network of stems serves to hold the sand in place. In addition, beach grass is able to withstand burial by elongation of the internodes (Figure 7)

The taller sand reed grass (Figure 8), on the other hand, is the dominant dune builder in places where "lesser wind or sand supply account for less rapid deposition rates or slow erosions as on many blowout windward slopes" (32). Another plant characteristic of the dune environment, bluestem bunchgrass (Figure 9), persists mainly on the sunny, south slopes of dunes. In areas where plant growth increases shade and competition on the dune, the population of bunchgrass will be reduced in abundance and vigor although plants may flourish in small openings in the undercover (32).

The moist depressions created by blowouts produce a favorable habitat for yet another invader of the dune environment, the jack pine. Successful colonization by this species depends on close proximity to the water table.

Basswood-maple series characteristic of the later successional stages on the dune, thrives on steep-lee slopes and protected pockets. Basswood is especially tolerant of sand burial. In fact, as one tree becomes buried, the exposed treetop may become a thicket of many trees. By shading and stabilizing the sandy surface, these trees accelerate the whole process of succession.

Moist areas on the margin of a beach or blowout pond may create favorable conditions for the germination of cottonwood seedlings. This tree, which thrives under sand burial due to its long, fast-growing roots, can come to dominate the summit of an otherwise barren blowout dune (15).

In addition to topographic and geographic factors responsible for the creation of microenvironments, a number of variables caused by vegetative growth com-

Figure 6. Marram grass in seed.

From: Daniel, 1977, p. 23.

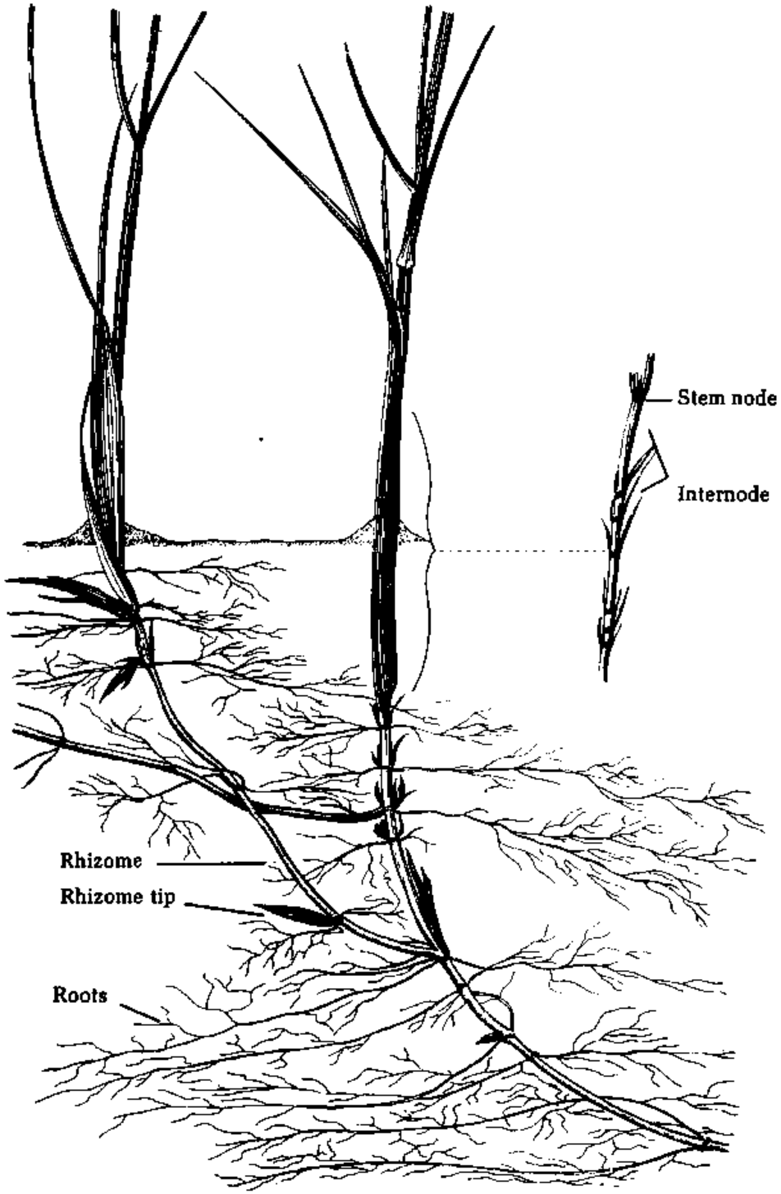


Figure 7. Marram grass, showing underground growth and the lower part of the grass stem.

From: Daniel, 1977, p. 24.

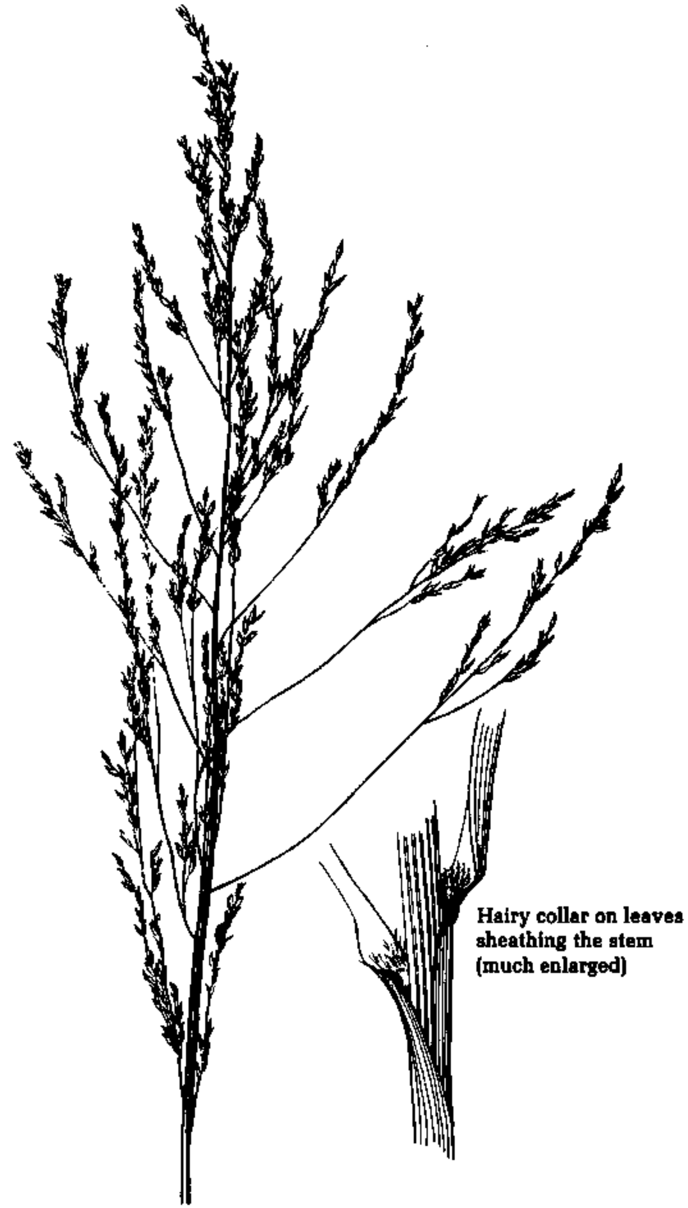


Figure 8. Sand reed grass.

From: Daniel, 1977, p. 28.

bine to produce an array of microclimates. For instance, plant species colonizing one area alter nutrient content, moisture level, and substrate stability to such an extent that the conditions become favorable for new species to establish.

The orderly process of development that involves changes in species structure with time, and which is accelerated by modifications of the physical environment by the plant and animal communities, is called succession. (see pages 11 and 12)

Figure 9. Little bluestem.

From: Daniel, 1977, p. 29.

Species Diversity and Productivity

Sand dunes are characterized by highly diverse, but unproductive populations or organisms. Due to the high degree of specialization among organisms inhabiting dune areas, any alteration of the dunes will have a direct impact on existing species.

The variety of microenvironments and moderation of climate offered in the dune environment permits a diversification of species that would not otherwise be expected. "In the spring, Lake Michigan warms slowly keeping the region cooler over an extended period of time, thus preventing buds from opening too soon during the early spring. In the fall, waters of Lake Michigan retain much of their summer warmth" (25). Many species of plants endemic to the Atlantic coastal plain are supported in this inland habitat (36).

The special environmental conditions made possible by sand dunes provide habitats for various rare assemblages and species of plants. In one survey conducted by Cranbrook Institute of Science, species characteristic of southern flora, such as black gum, papaw and tulip tree were found in the same area with northern varieties such as hemlock, Canada yew, and white pine. Another example of a unique plant association identified by Wells and Thompson (40) in their survey of a sand mining site is an assemblage of huckleberry and blueberry. Close proximity of microenvironments with varying soil moisture, light exposure and pH characteristics explain the bizarre combinations of plants found in transitional areas.

One outstanding factor responsible for the diversity of wildlife is the natural boundaries of various populations. Often, Michigan represents the farthest extent of the range of a particular plant or animal species. For example, numerous southern species of plants and animals reach their northern boundaries in dune areas. Many species are not native to Michigan, but pass through the area during migration.

Unlike other fauna and flora which may be spacially shifted, or temporarily decreased or increased in number by a sand dune change, some species may be irreversibly damaged or destroyed by a change in the dune environment. Endangered and threatened species of plants likely to be found in the dune environment are listed in Appendix A. Among them are dwarf lake iris, Pitcher's thistle, spotted wintergreen, and ginseng.

Animal species also make either temporary or permanent homes in dune areas. Endangered, threatened and rare species found on sand dunes emphasize the need for protection of their fragile habitats. Species of animals which may be found in dune areas and are listed on either Michigan or U.S. endangered and threatened species lists, include Indiana myotis, southern bog lemming, pine vole, Cooper's hawk, red-shouldered hawk, bald eagle, marsh hawk, osprey, peregrine falcon, piping plover, common tern, eastern box turtle, black rat snake, and bloater. "Increased stress on the environment is generally manifested in lower species diversity" (18). Management of the resource must plan to avoid disruptions to the ecosystem which result in increased uniformity of the environment and a corresponding decrease in species diversity.

Sand dunes, while characterized by a diversity of flora, are not especially productive environments. This in itself makes sand dunes critical environments. Constant sand movement, scarcity of nutrients and organic matter, rapid drainage of water, and high evaporation rates limit the extent of plant and animal growth. Free (14) points out that overdrainage, and not solely evaporation, is primarily responsible for the character of the dune flora. Although surface moisture evaporates quickly due to the low capillary capacity of sand, new moisture is supplied to the surface slowly, with the result that the total evaporation from sand is less than from soil containing organic matter.

Beach grass and some forbs are the dominant species found on the foredune or occurring in the first 20 years of dune succession, since they are able to colonize under the arid conditions of this harsh environment. Colonization of sand dunes by dune grasses allows for the invasion of other species.

Overall, low productivity and scarcity of nutrients limits the number of primary consumers that the environment can support. Mammals which may be found in sand dune areas along Lake Michigan include mole, shrew, bat, raccoon, weasel, mink, skunk, fox, squirrel, chipmunk, mice, lemming, vole, muskrat, rabbits, deer and woodchuck. Migrant and resident birds make for the diverse bird populations found in dune environments. In addition, numerous amphibians and reptiles such as salamanders, newts, toads, frogs, turtles, and snakes will be found in various environments within the sand dune system. Inhabiting nearby rivers, lakes, and streams are a variety of fish. Insect species present in the dune environment play an important role in the recycling of nutrients in the dune environment. (see page 12)

Plant and Animal Succession

Plant and animal succession is a continuous process beginning with the establishment of a climax forest. The entire successional series takes hundreds of years to complete. The dune environment is unique in that the various stages of plant and animal succession can be viewed simultaneously in a small area. Removal of forests on dunes will initiate the process of dune succession from its earliest stages. Similarly, and modification of the dune environment will interrupt the process of succession and weaken the stability of the dunes.

Succession is slow on sand dunes because the sand substrate makes establishment of plants difficult. Olson (32) estimates that about 1,000 years are required to reach a climax forest, the terminal succession stage of plant communities, on Lake Michigan dunes. Furthermore, in order that a typical climax beech-maple forest be reached, the soil must be moist with a high nutrient level as would be found in depressions beyond stable dunes. Absence of these characteristics on the more elevated exposed slopes in many sand dune ecosystems leads to the establishment of the oak forest as the terminal stage.

Dune formation begins at the top of the foreshore where tidal litter is deposited. Here conditions are favorable for the germination of some pioneer species. The litter reduces the daily temperature of the normally exposed sand surface and increases the nutrient content. Moisture is available due to the proximity of the plants to the coastal waters. All of these factors ensure the colonization of the beach by some of the viable seeds trapped in the litter. The scattered pioneer species interspersed in the tidal litter make up a line of vegetation called the strandline. Plants characteristic of the strandline include sea rocket, seaside spurge, and beach pea. Because this vegetation has a limited lifespan it will not be successful in stabilizing the shifting sand. However, it will play an important role in the ultimate formation of the dune environment.

Vegetation protruding from the sandy surface reduces windflow and allows for the deposition of sand. This process of dune formation will be arrested when the litter is buried and a smooth surface is restored. The extent of dune formation by this process depends on the physical features of the beach area. Narrow sandy shores may accumulate large quantities of tidal litter, but the insufficient supply of sand impedes dune formation. In contrast, wide sandy shores have an abundant supply of sand to enable large dunes to form (33).

Along the middle beach, the severe winds and extreme drying effect of the sun make habitation difficult. However, plants that are able to extend their roots to the water table can survive in this harsh environment. Sea rocket is usually the dominant species of this environment (8). Also, found in this environment is seaside spurge. These hardy annuals have special adaptations which allow them to distribute their seeds. Seasonally, these scattered plants serve to trap some sand particles.

On the upper beach, beyond the reach of waves, the flora is richer. It is here that perennial dune grasses like marram grass, sand reed grass, and little bluestem grass establish and begin the formation of embryo dunes. The vegetative growth influences the topography of the dune (30, 33). Furthermore, vegetation alters the nutrient and moisture content of the sand, making conditions favorable for species with different requirements.

Pioneer animal communities on the dunes such as tiger beetles, burrowing spiders and grasshoppers establish in response to the changing plant communities on the dune. In fact, some communities are instrumental in affecting the successional changes that occur. For example, as cottonwoods and dune grasses begin to grow, the digger wasps are continually burrowing, adding organic matter to the soil at a depth of a few inches.

Additional plant and animal species are found beyond the foredunes in depressions, dune ponds and protected areas where the accumulation of nutrients is possible. This factor, together with the level of the water table, allows for the invasion of cottonwoods, cherry and willow shrubs and a variety of herbs. The dominant rooted plant in a Lake Michigan dune pond is the rush.

In depressions, the accumulation of organic matter may bury the sandy soil so deeply that flora which cannot tolerate extreme moisture or drought can become established. "Increasing organic matter increases the capacity of the soil to retain nutrients" (33). Trees which need vast nutrient supplies, water, and a stable substrate develop on the back dunes. Climax dominants found in these moderate environments with adequate moisture include black oak, white oak, maples, red oak, beech, hemlock, and birches. "The most striking vegetation change occurs in the first few hundred years, although organic matter, moisture equivalents and exchange capacity continue to increase fairly rapidly for a thousand years or so" (32). Figure 10 shows the time sequence for plant succession and soil changes on Lake Michigan dunes. Variations in the normal sequence of succession and soil changes for Lake Michigan result from diverse sites or microenvironments within the sand dune ecosystem. These alternative dune successions are illustrated in Figure 11.

Management plans for sand dune areas should include an understanding of the successional events of the ecosystem if the interrelatonships within the ecosystem are to be maintained. The successional process occurs slowly reaching a climax forested condition in 1,000 years. Consequently, "any alteration to the sand dune ecosystem affecting plant succession will produce significant long-term changes in vegetation, habitats, species composition, species diversity and carrying capacity" (25).

Figure 10. Succession on Lake Michigan dunes.

YEAR	DOMINANTS
0-20	Ammophila breviligulata (beachgrass) and some forbs
20-50	Cottonwood Beachgrass Cherry Willow Herbs
50-100	Increasing variety of shrubs, trees and herbs Jack pine may dominate
100 -	Black oak may be among the first forest dominants Oak — Hickory Forest Beech — Maple Climax

From: Furlowe, 1977.

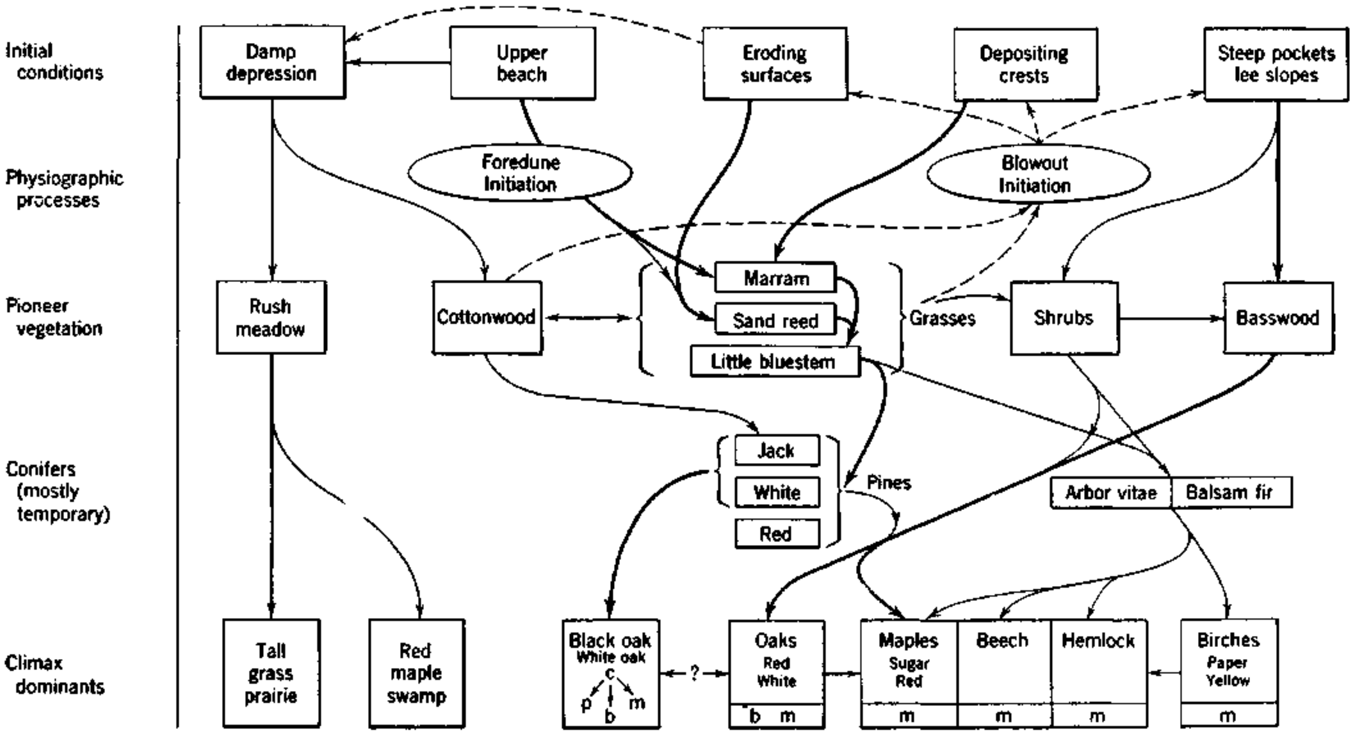


Figure 11. Alternative dune successions.

From: Clarke, 1954.

Carrying Capacity and Its Application to Sand Dune Management

The ultimate goal of sand dune management is to maintain the system at its optimum natural carrying capacity. To accomplish this goal it is necessary that the sources and flows of energy that power the system be at a maximum and that the system maintain an optimally balanced resource base.

Each habitat within the sand dune ecosystem is presumed to have a specific carrying capacity (the limits of the amount of life that can be supported by the habitat). This value is considered to be the potential of the habitat and differs from the standing crop, which is the mass of species present in an area at one time. Various primary supply factors called limiters control primary potential productivity. Nutrients, light intensity and storage capacities are examples of limiters which affect primary productivity on dunes. Modulators, such as temperature, habitat suitability, and water circulation are primary variable factors that govern total productivity (7).

1. LIMITERS

Various limiters affect the carrying capacity of the sand dune ecosystem and must be identified and monitored before effective management plans can be instituted.

a. Nutrients

The low nutrient level of the soil is one factor which inhibits vegetative growth on the dunes along Lake Michigan. A low nitrogen level is the primary limiting factor. Since the availability of nutrients only permits the production of a limited standing crop, little organic matter is added to the soil to remedy the situation. Due to the porous nature of the sand, the nutrients which do accumulate from decaying plant and animal matter are quickly flushed through the sand.

Plants have developed various mechanisms and associations which enable them to overcome nutrient deficiencies in the soil. In one symbiotic relationship between plants and fungi observed on Lake Huron dunes, the fungi *Endogone* assisted the dune grass *Ammophilia,* in binding sand particles together and in procuring water and nutrients. Consequently, plants with an association with fungi were observed to grow better than plants without such an association on Lake Huron dunes (19). Numerous field studies at Lake Michigan dunes have revealed the same type of association between plant roots and soil fungi (26). Alteration of the topsoil layer would reduce the amount of nutrients available in this already nutrient-poor sand.

At the other extreme, excessive discharge of nitrogenous compounds will percolate through the sand into the ground water. Eventually, these compounds will enter the lake through the ground water-coastal basin interconnections. Increased nutrient levels are positively correlated with increased eutrophication of lake waters (6). This phenomenon will interefere with the natural balance in the Lake Michigan ecosystem.

b. Light

A second factor which limits the primary productivity of ecosystems is light. Optimum productivity requires adequate sunlight. Turbidity, which is a measure of the total suspended solid particles in a body of water, greatly reduces the light penetration in coastal waters and adversely affects productivity. Although the erosion of clayey soils into lake water produces the greatest effect on turbidity, the erosion and resuspension of sand in lake waters can also have pronounced effects on turbidity. Turbidity interferes with basic biological processes such as primary production and fish spawning, with drinking water supply systems, and with commercial fishing products (35).

The problems resulting from turbidity are extensive. Damage caused by the erosion and retreat of coastal lands along Lake Michigan is evident in loss of houses, farmlands, forests, etc. However, the adverse effects of increased turbidity are not as obvious. Transparency of the water is used as an indicator of turbidity levels and can be read with an instrument called a Secchi disc. Variations in turbidity are produced by seasonal changes, climatic factors, and plankton blooms. Abnormal changes in cyclical turbidity patterns may indicate excessive sediment loading.

Ecosystem management plans should seek to enhance light penetration and thereby increase the carrying capacity of the system. Activities which will increase sediment loading in coastal waters and resultant turbidity levels should be kept under planned control.

c. Storage

The storage component of ecosystems, such as the sand supplied by dunes, is another limiting factor of extreme value which must be protected. "Storage is the capability of a natural system to store energy supplies in one or more of its component units" (6). "Since storm resistance increases with dune height, all human use of the barrier dune that devegetates, erodes, or lowers the dune, exposes the shorelands to increased storm damage" (6).

The function of sand dunes in protecting uplands from being eroded and flooded has been well documented (6, 12, 34). The dune and berm system acts as a storehouse of sand that impedes beach erosion and provides protection from storm waves and wind. The mechanics of this system is diagrammed in Figure 12. Although this schematic diagram shows storm wave attack on the beach and dune system of a marine coastline, the effect of wave attack on a freshwater system is virtually the same except for the absence of a tidal influence and a shorter wave period.

The vegetative cover which serves to stabilize the dunes must be protected in order to maintain the storage component of the coastal ecosystem. Roots provide one means of mechanical reinforcement for the dunes. Beach grass, *Ammophilia*, is the primary pioneer grass which is responsible for initiating dune building. Beach grass is capable of unlimited growth by spreading its roots both horizontally and vertically into the sandy substrate. Species regeneration occurs mainly from eroded root fragments. Seedlings, on the other hand, require more specialized conditions such as a damp hollow or a protected site on the lee side of the dune before germination can occur. Horizontal roots provide a network effective in stabilizing the dune. The ability of beach grass to grow by stem elongation is one adaptation which enables the plant to survive continuous burial. Two species of beach grass, *Ammophilia brevilligulata* and *A. arenaia* have been shown to tolerate an absolute limit of sand burial of one meter per year, but density diminishes rapidly if these conditions persist (20, 33). These species are responsible for the really high dune landscapes.

As the grasses are buried by deposits of sand, each stem segment elongates so that part of the plant remains above the sand surface. The length of each stem segment (internodal length) indicates the extent of sand burial. Thus, by measuring the internodal lengths of grasses, the depositional patterns of sand in previous years can be determined (Figure 13).

The amount of sand which will accumulate in a given year is related to vegetative growth. Once vegetation is buried, there will be less material to reduce wind flow and trap sand. Accretion will continue when new growth appears each year. Thus, activities which would remove the vegetative cover and restore the smooth surface of the dune should be limited through planning and management.

Changing water levels in the Great Lakes can have a pronounced effect on the sand supply available to the coastal ecosystem. The high lake levels from 1965 to 1975 caused significant erosion while the low lake levels from 1963 to 1964 caused accretion (11).

2. MODULATORS

Modulators, the variable factors which limit carrying capacity on a short term basis, i.e., temperature, dissolved oxygen, and minerals, should be monitored to ensure optimum levels for carrying capacity.

a. Physical Suitability

Physical suitability is the primary modulator responsible for the unique characteristics of the dune. The microhabitats created by the various exposures to sunlight, moisture, nutrients, wind, etc. permit a diversity of species to exist in this environment. Each species has adapted to the unique characteristics of its environment. Alterations of these microhabitats will limit the plant and animal species found there.

b. Groundwater Fluctuations

Groundwater fluctuations are one type of modulator which will affect the types of plants and animals found on the sand dunes. Species found on the dunes are those which have adapted to the arid condition. A rise in the ground water level would permit the invasion of the plants which require a greater availability of water to survive. The intrusion of other plants will lead to increased competition for available niches and will disrupt the special composition of the dune.

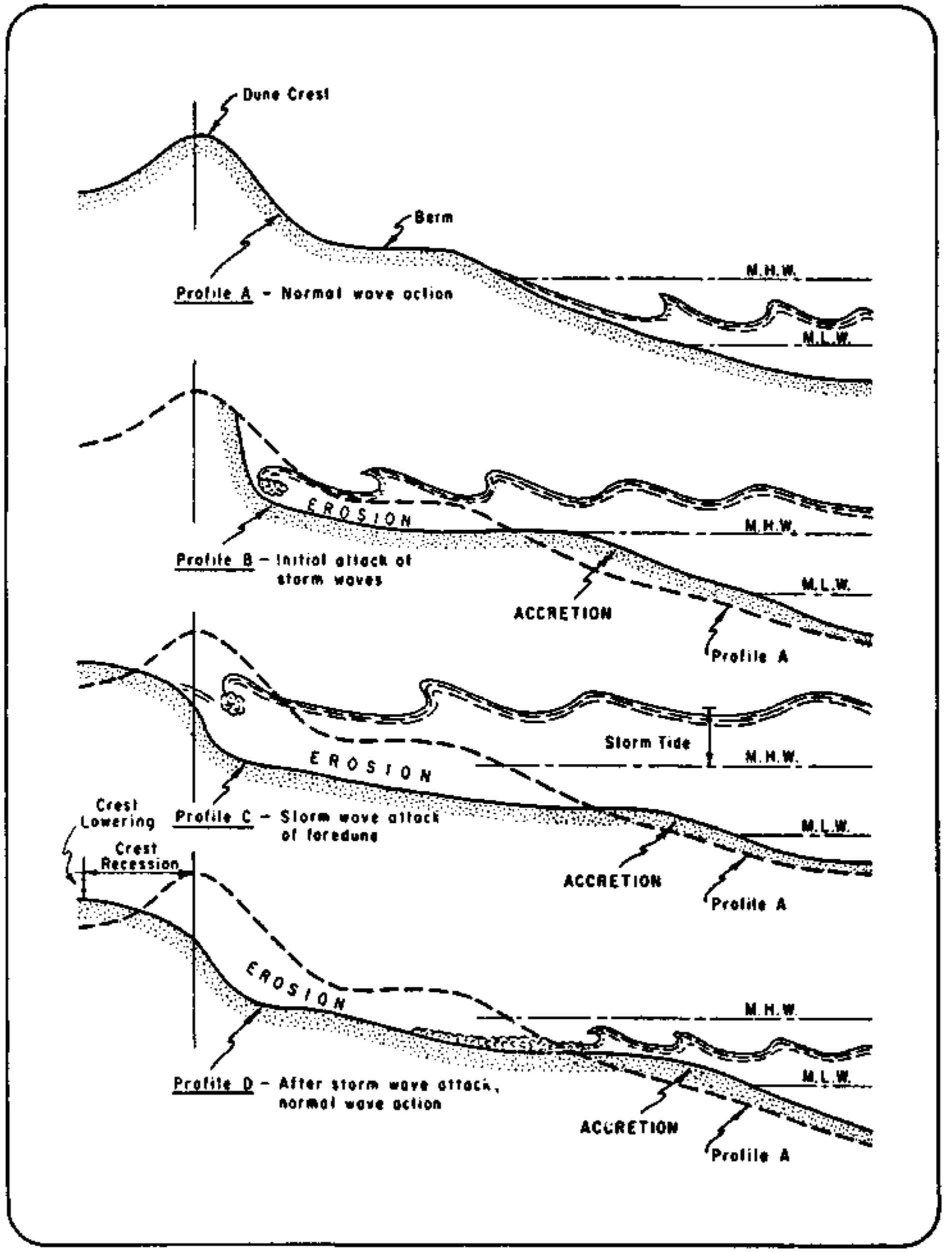


Figure 12. Schematic diagram of storm wave attack on beach and dune.

From: U.S. Army Corps of Engineers, Coastal Engineering Research Center, 1971, p. 1-11.

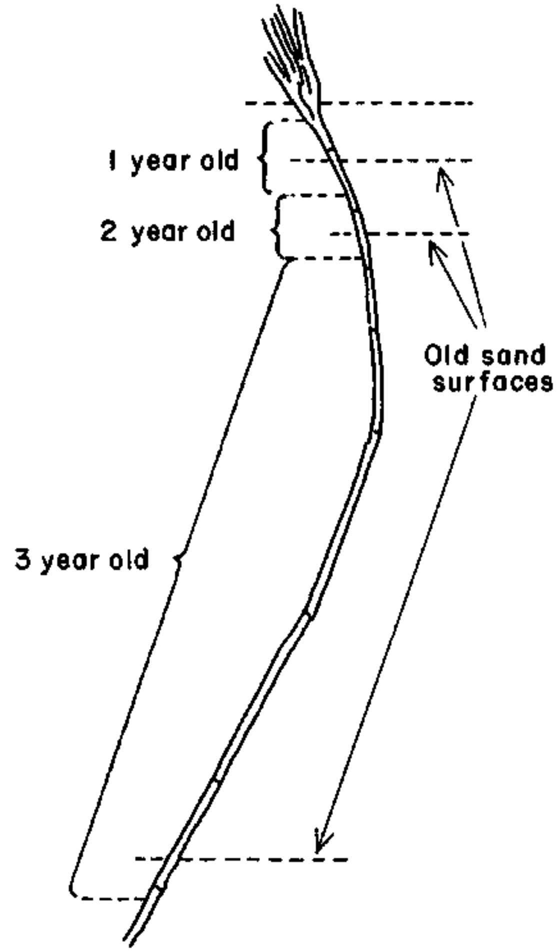


Figure 13. Three annual growth cycles of a buried marram grass stem. The spacing of internodes provides a measure of sand deposition. That portion of the stem between the enlarged parts where branches, stems and leaves arise is known as the internode. As the stem of marram grass is buried, the internodal length increases enabling part of the plant to remain above the surface.

From: Olson, 1958b, p. 348.

c. Vegetation

Similarly, the removal of vegetation will alter the microclimate and place stress on the remaining plants and animals. "Where vegetation exists, overall temperatures are most moderate and fluctuate less dramatically than areas devoid of vegetation. Moisture is held in all plant parts rather than immediately either evaporating or percolating to the groundwater" (23). Water vapor is given off from the surface of leaves in the process called transpiration. The rate at which moisture evaporates is dependent upon air temperature and humidity. Evaporation and transpiration of moisture, together with shade from vegetation, act to cool daytime temperatures and create a less hostile environment for the establishment of flora and fauna. The various soil conditions produced by plant succession, the relatively high humidity, and the lake modified temperatures creates a unique diversity and complexity of soils within the sand dune. Alteration of the soil substrate will interfere with plant succession on the dunes.

APPENDIX

The following threatened and endangered plant species may be found in sand dune areas along Lake Michigan.

Lycopodium Appressum	MI-T
Tradescantia bracteata (Spiderwort)	MI-T
Fuirena squarrosa (Umbrella grass)	MI-T
Eleocharis melandcarpa	MI-T
Psilocarya scirpoides (Bald Rush)	MI-T
Scleria reticularis	MI-T
Potamogeton capillaceus	MI-T
Polygonum careyi	MI-T
Geum triflorum	MI-T
Valerianella chenopodifolia	MI-T
Trillium recurvatum	MI-T
Trillium sessile (Toadshade)	MI-T
Carex Crus-corvi	MI-T
Carex seorsa	MI-T
Gentiana saponarai (Soapwort Dentian)	MI-E
Lycopodiuh xhabereri	MI-T
Cypripedium candidum (White lady slipper)	MI-T, US-T
Habenaria ciliaris (Orange fringed orchid)	MI-T
Habaneria leucophaea (Prarie fringed orchid)	MI-T, US-T
Isotria medoloides (Smaller whorled pogonia)	MI-E, US-E
Tipularia discoloh (Cranefly orchid)	MI-T
Diarrhena americana	MI-T
Triplasis purfuea (Sand grass)	MI-T
Uniola latifolia (Wild oats)	MI-T
Zizania Aquatica (Wild rice)	MI-T
Zizania aquatica (Wild rice)	MI-T
Eryngium yuccifolium (rattlesnake Master or Button-Snake)	MI-T
Aristolochia serpentaria (Virginia snakeroot)	MI-T
Cirsium pitcheri (Pitcher's thistle)	MI-T, US-T
Coreopsis palmata	MI-T
Silphium integrifolium	MI-T, US-T
Silphium laciniatum (Rosinweed or compass plant)	MI-T
Silphium perfoliatum (Cup plant)	MI-T
Cuscuta olomerata	MI-T
Baptisia leucantha (White or Prairie False Indigo)	MI-T
Gymnocladus dioica (Kentucky coffee tree)	MI-T
Castenea dentata (American chestnut)	MI-E
Sabatia angularis (Rose-pink)	MI-T
Hibiscus palustris (Swamprose-mallow)	MI-T
Ludwigia alternifolia (Seedbox)	MI-T
Polemonium reptans (Jacob's ladder)	MI-T
Populus Heterophylla (Swamp or black cottonwood)	MI-T
Trillium undulatum (Painted trillium)	MI-T
Aesculus glabra (Ohio buckeye)	MI-T
Potamogeton hillii	MI-T
Agropyron dasystachyum	MI-T
Orchis rotundifolia (Round leaved orchid)	MI-T
Potamogeton confervoides	MI-T
Dryopteris felix (Male fern)	MI-T
Iris lacustris (Dwarf lake iris)	MI-T, US-T
Juncus styglus	MI-T
Habenaria unalascensis (Alaska orchid)	MI-T
Ruppia maritima (Ditch grass)	MI-T
Erigeron hyssophfolius	MI-T
Solidago houghtonii (Houghton's goldenrod)	MI-T, US-T
Tanacetum huronese, Lake Huron Tansy	MI-T
Armoracia aquatica (Lake-cress)	MI-T
Draba arabisans	MI-T
Pterospora andromedea (pine drops)	MI-T
Pinguicula vulgaris (Butterwort)	MI-T
Mimulus glabratus (Monkey flower)	MI-T, US-T
Calypso Bulbosa (Calypso or Fairy Slipper)	MI-T
Cypripedium arietinum (Ram's Head lady slipper	MI-rare, US-T
Eleocharis atropurpurea	MI-T
Hemicarpa micrantha	MI-T
Scirpus hallii	MI-E
Habenaria flava (Tubercleo orchid)	MI-rare, US-T
Triphora trianthophora (Nodding pogonia Three birds orch)	MI-T
Asclepias hiriella	MI-T
Cirsium hillii (Hill's thistle)	MI-T
Solidage remota	MI-T
Opuntia fragilis (Fragiles prickly-pear)	MI-E
Orobanche fascirculata (Broom rape)	MI-T
Eleocharic trischostat	MI-PR Ext.
Panax quinquefolius (Ginseng)	MI-T, US-T
Mertensia virginica (Bluebells)	MI-T
Pos paludigena	MI-rare, US-T
Lycopodium sp.	MI-E
Woodwardia areolata (Netted chain fern)	MI-PR, Ext.
Acleria pauciflora	MI-T
Juncus scirpoides	MI-T
Aristida tuberculosa	MI-PR, Ext.
Potamogeton lateralis	MI-PR, Ext.
Aster sericeus	MI-T
Helianthus microcephalus (Small wood sunflower	MI-T
Petalostemon purpureum (Red prairie clover)	MI-E

MI-T	Found on Michigan Threatened Species List
MI-E	Found on Michigan Endangered Species List
MI-rare	Found on Michigan Rare Species List
MI-Pr	Ext. — Probably extinct in Michigan
US-E	Found on U.S. Endangered Species List
US-T	Found on U.S. Threatened Species List

From: State of Michigan Department of Natural Resources, Geological Survey Division, 1979.

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