This is to certify that the
thesis entitled

APPLICATION OF DIGITAL PHOTOGRAMMETRIC METHODS
IN THE INTERPRETATION OF LAND COVER CHANGE
ON THE COASTAL DUNES OF WARREN DUNES STATE PARK,
BERRIEN COUNTY, MICHIGAN, 1978-1999

presented by

Tiffiny Ann Rossi

has been accepted towards fulfillment
of the requirements for the

M.A. degree in Geography

Alan F. Arbogast
Major Professor's Signature

12/12/03

Date

APPLICATION OF DIGITAL PHOTOGRAMMETRIC METHODS IN THE INTERPRETATION OF LAND COVER CHANGE ON THE COASTAL DUNES OF WARREN DUNES STATE PARK, BERRIEN COUNTY, MICHIGAN, 1978-1999

By

Tiffiny Ann Rossi

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF ARTS

Department of Geography

2004

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Abstract

APPLICATION OF DIGITAL PHOTOGRAMMETRIC METHODS IN THE INTERPRETATION OF LAND COVER CHANGE ON THE COASTAL DUNES OF WARREN DUNES STATE PARK, BERRIEN COUNTY, MICHIGAN, 1978-1999

By

Tiffiny Ann Rossi

Warren Dunes State Park (WDSP) is part of an aggregation of dunefields along the Lake Michigan coastline and is also one of the most visited state parks in Michigan. Previous research on Lake Michigan coastal dunes discusses the link between vegetation and dune stability. Land cover in WDSP was analyzed using digital orthophotography in the context of this research. The possibility of human impact on coastal dunefields was also explored by comparing land cover changes in a high-use area of the park to a natural area. Historic aerial photography was orthorectified to produce the digital orthophotography used in the land cover analysis.

Two methods of orthorectification were tested in this study. Extracting a Digital Terrain Model (DTM) from the bundle-block adjusted aerial photography and using the DTM to orthorectify the images produced orthophotos with the best positional accuracy. Interpretation and analysis of the digital orthophotography revealed that land cover changes at WDSP followed the model of ecological succession on Lake Michigan sand dunes suggested in previous research. The results of this study also indicate that rates of land cover change were variable over the period of study and may be tied to lake level fluctuations. Additionally, this study suggests erosion is more prevalent in the high-use area than in the natural area of the park.

Dedicated to the memory of Melissa Anne Smith,

August 22, 1977 - July 8, 2000.

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ACKNOWLEDGEMENTS

I would like to express my sincere appreciation for the many individuals that have aided, guided, or supported me. Without their help, this thesis would not have become a reality. I especially wish to thank my advisor and committee chairperson, Dr. Alan Arbogast for his patience, guidance, and encouragement throughout my academic career. I would also like to thank Dr. Ashton Shortridge and Dr. David Lusch for all the helpful and friendly technical knowledge they provided to me while they served on my committee.

I wish to thank all of the people who provided me with materials, technical assistance, and knowledge to pursue my research: Bob Goodwin (MSU RS&GIS), MSU Remote Sensing and Geographic Information Science Research and Outreach Services (MSU RS&GIS) for the Trimble ProXRS GPS units, Aaron Krueger and Erin Kelley (field assistants), Scott Drzyzga, Scott Stevens (USGS OSL), Phil Ross (USACE), the rangers and staff of WDSP, Sherman Hollander (MDNR), and Penny Holt (MDEQ).

A special thanks goes to the entire U.S. Geological Survey Staff in Lansing for all the support they provided to me during my time as a student trainee Geographer.

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Within the Geography Department, I appreciate the help from the Geography Department Staff: Sharon Ruggles, Ellen Schuster, Marilyn Bria, Judy Hibbler, Jim Brown and Wilson Ndovie. Special thanks goes to Dr. Randall Schaetzl, graduate advisor, for the assistance he provided to me early in my program. To the many graduate students who helped me along the way, thanks for the ideas and inspiration, and making me laugh when I needed it.

I also wish to express thanks of a personal nature to those that provided love, guidance or moral support to me throughout this entire process: To my parents, who have encouraged me to succeed in school and all of life's endeavors. To Raphy, my brother: Thanks for reminding me how to laugh. To my "Lansing friends" Reagan, Jeff, Wendy, Forest, Andy, Fred, Kris, Skinny Dave, and Shelly: you're simply the best group of friends anyone could ask for. I would especially like to thank my dear friend Wendy Tate, who went out of her way to edit my thesis and print copies for my committee while I was in Finland.

Lastly (but certainly not least), I wish to express my profound gratitude to my husband, Risto. Thank you for your never-ending love and patience. Minä rakastan sinua aina.

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BP: Years Bef

DEM: Digital E

DGPS: Differen

DTM: Digital T

GIS: Geograph

GPS: Global Po

GCP: Ground C

INS: Inertial N

MDNR: Michig

NAD 83: North

NAVD 88: No

NED: Nationa

NDVI: Norm

NSSDA: Nat

PDOP: Posit

PMT: Post M

RMSE: Root

TM: Themat

USGS: U.S.

WDSP: Wa

Abbreviations

B.P.: Years Before Present

DEM: Digital Elevation Model

DGPS: Differential Global Positioning System

DTM: Digital Terrain Model

GIS: Geographic Information System

GPS: Global Positioning System

GCP: Ground Control Point

INS: Inertial Navigation System

MDNR: Michigan Department of Natural Resources

NAD 83: North American Datum of 1983

NAVD 88: North American Datum of 1988.

NED: National Elevation Dataset

NDVI: Normalized Differenced Vegetation Index

NSSDA: National Standard for Spatial Data Accuracy

PDOP: Positional Dilution of Precision

PMT: Post Marine Transgression

RMSE: Root Mean Square Error

TM: Thematic Mapper

USGS: U.S. Geological Survey

WDSP: Warren Dunes State Park

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Chapter 1

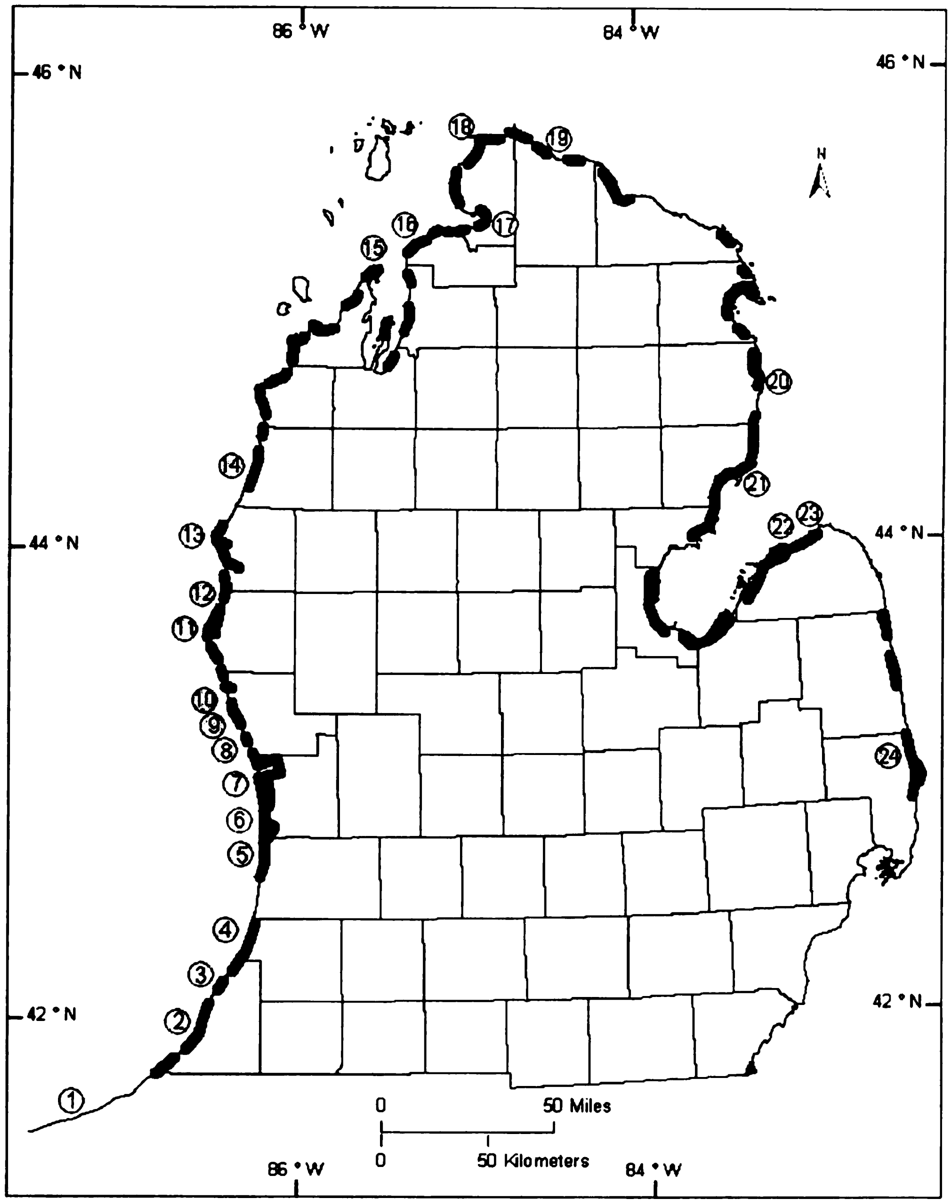
Introduction

Lake Michigan may feature the largest aggregation of freshwater dunes in the world (Buckler, 1979; Fig. 1:1). These coastal dunes are transient, dynamic landforms that respond to environmental change in complex ways. Coastal dunes are especially sensitive to variations in sediment supply, sea or lake-level fluctuations, and changes in land cover. They serve a critical role in coastal stability by storing and receiving sand blown from adjacent beaches. Additionally, coastal dunes also supply sand back to the beaches. This continual exchange of sediment between beaches and dunes is important in a coastal system, as it supplies fresh sediment and nutrients for vegetative growth on dunes (Carter, Nordstrom, and Psuty, 1990).

Due to Michigan's humid climate, dense vegetation covers many coastal dunes (Roethele, 1985). This vegetation effectively stops and traps eolian sand, promoting dune stabilization (Woodhouse, 1978). If the protective land cover is removed or disturbed by natural or anthropogenic causes, bare sand is susceptible to eolian transport (Goudie et. al, 1999). This exposed sand can subsequently bury anything in the path of its migration (Wilson, 1979, 2000).

Several state parks lie within dunefields along the Lake Michigan coastline, providing numerous recreational opportunities for Michigan residents (Fig. 1:1). Recreational use of these parks ranges from day-use to camping and

Figure 1



1 Indiana Dunes
2 Warren Dunes
3 Grand Mere
4 Van Buren
5 Saugatuck
6 Holland
7 Grand Haven
8 P.J. Hoffmaster
9 Muskegon
10 Duck Lake
11 Silver Lake
12 Charles Mears
13 Ludington
14 Orchard Beach
15 Leelanau
16 Fisherman's Island
17 Petoskey
18 Wilderness
19 Charlevoix
20 Newegon
21 Tawas
22 Albert E. Sleeper
23 Port Crescent
24 Lakeport

Figure 1:1. State parks and coastal dune occurrence. From Loope and Arbogast (1999) and MDNR (2003).

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swimming. The day use parks (e.g. Saugatuck Dunes State Park and Grand Mere State Park) are managed for low-intensity recreational use and generally feature hiking trails, natural areas, picnic areas, and swimming beaches. These parks primarily attract nature enthusiasts, birdwatchers, and hikers (MDNR, 2002) and attract less annual visitors than parks with campgrounds (Wells, personal comm., 2000).

State parks with campgrounds (e.g. P.J. Hoffmaster State Park and Ludington State Park) are managed for high-intensity recreational use and generally attract high volumes of visitors for a variety of recreational opportunities. Facilities at these parks generally include hundreds of campsites, swimming beaches, hiking trails, and picnic areas (MDNR, 2002).

One of the most visited state parks in Michigan is Warren Dunes State Park (WDSP; Fig. 1:2). Since the late 1970s, more than one million people have visited this park annually, with 1,511,369 park visitors in 2001 (Herta, written comm., 2002). The park is a popular recreational spot for campers, hikers, naturalists, and hang gliders. WDSP has 180 modern dune campsites, several picnicking areas and a beach with bathhouses and a concession stand. The park also has six miles of hiking trails through forest and open sand-dune areas. Many of these hiking trails cross through dune blowouts. The heavy recreational use in this park thus destroys stabilizing land cover, consequently reactivating or preventing stabilization of the sand dunes.

Figure 1:2. Swimming beach and Pike's Peak dune at Warren Dunes State Park (June 16, 2002).

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MDNR acknowledges that foot traffic and sustained westerly winds prevents vegetation from growing in to stabilize the blowouts (MDNR, 1996).

Because vegetation plays such a crucial role in dune stability, land cover can be monitored to detect changes in dune behavior. This can be facilitated using remotely sensed imagery over several time periods (Fransaer, 1992). Past researchers (Businksi, 1992; Fransaer, 1992; Hazlett, 1981; Stembridge, 1978) have used traditional photogrammetric methods to monitor land cover and vegetative conditions in dune environments. However, advancements in digital photogrammetry have provided many advantages over traditional photogrammetric methods (Chandler, 1999). Such advances include automated tools to produce Digital Elevation Models (DEMs), a wide range of competitively priced photogrammetric software, and less expensive PC or UNIX workstations, as opposed to expensive photogrammetric stereoplotters (Chandler, 1999). Additionally, production of digital orthophotography from historic aerial photography can produce imagery to be handled on a GIS workstation for quantitative analysis (Höhle, 1996).

Problem Statement

Much of the recent research regarding Lake Michigan coastal dunes has related formation of these dunes with lake-level fluctuations (e.g. Dow, 1937; Olson, 1958d; Dorr and Eschman, 1970; Buckler, 1979; Thompson and Baedke, 1997; Arbogast and Loope, 1999; Loope and Arbogast, 2000). These studies have focused upon a

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focused upon ancient processes and cover the entire lifespan of the dunes (thousands of years). Uncertainties still exist with regard to the formation of these dunes and the factors that influence coastal dune formation. Very little research has been conducted within small time frames and within the period of human record. To increase our understanding of the evolution and history of Lake Michigan coastal dunes, more research needs to be conducted within the period of record.

Previous studies have utilized historic aerial photography to monitor or characterize coastal dune vegetation (Businksi, 1992; Fransaer, 1992; Hazlett, 1981; Stembridge, 1978). However, these previous studies have relied upon traditional photogrammetric methods. Although the efficacy of these methods has been well documented, they are difficult to implement in geographic information system (GIS) analysis.

The literature available regarding the use of softcopy photogrammetry and GIS in coastal dune environments is scarce. This study implements softcopy photogrammetry to produce digital orthophotos. Since digital orthophotos can be fully integrated into a GIS, data can be collected from the orthophotos, quantitatively analyzed, and displayed using the GIS.

Purpose

The primary purpose of this study is to collect land cover data in a coastal dunefield to establish whether the dunes or portions of the dune complex are progressing

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progressing towards ecological succession or eroding. This study will focus upon a small, modern time scale to monitor land cover changes.

Additionally, this thesis analyzes the land cover trends in context of resource management. To monitor the possibility of human impact on coastal dunefields, land cover change in recreational and natural areas of a park will be compared. These goals will be facilitated through the analysis of historic aerial photography. One potential benefit of this study is a body of methods that the MDNR may use to remotely monitor change in these coastal dune environments. These methods may offer data to aid management strategies.

The dramatic variance in relief, coupled with a lack of permanent landmarks, presents unique challenges when employing softcopy photogrammetry to orthorectify aerial imagery of a dunefield. A secondary purpose of the study is to test two methods of orthorectification of historic aerial imagery to determine which method results in better positional accuracy. The aerial imagery of the dunefield will be processed using softcopy photogrammetric methods and will be quantitatively analyzed using a GIS. Thus, it is intended that this research may also add to the body of remote sensing literature that addresses coastal dune research.

Research questions that will be addressed are:

1. Which method of orthorectification produces the most accurate imagery for vegetative change analysis on coastal dunes?

2. Where has change occurred on a coastal dunefield and what types of change have occurred, if any?
3. Has change occurred at a constant rate, or has change been variable over the period of study?
4. What are the trends of land cover over the study interval in both recreational and natural areas and how do the two areas compare?

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Chapter 2

Literature Review

Coastal Sand Dunes

An understanding of eolian processes is essential to the study of coastal sand dunes. In this context, this section presents a background of the mechanics of eolian sand transport and the formation of coastal sand dunes. According to Carter (1988), sand dunes are eolian bedforms that develop where wind loses the ability to transport sand. They are typically comprised of very well to moderately well sorted sand-sized grains with average grain size ranging from fine to medium (0.16-0.33 mm) (Bauer and Sherman, 1999). Dunes range from small, short-lived features to large, persistent conglomerations of dunes known as dunefields (Carter, Nordstrom and Psuty, 1990).

In sandy coastal environments, dunes are a basic part of the geomorphic system (Bauer and Sherman, 1996). Coastal dunes form in wide expanses above the high water mark, and can sometimes extend up to 10 km inland (Carter, 1988). Their geographic distribution is worldwide (Fig. 2:1), but they are most prevalent on dissipative coasts with strong onshore winds and an abundant supply of sand-sized particles (0.2 to 2mm) (Carter, 1988; Carter, Nordstrom and Psuty, 1990).

The necessary conditions for the formation of eolian dunes include: 1) an extensive surface for sand deposition and dune evolution, 2) a readily available sand supply

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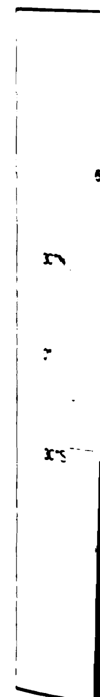

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sand supply, and 3) winds of sufficient strength to entrain and transport sand in a continuous direction for a sustained period of time. Although these conditions are essential, they are not solely sufficient to explain the development of coastal dunes (Bauer and Sherman, 1999). Livingstone and Warren (1996), suggest a broader framework of coastal dune evolution that incorporates a complex mix of eolian process, structural geology, and marine, estuarine, fluvial, slope, pedological, ecological and cultural processes.

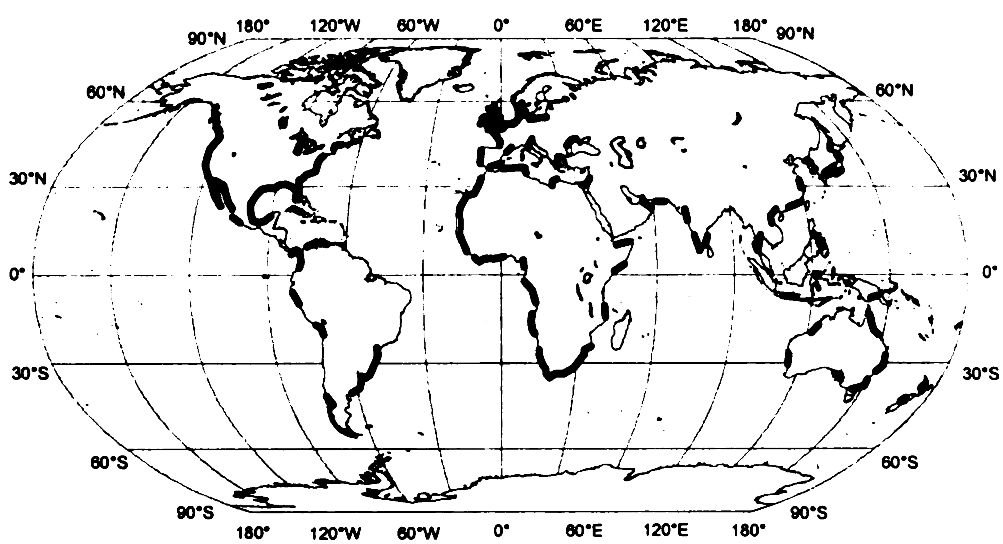

Figure 2:1. Distribution of major dune coasts of the world (width of dune fields not to scale). From Carter, Nordstrom and Psuty (1990).

Eolian Sand Transport and Coastal Dune Formation

The formation of coastal dunes is a complex process, but is essentially dependent upon the integration of a sediment source, wind strength, a nearby, wave-protect

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wave-protected site, and vegetation (Sherman and Hotta, 1990). Sediment is supplied to coastal dunes from beaches, where waves and currents deposit sand. When this sand becomes subaerially exposed by seasonal or climatic lake-level changes, the sand dries and is exposed to aerodynamic processes (Carter, 1988).

Eolian sand transport results from the transfer of momentum from air to sand (Sherman and Hotta, 1990). This energy originates from wind when it shears against a beach or other surfaces (Livingstone and Warren, 1996). Described in terms of shear stress, this process is closely linked to wind velocity (Sherman and Hotta, 1990).

When gravity and cohesive forces (i.e. soil moisture) are overcome, individual grains of sand will mobilize when the shear stress exceeds a threshold value that is dependent upon surface roughness and wind velocity (Sherman and Hotta, 1990). Sand movement begins with entrainment, which is characterized by the processes of lift and/or drag. Lift can be described according to Bernoulli's principle (1738), which states that there is an inverse relationship between wind and air pressure (i.e. Livingston and Warren, 1996). Where high velocity winds encounter slower moving air near the surface, a pressure gradient is produced between air near the sand surface and air just slightly above. Grains protruding into this zone of lower pressure are susceptible to lift (Livingstone and Warren, 1996).

Drag, being more powerful than lift, is expressed as surface drag and form drag. Surface drag is the friction between a sand particle and the air, resulting in the rolling of sand particles. Form drag is caused by a pressure differential between the windward and leeward sides of sand particles, culminating in the rolling and sliding of sand particles (Livingstone and Warren, 1996).

Once entrainment occurs, sand grains migrate by these distinct methods: creep, saltation, and suspension (Fig. 2:2). Sherman and Hotta (1990) suggest that saltation and creep are very common on beaches and coastal dunes.

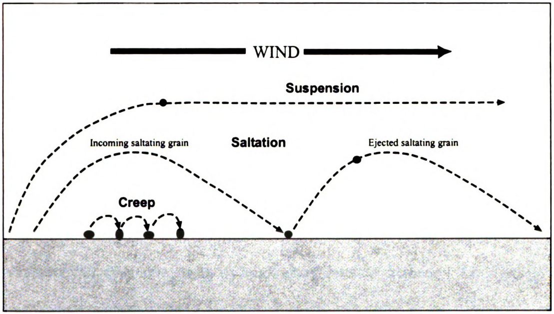

Figure 2:2. Mechanisms of eolian sediment transport. Modified from Livingstone and Warren (1996).

The pivotal process of eolian sand movement is saltation, since it drives all of the other processes of eolian sand transport (Livingstone and Warren, 1996). Saltation refers to the "leaping" of sand particles ejected into the air. These ejected, airborne particles gain momentum from the higher wind velocities above the sand surface, fall back to the ground and collide with other sand grains in a parabolic tra

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parabolic trajectory (Livingstone and Warren, 1996; Gillette, 1999). The collision of sand grains initiates a chain reaction, causing the impacted sand grains to bounce into the air.

Creep involves coarser particles than saltation. Particles traveling by creep move in two distinct ways. The first of these is the rolling of particles across the sand surface as a result of impact from finer, saltating grains. The other method is induced by gravity and results in particles rolling into tiny impact craters caused by saltation (Livingstone and Warren, 1996).

Suspension is the condition in which entrained sand particles follow turbulent motion (whereas in saltation, the particles do not). Although sands rarely go into suspension, the undulating topography of dunes can induce turbulence and help raise coarse particles into suspension. Suspension has been found to be an important process in the formation of foredunes, where high winds may carry coarse grains of sand inland for several meters (Livingstone and Warren, 1996).

Sand transport is influenced by several factors, including, but not limited to, slope, dune form, surface moisture and vegetation. Due to the effects of gravity upon sand grain collisions, sand transport increases on downward slopes and decreases on upward slopes (Lancaster, 1995). Additionally, as wind flows over the surface of a dune, especially that with a sharp crestline, airflow velocity increases, thus increasing shear and enhancing entrainment (Carter, 1988).

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Surface moisture is also an important control on entrainment and transport. Grain movement is halted by complete saturation even under very windy conditions (Livingston and Warren, 1996). As surface moisture increases, the threshold velocity required to entrain damp sand also increases (Lancaster, 1995).

Vegetation is an important control of sand transport and dune form on coastal sand dunes (Carter, 1988). Vegetation restricts the movement of sand by trapping it or by acting as an anchor to prevent mobilization. When wind flows over a stand of vegetation, the wind encounters a false ground surface created by the vegetation. This process creates a pool of still air beneath the false ground surface, which is generally located around two-thirds the height of the vegetation. As grains are blown into vegetation stands and meet these pools of still air, the particles lose momentum and are deposited in or very near the stand (Carter, 1988).

Coastal dunes generally develop on the beach backshore, where barriers, such as vegetation or debris, inhibit the transportation of sand via wind (Carter, 1988; Fig 2:3). Small, pyramidal dunes form within clumps of vegetation and shadow dunes develop behind debris. Vegetation mats reinforce the incipient dunes, creating a hummocky surface. Overwash processes partially erode the seaward side of the dunes, forming a scarped ridge. Scarping exposes more sand to eolian transport, and creates an area favorable for sand deposition. Vegetation stabilizes the hummocks again and new hummocks form. The incipient di

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incipient dunes begin to grow and coalesce. Sand deposition shifts seaward towards the scarped ridge and true foredunes begin to form (Bauer and Sherman, 1999).

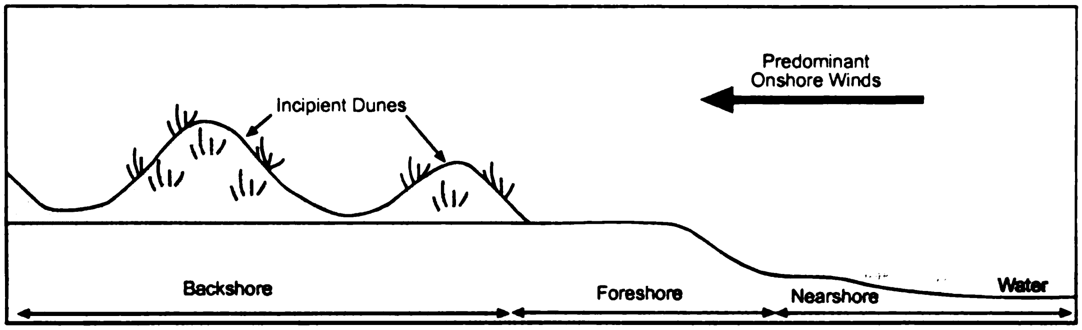

Figure 2:3. Coastal profile with incipient dunes (modified from Collins, 2002).

A wide range of environmental controls also influence coastal dune development. Perhaps the two most important controls are sediment supply and sea or lake-level changes. Over relatively short time intervals, sediment supply is the most important environmental control. However, sea or lake-level fluctuations become predominant controls over longer periods of time (Carter, Nordstrum and Psuty, 1990).

When sea or lake-levels are high, coastlines are eroded by wave attack. In this manner, vast amounts of sediment are transported alongshore and can accumulate to form new coastal dunes or deposit in previously established dunes. During periods of low sea or lake-level, sediment may also be supplied from offshore deposits that become sub-aerially exposed (Carter, Nordstrum and

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Psuty, 1990). This sediment transfer can lead to extensive mobilization of sand if the dunes remain unvegetated.

Coastal Dune Classifications and Morphology

Coastal dunes can be broadly defined as primary dune forms and secondary dune forms (Fig. 2:4). Primary dune forms are those that are directly influenced by coastal processes (Livingston and Warren, 1996). Primary dunes include small ephemeral dunes (Livingstone and Warren, 1996) and incipient foredunes of the backshore (Carter, Nordstrom, and Psuty, 1990). Foredunes are long, linear features with gentle, leeward slopes. The formation of foredunes is favored when sand transport is moderate and beach grasses enhance deposition of sand (Livingston and Warren, 1996). Foredunes commonly form in a seaward-advancing manner, but may also form in a landward-advancing manner when in conjunction with marine transgressions (Bauer and Sherman, 1999).

Dunes inland from the beach are considered secondary dunes (Bauer and Sherman, 1990). Secondary dunes include established foredunes, blowouts and parabolic dunes. Blowouts are elongated wind hollows, depressions, troughs or swales that are often erosional features (Bauer and Sherman, 1999; Carter, 1988). Blowouts are commonly thought to represent destabilization and reactivation of sand dunes usually in response to loss of land cover or an increase in sand supply (Bauer and Sherman, 1999; Carter, 1988).

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Figure 2:4

Blowouts begin to evolve in places where land cover is thin, forming an initial notch in the landscape. The notch widens and deepens as sand is blown away within the notch, forming a depositional lobe downwind. Erosion continues and the notch grows into a blowout with a deflation hollow. It grows until a deflation limit is reached (i.e. only coarse particles too heavy to be transported via wind remain; or water has filled the deflation hollow; Bauer and Sherman, 1999; Carter, 1988). Eventually, blowouts may close again through a "healing" process (Gares and Nordstrom, 1995). Sand deposition creates a shadow dune at the throat of the blowout, which grows and eventually seals off the throat of the blowout, preventing further erosion (Bauer and Sherman, 1999).

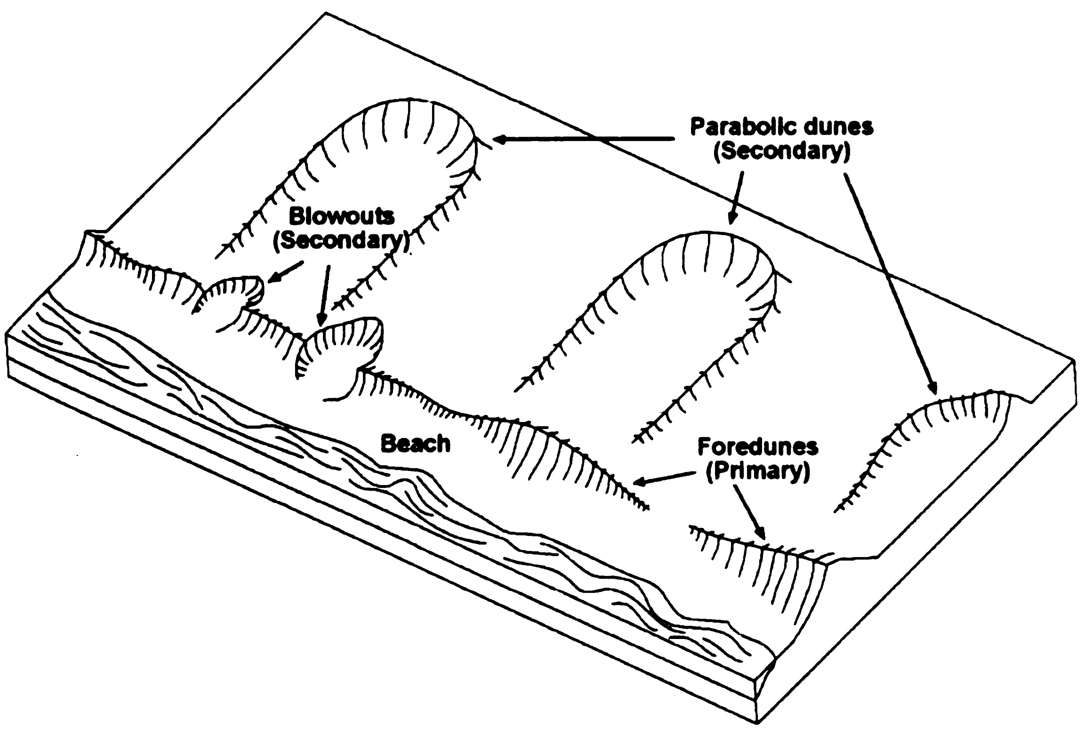

Figure 2:4. Diagram of coastal dune types. Modified from Livingston and Warren (1996).

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Parabolic dunes are believed to develop from blowouts that have reached the deflation limit (Livingston and Warren, 1996). They are U- or V-shaped with limbs that point upwind (Livingston and Warren, 1996). They are commonly found in nested, concentric groups of dunes, appearing to have migrated along the same path. These nested patterns of parabolic dunes are an indication of alternating periods of dune activation and stability (Livingstone and Warren, 1996). Vegetation helps control the shape of parabolic dunes, taking root upon the limbs where less sand deposition occurs. The vegetation stabilizes the limbs, retarding or halting mobilization and allowing the central crest to migrate forward (Livingstone and Warren, 1996).

Coastal dunes that are actively migrating downwind over previously established terrain are broadly categorized as transgressive dunefields (Hesp and Thom, 1990). Transgressive dunefields vary in size from small sheets of a few hundred square meters to small sand seas of several square kilometers. They commonly occur in temperate humid regions with an abundance of coastal sand and high onshore winds and are mostly unvegetated while active (Hesp and Thom, 1990).

The term "transgressive dunes" may be applied to be both active dunes and stabilized dunes where evidence shows the dunes have migrated inland over vegetated terrain, bedrock or lagoons. Such evidence includes buried soils, peat or tree stumps that are exposed on eroded dune faces (Hesp and Thom, 1990). The term may also be used in a generic manner, since it encompasses a variety of

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variety of coastal dune features including, but not limited to, blowouts, parabolic dunes, and cliff-top dunes (Hesp and Thom, 1990).

Transgressive dunes are initiated by a supply of beach sand available for eolian transport or the destabilization of pre-existing dunes. Beach erosion associated with rising sea levels combined with an abundant supply of sand may lead to the formation of transgressive dunefields (Hesp and Thom, 1990). Sand supply may become abundant and available to the nearshore-beach-dune system from the mouths of nearby rivers or from longshore drift (Hesp and Thom, 1990). Preexisting dunes may destabilize due to changes in storminess or shoreline erosion (Hesp and Thom, 1990).

International Coastal Dune Studies

Because coastal dunes have worldwide distribution, a large body of coastal dune research exists. The majority of this research is centered upon European, Australian and North American coastal dunefields. The context of these studies ranges from ecological and management issues to geomorphic research on process and evolution. The intent of this section is to provide a brief overview of examples of coastal dune research that has been conducted in different regions of the world.

In Australia, the eastern coastline is marked by transgressive and parabolic dunes (Pye and Bowman, 1984). Pye and Bowman (1984) used radiocarbon dates and paleosol development in transgressive dunefields on

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Australia's east coast to determine the causes for dune building activity during the Holocene. The results they obtained from five separate sites showed an episode of transgressive dune instability (erosion or migration) between 10,000 and 6,000 B.P.

The timing of this instability corresponds to the postglacial marine transgression (PMT), when sea levels rose 30 m to the present day elevation (Pye and Bowman, 1984). The presence of well-developed paleosols indicates that eolian deposition slowed around 7,000 B.P. as the rate of sea level rise also declined. Their conclusion was that the rate of sea level change during the PMT was the catalyst for dune instability from 10,000 to 6,000 B.P.

Short (1988) observed that most sandy shores on the southern coast of Australia are backed by coastal dunes that evolved during the Quaternary. Dune types found on the southern shores of Australia are prograding foredunes, extensive parabolic dunes and blowouts, transverse dunes, and clifftop dunes. The timing of dune formation on the southern coast of Australia was difficult to establish due to scarcity of datable materials, the size of the dunes, the difficulty of access, and multiple episodes of dune activity. Despite this limitation, Short (1988) made correlations of the age of the clifftop dunes to similar dunes on the eastern coast of Australia.

According to Short (1988), the first major episode of dune building on the eastern coast of Australia corresponded to the PMT and occurred between 9,000 and 7,500 B.P. The clifftop dunes of southern Australia most likely formed around the same time, when wave energy and sediment supply was high due to the rising water levels. The clifftop dunes likely formed sand ramps that topped over the rocky cliffs of the southern shoreline. Once the PMT halted and stillstand conditions developed, the sand ramps would have been eroded and abandoned the dunes atop the rocky cliffs, far from a sediment supply (e.g. the beach) (Short, 1988).

Other episodes of dune activity on the eastern coast of Australia occurred between 3,500 and 2,000 B.P., and a present phase began about 1,000 B.P. The few radiocarbon dates available on the southern coast of Australia were taken from active dunes migrating over barriers that were formerly prograding during the mid-Holocene. These deposits date between 2,700 and 1,500 B.P. and represent a late Holocene phase of dune activity, roughly correlating the timing of activity in the south with that of the east. The present dune activity on the southern coast may, therefore, also be correlated to activity on the eastern coast of Australia (Short 1988).

From his observations, Short (1988) developed a description of the sequence of dune building on Australia's southern coast. Primary dune forms, or foredunes, probably began forming between 11,000 and 6,000 B.P. during the PMT. Following the stillstand, sand supply diminished and foredune instability led to the formation of the secondary parabolic dunes and blowouts.

In Europe, the majority of coastal dune research is conducted in the Netherlands. Arens et al (1995) studied the flow of wind over dunes in the

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Netherlands. Their research focused upon Dutch foredunes in three different geographical locations. The Schiermonnikoog study site had low, vegetated foredunes that had been stabilized over a period of 16 years using sand fences. At Groote Keeten they observed high, unvegetated foredunes with steep seaward-facing slopes. The third site at Nieuw-Haamstede had heavily vegetated, stabilized foredunes that reached heights over 20 m (Arens et al., 1995).

The methods employed by Arens et al (1998) included the collection of relative wind speed and wind direction at different topographical positions on the foredunes. Sampling in this fashion provided insight as to where deposition and erosion was occurring on foredunes. Their research led to several conclusions about the airflow over foredunes and its relationship to sediment transport (Arens et al., 1995).

On dunes less than 20 m high, sand could be transported from the beach to the foredune, even in the presence of dense vegetation. The foredune ridges act like a sandtrap. Thus, landward transport of sand from the foredunes is negligible. Topography is a predominant influence upon wind speed. Maximum speed-up of the airflow increases with height of the foredune. This results in a dramatic increase of the sand-carrying capacity of wind over foredunes. A final conclusion drawn from the Arens et al (1995) study is that there is a direct relationship between wind direction and relative wind speed. Winds perpendicular to the beach cause deceleration of winds at the dunefoot

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and favors deposition there. This process decreases as the winds turn parallel to the beach. Maximum speed-up also occurs with perpendicular onshore winds, smaller with oblique winds, and absent with parallel winds (Arens et al., 1995).

A final example of international research of coastal dunes is in North America. Orme (1990) studied the timing and causes of coastal dune activity at Morro Bay, California. Here, coastal dune activity is divided into four main phases: young paleodunes with a maximum age of 27,000 B.P.; older parabolic dunes with maximum age of 4,160 B.P.; younger parabolic dunes and lobate dunes with maximum age of 1,730; and active dunes that are less than 200 years old. Thus, the coastal dunes in Morro Bay have a record of episodic deposition and reactivation (Orme, 1990).

The Pleistocene deposits in the young paleodunes are most likely associated with an interstadial interlude shortly after 27,000 B.P. The most probable scenario for formation of the older parabolic dunes was the end of the Flandrian transgression. At the end of the transgression, they most likely began to form as barchnoid or transverse dunes. As sea level stabilized, sediment supply to these dunes was probably lost and subsequent blowing out of these dunes occurred, forming parabolic morphologies. The younger parabolic dunes were most likely a result of erosion of the older parabolic dunes due to fires and loss of stabilizing vegetaton (Orme, 1990).

The recent, active dunes are a result of several influences over the last 200 years, with the most intense dune activation occurring since 1947. Destruction of vegetation i

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vegetation from fire, grazing, off-road vehicle, and military activities are probable influences on the recent instability of this dunefield. Modification of the Morro Bay entrance channel and the repositioning of Morro Creek is another possible influence. Lastly, relative sea-level rise could be another possible influence driving recent dune activation. The most relevant conclusion Orme (1990) presented is that the impacts of natural forces are being augmented by human activities and will present management challenges in the future (1990).

Lake Michigan Coastal Sand Dunes

The research regarding Lake Michigan coastal dunes can be broadly categorized into two bodies of investigation: ecological and vegetation studies, and geomorphic studies. The early research focused on the ecology of coastal dunes and was mostly qualitative in nature. Subsequent studies were geomorphological in nature and became increasingly quantitative.

Role of Vegetation in Lake Michigan Dune Environments

Cowles (1899) considered Lake Michigan dunes to be a unique environment to study plant succession due to the harsh conditions for survival. In this region, dune plants must endure temperature and sunlight extremes; strong, sustained winds, nutrient-poor soils, and scanty water supplies due to highly permeable sand (Cowles, 1899). Cowles (1899) studied dunes in Indiana Dunes State Park, on the southern shores of Lake Michigan.

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According to Cowles (1899), the coastal dune environment can be described in terms of ecological stages. The most basic stage is the beach, then in succession, stationary beach dunes, active or wandering dunes, arrested or transitional dunes, and passive or established dunes. The beach zone is the harshest of the environments. Plants that occupy the beach zone must endure intense sunlight and strong, desiccating winds. The conditions for plant survival become less severe with each successive stage. Established dunes must pass through several stages before culminating in a diversified, deciduous forest (Cowles, 1899).

Olson (1958a, 1958c) expounded upon Cowles' description of dune formation, characterizing the ecological stages as successional stages. Olson's dune succession consisted of three primary stages: pioneer, intermediate and mature. According to Olson (1958a), pioneer stage communities are found on dunes near the lake and must tolerate the constant influx of sand, while dunes inland receive little input of sand and can support perennial vegetation (1958a, 1958c).

Olson's (1958a, 1958c) studies concluded that the succession of plants on Lake Michigan coastal dunes starts with the growth of American beachgrass (*Ammophilia breviligulata*), which stabilizes incipient dunes so that other species of plants may take root. American beachgrass, is tolerant of erosion and is dependent upon sand accumulation for vigorous growth. Thus, American beachgrass is found in areas that offer little stability and protection from wind

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erosion and sand deposition. Because American beachgrass has adapted to such harsh environments, it is associated with the formation of foredunes near the lakeshore (Olson, 1958c).

Sand reed grass (*Calamovifa longifolia*) is often found with American beachgrass and is considered a major stabilizer of eolian sand. This pioneer grass is generally found where sand deposition rates are lower than in areas occupied exclusively by American beachgrass or on nearly stabilized dunes. Sand reed grass is also less tolerant to wind erosion than American beachgrass (Olson, 1958c).

The presence of little bluestem bunchgrass (*Andropogon scoparius var. septentrionalis*) on a dune indicates a great reduction in sand deposition as compared to dunes inhabited by sand reed grass or American beachgrass. Therefore, little bluestem bunchgrass indicates a dune that has been stable for a few years (Olson, 1958c). Likewise, the presence of cottonwood (*Populus deltoids*) and balsam poplar (*Populus balsamifera*) shrubs indicate a nearly stable dune. These shrubs are also able to grow even if partially buried by sand (Olson, 1958c).

Sand deposition greatly decreases or ceases with increasing distance from the lake, allowing the growth of herbaceous perennials and woody shrubs and trees to replace that of the pioneer plants. These plants indicate the intermediate stage of succession and generally inhabit dunes that are mostly stable and receive little sand deposition (Olson, 1958c). Red osier dogwood (*Cornus* *stonifera*), choke cherry (*Prunus viriana*) and sand cherry (*Prunus pumila*) inhabit dunes in the intermediate stage of succession. These shrub species establish rapidly once sand deposition stops or slows to a few centimeters per year.

The last stage of plant succession on dunes is the mature stage, when dunes are fully stabilized. Little or no deposition of sand occurs on stabilized dunes. White pine (*Pinus strobus*) and jack pines (*Pinus banksiana*) become predominant upon dunes stable for several decades or centuries, replacing the intermediate plant communities. Hardwoods such as red, black and white oak (*Quercus rubra, Q. velutina*, and *Q. alba*), and sugar and red maples, (*Acer saccharum* and *A. rubrum*) replace the coniferous species once the dunes stabilize (Olson, 1958c).

Although ecological and geomorphic research on Lake Michigan coastal dunes continued after Olson, Lichter's (1998) work was the next significant research to build upon Olson's methods and theories. His research was conducted in northern Michigan at Wilderness State Park in Emmet County. The dunes in his study area were primarily a sequence of dune-capped beach ridges that formed during episodes of receding lake levels or during low lake levels phases. The growth of vegetation on these beach ridges acts as a site for dune formation and is also integral to secondary development of coastal dunes. The ability of vegetation to stabilize the dunes during high lake levels and wave erosion determines whether beach ridges retain their shoreline parallel configurati

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configuration or develop blowouts that will gradually form parabolic dunes (Lichter, 1998).

Lichter focused on young beach ridges, less than 500 years old, because vegetation changes are most pronounced on these young dunes. His research revealed patterns of vegetation succession similar to those described in Cowles (1899) and Olson (1958a), with the addition of timing associated with the successional stages. The first dune ridge was less than 25 years old and was dominated by beach grass, but other pioneer species (willow (*Salix* spp.) and sand cherry) were also present. On older, inland dune ridges (55-175 years old), beach grass declined and shrubs such as bearberry (*Arctostphylos uva-ursi*) and juniper (*Juniperus communis*), and little bluestem bunchgrass dominated. This vegetation was succeeded by mixed pine forest on dune ridges that were 225-440 years old (Lichter, 1998).

Geomorphic Research on Lake Michigan Coastal Dunes

Coastal dune research on the Lake Michigan shoreline has not been limited to ecological research. Geomorphic research related to Lake Michigan coastal dunes has concentrated on the processes controlling dune formation, lake-level oscillations and the timing of dune evolution (e.g. Dow, 1937; Olson, 1958d; Dorr and Eschman, 1970; Buckler, 1979; Thompson and Baedke, 1997; Arbogast and Loope, 1999; Loope and Arbogast, 2000).

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Dow (1937) noted that many of the sand dunes of northern Lake Michigan exist on high headlands; thus, he referred to them as "perched dunes." The term perched dunes refers to eolian bedforms that overlay non-eolian sediments and are elevated above the present lake level. This includes dunes that are perched high above the lake on moraines and those dunes that overlay the postglacial beaches of the Nipissing and the Algonquin Great Lakes. Dow (1937) investigated perched dunes at Sleeping Bear Point in Empire, MI to determine the driving processes behind the formation of the dunes perched atop the Port Huron Moraine.

Dow (1937) concluded that the majority of the sand supplied to the dunes is fine sand blown up from the moraine. The fine sands from the moraine begin their journey upward when the steep slip faces erode, exposing fresh material to eolian transport. The coarse particles slide downward due to gravity, while the fine particles are entrained by strong winds and deposit atop the bluff. Dow also noted that erosion of the moraine is accelerated when lake levels are high and when waves directly undercut the bases of the bluffs (1937).

Whereas Dow (1937) focused his research on large, perched dunes, Olson (1958d) studied the processes involved in the development of foredunes. Olson's research was conducted on the southern shores of Lake Michigan. According to Olson (1958d), foredune formation is dependent upon oscillations in lake level, which he predicted occurred roughly every 30 years.

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Foredune ridge formation commonly begins in the shallow waters offshore where waves break and subaqueous ridges form. When lake levels drop, these beach ridges become subaerially exposed. This drop in lake level leaves wide expanses of beach open to eolian transport. An eolian cap forms on the ridge and is colonized by pioneer vegetation. This in turn will initiate the formation of new foredunes or widen pre-existing foredunes. When net sand accumulation is too low to form offshore bars, beach ridges will form at the former berm, or wave-cut cliff with a drop in lake level. These beach ridges then become capped with eolian sand, thus forming foredunes (Olson, 1958d). As vegetation stabilizes these foredune ridges they become preserved upon the landscape.

A series of 90 such preserved beach ridges from Gary to Hammond, Indiana provided a chronosequence for Olson (1958d) to determine the timing of lake level oscillations that relate to foredune formation. Radiocarbon dating provided a 2700-year period of time for the formation of these 90 beach ridges. Because the beach ridges were spaced in relatively even intervals, Olson (1958d) was able to estimate that the 30-year interval for lake level oscillations relevant to the formation of foredunes.

After Olson's (1958d) work, there is an extended gap in significant research on the geologic characteristics of Lake Michigan coastal dunes until Buckler's work in 1979. In response to the State of Michigan Sand Dune Protection and Management Act (Act No.222, P.A. 1976), Buckler (1979) established

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established a dune classification scheme for Lake Michigan coastal dunes based on dune form, relative relief, orientation, arrangement, and the relationship of the dune form to the underlying material (Buckler, 1979).

Buckler (1979) identified nine dune forms in his classification scheme, some of which are not genetically eolian deposits but were, nonetheless, desired to be protected under the Sand Dune Protection and Management Act. The dune forms Buckler (1979) defined in his classification scheme were parabolic dunes, linear dune ridges, dune terraces, dune platforms, domal dunes, complex dune fields, dune flats, marginal sand aprons, and interdune lowlands. The most commonly identified features in his classification were parabolic dunes, linear dune ridges, dune terraces, complex dune fields, dune flats and marginal sand aprons. The discussion of Buckler's (1979) research will focus upon these most commonly identified dune forms.

Parabolic dunes are perhaps the most frequently noted dune forms in the Lake Michigan coastal environment (Buckler, 1979). They are bow-, U-, or hairpin-shaped with limbs that increase in height inland. The limbs of parabolic dunes are generally oriented perpendicular to the shoreline, although at times they are obliquely oriented. The windward slopes of parabolic dunes are characterized by concave, relatively gentle slopes that steepen near the crest and apex. The leeward slopes of parabolic dunes are convex and steep (Buckler, 1979).

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Linear dune ridges are long ridges of sand that are most commonly oriented parallel to the present shoreline (Buckler, 1979). Frequently, linear dune ridges have a gentle lakeward slope and a steeper leeward slope. However, when ridges are found adjacent to the lake the lakeward slopes may be scarped. Ridges may be found as singular features or in multiples with swales between ridges. (Buckler, 1979).

A dune terrace is typically parallel to the shoreline and is bounded by a higher bluff slope on one side (a dune form, moraine, or another terrace) and lower relief on the opposite side (usually the beach; Buckler, 1979). The surface is usually level, but may be somewhat hummocky. The terrace may have gentle to rather abrupt slopes and is generally less than 15 feet (4.6 meters) above the lower level. Dune terraces may also be somewhat irregularly shaped, especially if associated with the margin of another dune type (Buckler, 1979).

Complex dune fields are generally characterized by hummocky, chaotic terrain where the dunes lack orientation (Buckler, 1979). Slopes may vary from gentle to steep and the relief may appear undulating, or rugged. Complex dune fields may be transitional zones between two different dune types (Buckler, 1979).

A dune flat is a smooth, gentle or horizontally sloped depositional surface (Buckler, 1979). Dune flats are not specifically eolian features and largely apply to sandy deposits of lacustrine origin (Buckler, 1979). Marginal sand aprons are transitional zones along the landward side of a sand dune area (Buckler, 1979).

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Dune sand may or may not be continuously dispersed over the surface. In some areas it may only be a thin deposit and in other areas it may be deflated. Generally, the relief in marginal sand aprons is not determined by dune forms but by the underlying material. However, some isolated dune types might be found on marginal sand aprons (Buckler, 1979).

Buckler (1979) also delineated "barrier dunes," which are additional features protected under the Sand Dune Protection and Management Act of 1976. Because the legal definition of a barrier dune (in Michigan) is ambiguous, Buckler (1979) decided not to include it in his dune form classification scheme. Rather, he listed the barrier dune classification as its own separate entity (Buckler, 1979). According to Buckler (1979), a barrier dune is a sand dune formation that separates the shorezone from the inland environments.

Buckler (1979) believed that the barrier dunes in Michigan are the largest collection of freshwater dunes in the world. He also noted that once these features are destroyed, they will not be replaced under current climatic and geomorphic conditions (Buckler, 1979). According to Buckler (1979) these barrier dunes mostly formed during the Nipissing glacial lake stage and also while the Nipissing lake levels fell.

After Buckler's (1979) investigation, the geomorphic research on Lake Michigan dunes was not actively pursued again until the 1990's. The research in the early 1990's used beach ridges as indicators for prehistoric lake level fluctuations. This work built upon Olson's (1958d) study of foredune ridges, which are

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which are beach ridges with eolian caps. Thompson (1992) began this research in his study of the Toleston Beach strandplain of southern Lake Michigan. The strandplain is comprised of more than 150 beach ridges. Preserved within this series of beach ridges is one of the longest records of late Holocene lake level fluctuations in the Great Lakes (Thompson, 1992).

Thompson (1992) used vibracores to obtain material suitable for radiocarbon dating in the wetland swales between beach ridges. This method was performed under the assumption that the wetlands formed in the swales between beach ridges, shortly after the beach ridges formed lakeward of the swales. He also used vibracores from within the beach ridges to find foreshore deposits associated with prior lake levels and to determine the elevation of these deposits (Thompson, 1992).

Thompson's findings enabled him to create lake level curves for the southern Lake Michigan basin that extended back about 4,000 years. These curves revealed three scales of quasi-periodic lake level fluctuation. The shortest term and smallest scale fluctuation was approximately 31 years with an elevation fluctuation of 0.5 to 0.6 meters. This short cycle supports Olson's (1958d) roughly 30-year lake level oscillation. Additionally, Thompson's (1992) lake level curves showed an intermediate scale fluctuation with an occurrence of roughly 151 years and an elevation fluctuation of 0.8 to 0.9 m. The largest scale fluctuations were found to occur at 500 to 600 year intervals and with an elevation range of 1.8 to 3.7 m (Thompson, 1992).

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Moreover, Thompson (1992) suggested that though lake levels followed a general trend of decline after the Algoma highstand (3200 B.P.), there were long-term high stands at about 2300, 1700, 1175 and 600 B.P. The shoreline of southern Lake Michigan during these time periods was undergoing progradation, or progressive, lakeward deposition, while on the southeastern shores dunes were developed and building (Thompson, 1992).

Thompson and Baedke (1995) tested Thompson's (1992) results in the northern portion of the Lake Michigan basin at the Thompson Embayment beach ridge complex near Manistique, MI. Using Thompson's (1992) methods, Thompson and Baedke (1995) found results in northern Michigan to corroborate the three scales of quasi-periodic lake level fluctuations. However, the results differed in that the highstand around 1700 B.P. caused erosion of beach ridge profiles in the northern part of the basin at the Thompson Embayment, whereas no erosion occurred in the south at Toleston Beach. Thompson and Baedke (1995) concluded that this discrepancy was due to differences in sediment supply between the two regions.

Sediment supply along the southern shores of Lake Michigan is high because this region receives input from both the eastern and western shores of the lake. The southern portion of the lake is therefore a sediment sink. Thus, the high sediment supply offsets the landward progression of the shoreline as waters rise. The Thompson Embayment in the north received less sediment flux than the Tolest

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the Toleston Beach in the south, and thus, the rising water levels eroded the beach during this highstand (Thompson and Baedke, 1995).

Subsequently, Thompson and Baedke (1997) continued this work at five beach ridge complexes elsewhere in the Lake Michigan basin to determine long-term patterns of each ridge development and the timing of high lake levels. Similar methods to the previous studies were used, but a least-squares regression was used to balance extreme outliers in the radiocarbon data that may be due to contamination errors. This study links formation of small beach ridges to ~30-year oscillations in lake-level. Groups consisting of approximately four to six beach ridges were found to have developed over a longer term, on the order of ~150-year fluctuations of lake-level (Thompson and Baedke, 1997).

More recent research has shifted from foredune and beach ridge research to the massive, transgressive dune complexes that so prominently mark the eastern coastline of Lake Michigan (Arbogast and Loope, 1999). These dunes are consistent in size and form as perched dunes (e.g., Dow, 1937), but have formed on topographically lower lake plains associated with the proglacial lake history (Arbogast and Loope, 1999). These lake-terrace dunes were believed to have largely formed between 6,000 and 4,000 B.P. (Hansel et al., 1985) during the Nipissing transgression of ancestral Lake Michigan (Dorr and Eschman, 1970; Buckler, 1979). However, this hypothesis had not been systematically tested until Arbogast and Loope (1999) conducted research on lake-terrace dunes along the shore of central lower Michigan.

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Arbogast and Loope (1999) used stratigraphical and radiocarbon dating methods to determine the approximate timing of dune evolution at four sites: Nordhouse Dunes (near Manistee, MI), the Nugent Quarry and Jackson Quarries (near Muskegon, MI) and the Rosy Mound Quarry (near Grand Haven, MI). Radiocarbon dates were obtained from buried soils formed within the uppermost lacustrine surfaces found at all four sites. The radiocarbon dates suggested that the onset of dune building was not concurrent between the sites. At the northern-most site, Nordhouse Dunes, these soils were buried by eolian deposits between 4,900 and 4,500 B.P. The cause of dune migration at this site was likely the result of rising waters during the Nipissing transgression (Arbogast and Loope, 1999). Rising lake levels would have destabilized the lakeward face of the lake terrace in a manner consistent with the perched dune model (e.g. Dow, 1937, Marsh and Marsh, 1987).

At the remaining sites, radiocarbon ages of buried soils found within the uppermost proglacial lake sediments suggest that they were buried by eolian sand after the Nipissing transgression and highstand. At the Nugent and Jackson Quarries, the lake-terrace soils were buried by eolian deposits between 4,300 and 3,900 B.P. Dune building here began as lake levels fell from the Nipissing highstand, but may be associated with bluff destabilization at a peak within the regression (Arbogast and Loope, 1999).

Burial of the lake-terrace soil at Rosy Mound Quarry occurred between 3,300 and 2,900 B.P. Dune building here correlates nicely with a peak after the

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Nipissing, the Algoma phase (Larsen, 1985), and thus probably occurred due to bluff destabilization and increased sand supplies caused by rising lake levels (Arbogast and Loope, 1999).

Arbogast and Loope (1999) also concluded that the models for dune evolution and behavior relative to lake levels was poorly understood and needed further exploration. In 2000, Loope and Arbogast continued their research on Lake Michigan coastal dunes. This research integrated the foredune and perched dune models of dune building to explain dune behavior on the eastern shore of Lake Michigan. Additionally, this research further established a link between eolian activity and lake level oscillations developed by Thompson and Baedke (1997). Most importantly, this study tested the hypothesis that dune building on the eastern Lake Michigan shoreline is related to the Nipissing transgression (i.e., Dorr and Eschman, 1970; Buckler 1979).

Loope and Arbogast's (2000) study area was comprised of 32 localities spanning over the eastern coastline of Lake Michigan. Seventy-five buried soils were identified throughout the study area and sampled for radiocarbon dating. The radiocarbon dates provided an approximate time of burial of these soils by eolian sediments. Of these samples, 64 had calibrated radiocarbon ages ranging from 4750 and 110 B.P. and were included in their analysis. Eleven of the soils dated as modern (Loope and Arbogast, 2000).

Loope and Arbogast (2000) concluded that dune building on the eastern Lake Michigan coastline was episodic during the late Holocene and alternated with per

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with periods of stability as evident from the presence of multiple paleosols interspersed between eolian sediments. The timing of soils burial also shows that a majority of dune building is linked to post-Nipissing lake level peaks. Moreover, 75 to 80% of the sand volume in a portion of their study area overlaid soils dated at 1,500 B.P. or younger.

Loope and Arbogast (2000) concluded that dune building at the Platte Bay portion of their study area between 3,500 and 1,100 B.P. began as a series of beach ridges (e.g. Thompson and Baedke, 1997); these beach ridges formed in accordance with Olson's foredune model (Olson, 1958d). When lake levels were low, foredunes capped many of the beach ridges (Loope and Arbogast, 2000).

Radiocarbon data from the Platte Bay area showed that during subsequent ~150-year peaks, the beach ridges were eroded by waves and scarped the ridges into lakeward-facing bluffs. Perched dunes formed in the lee of the bluffs as waves continued to erode the bluff. This suggests that dune building associated with the ~150-year peaks can be explained in accordance to the modified perched dune model (Dow, 1937; Marsh and Marsh, 1987; Loope and Arbogast, 2000). This model suggests that on proglacial lake-terraces, dune building occurs when lake levels are high and waves erode beach ridges, forming a lakeward-facing bluff. Sand dislodged from the bluff face via wave action is carried with the wind to deposit on the lee of the bluff (Loope and Arbogast, 2000).

In 2001, Lepczyk conducted research on coastal dunes at Petoskey State Park, outside the northern limits of Loope and Arbogast's (2000) study area.

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Lepczyk (2001) used radiocarbon dates obtained from organic material found in buried paleosols and optically stimulated luminescence (OSL) dating of eolian sands to establish limiting ages of the evolution of dunes within her study area. Lepczyk (2001) identified five geomorphic units in the park, with each unit successively located lakeward of the latter unit in a matter consistent with a transgressive dunefield.

The easternmost geomorphic unit was the Lake Terrace. The elevation of these sediments corresponds with Nipissing lake levels. These sediments were found under the next geomorphic unit, the massive parabolic dunes (Lepczyk, 2001). The results from Lepczyk's (2001) study reveals that dune building of the massive parabolic dunes began around 4800 to 4400 B.P. as lake levels rose during the Nipissing II transgression. OSL dates collected from the uppermost unit of eolian sand suggest that dune building continued until approximately 2060-2300 B.P. at the southern end of the dunefield and 980-1080 B.P. at the northern end of the park (Lepczyk, 2001).

The third geomorphic unit identified by Lepczyk (2001) in Petosky State Park was the inset dunes. Field observations and radiocarbon dating suggest that this unit is formed upon shorezone, lacustrine sediments from the Nipissing II trangression. As lake levels dropped, lacustrine sands and an eolian cap were deposited over the shorezone deposited. A soil formed at around 2800-2700 B.P., indicating a period of stability that corresponds with the Algoma transgression. The soil was buried by eolian deposits, indicating that dune building had been reactivat

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reactivated at the end of the Algoma transgression. An OSL date suggests that dune building ceased in this geomorphic unit at about 1750 B.P. (Lepczyk, 2001).

The fourth geomorphic unit identified by Lepczyk (2001) had no buried soils to sample for radiocarbon dating. However, the elevations of the underlying lake sediments suggests that these dunes formed over lacustrine sediments from the Algoma transgression. Thus, dune building in this unit likely occurred after the Algoma transgression. Because of the lack of datable material, Lepczyk used results from Thompson and Baedke (1997) to provide a minimum limiting age for the incipient dune unit of approximately 1300 B.P. (Lepczyk, 2001).

The last unit identified by Lepczyk (2001) was the active dunes and beach unit. Stratigraphic evidence correlates with work conducted by Thompson and Baedke (1997) and suggests that this unit has formed within the last 1,000 years. From radiocarbon dates obtained from buried soils within this unit, Lepczyk (2001) determined that there were at least 3periods of eolian activity in the active dunes and that dune building alternated with periods of stability.

The timing of dune building of these three periods was at 0-300 B.P., 470-290 B.P. and 515-315 B.P. Lepczyk (2001) also notes that soil development in these buried soils is weak, indicating the periods of stability were very brief. The active unit was also problematic from a park management standpoint, as migrating sand threatened to bury over some of the park's campground area due to natural and human induced processes (Lepczyk, 2001).

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The conclusions of Lepczyk's (2001) study suggest that dune building of the massive dunes at Petoskey State Park occurred within the last 4,000 years, corroborating the earlier work of Loope and Arbogast (2000). Additionally, Lepczyk (2001) found that eolian activity within Petoskey State Park was cyclic, alternating between periods of dune building and stability. Furthermore, Lepczyk (2001) compared Thompson and Baedke's (1997) lake level curves to results from her study. The comparison suggested that these changes are most likely related to lake level fluctuations (Lepczyk, 2001).

Van Oort et al. (2001) also expanded the research of Loope and Arbogast (2000) to determine the dune building of large, parabolic dunes on the southeastern shore of Lake Michigan. Van Oort et al. (2001) studied dunes in Van Buren State Park near South Haven, MI. In their investigation, Van Oort et al. (2001) mapped and classified buried soils in exposed dune faces, and collected samples from the A-horizons of the buried soils for radiocarbon dating.

The stratigraphic evidence and radiocarbon dates suggest that the dunes in Van Buren State Park started building on lacustrine deposits around 5,500 B.P. during the Nipissing high stand (Van Oort et al., 2001). Active dune growth continued until about 3,500 B.P. Paleosol development and configuration suggested that the dunes began as low foredunes that merged into dune platforms (Van Oort et al., 2001). The lower sequence of alternating eolian sand and weakly developed soils (Entisols) suggest that dune building during this early period was episodic (Van Oort et al., 2001).

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Above the lower Entisol sequence is a moderately developed soil (an Inceptisol). Four samples collected across the study area revealed overlapping radiocarbon dates in the range of 500-0 B.P. (Van Oort et al., 2001). The presence of a buried Inceptisol at Van Buren State Park indicates a relatively long period of stability (Van Oort et al., 2001). In the north central portion of their study area, an Entisol underlying the Inceptisol was buried by eolian deposits between 2,145 and 1,955 B.P. These radiocarbon dates suggest a period of stability that lasted at least 1,500 years (Van Oort et al., 2001).

An upper, alternating sequence of eolian sand and Entisols overlaid the Inceptisol throughout the Van Buren State Park study area. The resolution of the radiocarbon dating limited the ability to date these soils. The alternating sequence of eolian sand and Entisols implies a alternating periods of dune building and dune stability. Van Oort et al. (2001) were able to obtain a radiocarbon date from the uppermost Entisol in the south central portion of their study area, revealing a burial date between 200 and 0 B.P., with activity still continuing at the time of publication (Van Oort et al., 2001).

From the results of their study, Van Oort et al. (2001) concluded that the dune evolution at Van Buren State Park was similar to dunes south of Holland, MI studied by Arbogast et al., 1999. Both dune areas showed episodic dune growth that began during the Nipissing high stand, followed by an Inceptisol that marked a long period of stability, and lastly a new period of dune migration that buried the Inceptisol and is still active at present (Van Oort et al., 2001).

However, radiocarbon date evidence suggests that the onset of the period of stability, which formed the Inceptisol, may have been somewhat earlier in Holland than at Van Buren State Park (Van Oort et al., 2001). Additionally, the onset of the new period of dune migration may have begun slightly earlier at Holland than at Van Buren State Park (Van Oort et al., 2001).

Van Oort et al. (2001) also note that a study in Indian Dunes State Park also indicates that dune building there began at approximately the same time and an Inceptisol was observed there that was buried approximately 300 B.P. by eolian sand (i.e. Gutschick and Gonsiewski, 1976). This evidence, coupled with the evidence in Van Buren State Park and Holland, MI suggests that the barrier dunes on the southeastern shore of Lake Michigan share similar geomorphic histories (Van Oort et al., 2001).

The most recent research from Arbogast et al. (2002) further tested the results from Loope and Arbogast (2000) and Van Oort et al. (2001) in an approximately 1-km section of coastline south of Holland, MI. For the Holland study, Arbogast et al (2002) used dune stratigraphy and radiocarbon dates from soils buried by eolian sediment to reconstruct the evolution of these dunes in relation to lake level fluctuations.

Arbogast et al. (2002) concluded that dune building at the Holland site was episodic and interrupted by brief periods of stability. Dune growth began during the Nipissing high stand (~5,500 B.P.). After this initial growth, the dunes grew rapidly between ~4,000 and 2,500 B.P. This early period of growth

correlates best to conditions of falling lake levels. Thus, sand was likely supplied to the dunes from the broad, exposed beach in accordance with Olson's (1958d) foredune model. Later periods of dune building at 3,200 B.P., 2,400 B.P., and 900 B.P. were most likely tied to high lake levels and is consistent with the perched dune model suggested by Loope and Arbogast (2000).

Additionally, an extended period of stability was found at each dune site, marked by a buried Inceptisol (Arbogast et al., 2002). The radiocarbon dates of the underlying Entisols indicate that the period of stability lasted approximately 2,000 years. The Incepticol was buried between 900 and 500 B.P. (Arbogast et al., 2002). In the past 500 years, the dunes have had episodic periods of migration and stability, with dune migration observed at present (Arbogast et al., 2002). These findings correlate well with the findings of Van Oort et al. (2001), suggesting that these dunes share a common geomorphic history with dunes in Van Buren State Park.

Remote Sensing in Dune Areas

Most of the research regarding Lake Michigan coastal dunes has been facilitated through exhaustive and time-consuming field surveys and data collection in the field. In many cases, remote sensing can be used to provide quantitative information, while reducing the amount of time spent in the field. Remote sensing is also an effective technique for many monitoring and inventory purposes (Somers et al, 1991).

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Remotely sensed data acquisition can be facilitated through the use of aerial photography, satellite imagery, and spectral data collected from various sensors, amongst other methods. Data collected using these remote sensing methods may be analyzed to produce information about objects, areas, or phenomena (Lillesand and Kiefer, 2000).

In coastal dune research, remote sensing has been applied as a precursor to many of the field studies. For example, many researchers will collect and examine aerial photography before conducting field surveys or to qualitatively describe the landscape conditions for their study areas (e.g. Olson, 1958a; Hazlett, 1981; Pye and Bowman, 1984; Jungerius et al., 1991; Lichter, 1994, 1998).

Remote sensing may also be applied to dune environments in quantitative analyses. Stembridge (1978) used aerial infrared photography to explore methods to detect dune growth upon vegetated coastal dunes in North Carolina. He developed a method that used image intensity as a proxy for sand accretion. *Ammophila breviligulata* grows vigorously where there is sand accretion. The presence of both *Ammophila* and newly deposited sand produced areas of high image-density on color infrared photography. A comparison of mean image density and mean dune elevation showed a high positive correlation between image density and sand accretion (Stemridge, 1978).

Remote sensing platforms can also provide quantitative data to study phenomena over time. Temporal effects influence virtually all remote sensing operations. The process of change detection is based upon the ability to measure tempo

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temporal effects. Change detection uses multitemporal data to determine areas of land cover change between successive dates of imagery (Lillesand and Kiefer, 2000).

For example, Businski (1992) used aerial photography to interpret vegetative cover change from 1938 to 1987 on the Sleeping Bear Dunes complex in Michigan. This research resulted in land cover maps in addition to estimates of the acreage and fragmentation of the land cover. Businski (1992) concluded that vegetation cover types became more fragmented through time. Additionally, she determined that while certain land cover types lost acreage (Forest, Continuous Grass and Unvegetated), other vegetation cover types gained acreage (Discontinuous Grass and Grass and Shrubs) (Businski, 1992).

Additionally, Fransaer (1992) employed aerial photography in concert with field surveys to produce differential dune vegetation maps of coastal dunes in Belgium and the Netherlands. These maps were produced first by interpreting vegetation cover classes from aerial photography from 1982-1991. A differential dune vegetation map was then constructed that highlighted areas of vegetation change. Similarly, topography was collected for the dunes during the same time period and a differential topography map was created to show areas of topographic change. When overlaid upon each other, the differential dune vegetation and differential topography map revealed a direct link between changes in land cover and evolution of topography (Fransaer, 1992).

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Brown and Arbogast (1999) also performed a change analysis. In their study they used aerial photography to estimate sand flux from 1965 to 1987 on coastal dunes in Ludington State Park, Michigan. In their research, Brown and Arbogast (1999) used softcopy photogrammetry to produce digital elevation models (DEM) representing different time periods. Through cut and fill analysis, the DEMs were then employed to map and visualize topographic change, as well as quantify volumetric changes in sand accumulation. Blowouts were observed wherever dune elevations had substantially decreased between the two time periods. Additionally, the cut and fill analysis revealed that sand aggradation in Ludington State Park exceeded sand degradation (Brown and Arbogast, 1999).

Although the aforementioned research has integrated aerial photography into the investigations, satellite imagery has also been used to quantify data in dune environments. When Landsat 1 was launched on July 27, 1972, satellite imagery improved the study of sand dunes around the globe (McKee, 1979). The imagery from Landsat 1 was used in a project called "The Morphology, Provenance, and Movement of Desert Sand Seas." This project facilitated descriptions of dune form and distribution, in addition to comparing dunes in different regions of the world (McKee, 1979).

More recent research involving Landsat imagery has also been conducted. In their study of dunes in northwest Botswana, Jacobberger and Hooper (1991) used Landsat Thematic Mapper (TM) imagery to analyze reflectance patterns of land cover. Their research suggests a geomorphological link with reflectance and Normalized Difference Vegetation Indices (NDVI). They also concluded from NDVI that dune crests had higher seasonal variability than interdune corridors, even though total vegetation density could be equal in both areas (Jacobberger and Hooper, 1991).

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Chapter 3

Study Area

The study area for this investigation is Warren Dunes State Park (WDSP). Various recreational activities at WDSP attract over one million visitors per year. These activities include, but are not limited to: camping, swimming, hiking, picnicking, hunting, and skiing. The park features massive, active coastal dunes, some rising nearly 76 meters (240 feet) above the lake. Because WDSP is an important recreational resource to the State of Michigan, one might assume that a fair amount of research has been conducted within the park. However, very little published research is available about WDSP.

The park is a large (7.9 km^2) park located along the southeastern shore of Lake Michigan. It is located within Berrien County (T6S, R20W) and extends 5.2 km in a northeast-southwest direction and 1.5 km from east to west. Red Arrow Highway and Interstate 94 border the park to the east, the city of Bridgman abuts the park to the north, and Browntown Road lies to the south of the park (Fig. 3:1).

Topographic relief within the park varies from 176.5 m (approximate mean lake level for Lake Michigan, NGVD 1929) to approximately 245 m (USGS, 1978). The majority of the park can be described as barrier dune, according to Buckler's (1979) classification scheme. However, more specific dune forms identified within the park are linear dune ridges, parabolic

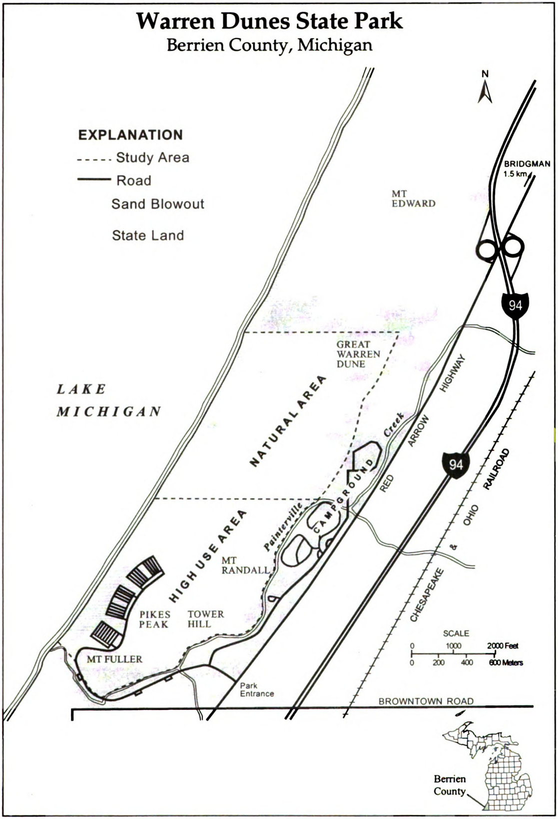

Figure 3:1. Map showing Warren Dunes State Park, including the "High-Use Area" and "Natural Area" (Modified from MDNR, 1996).

dunes, dune platforms, a marginal sand apron and dune flats (Buckler, 1979).

The terrain is marked by massive, active blowouts, some extending approximately 1,030 meters inland from the lakeshore (as measured at the greatest extent of Mt. Randall; Fig. 3.2). The eastern portion of the park features forested dunes with weakly developed soils and low areas behind the dunes with poorly drained soils (Larsen et al, 1980).

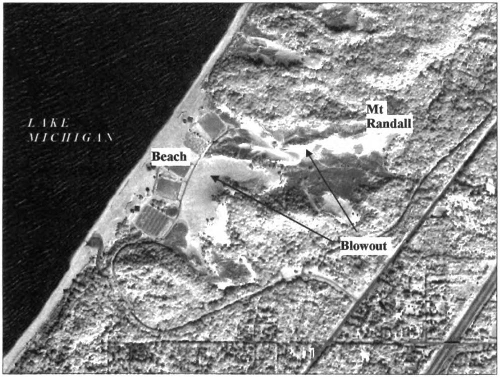

Figure 3:2. IKONOS image of WDSP depicting the extent of the blowout near Mt. Randall and the beach in 2001.

From a management perspective, the park can be divided into two areas, which will be referred to as the "High Use Area" and the "Natural Area" (Fig. 3:1). The High Use Area is a recreational area and thus experiences heavy foot traffic.

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traffic, especially in the summer when the park beaches are open. The Natural Area receives less foot traffic because it is located away from the beach areas. This division was based upon information provided by the park manager (Hill, Richard, Park Manager WDSP, personal comm., 2000) and from the MDNR (1996) map of the park.

Late Quaternary Geology

Fluctuations in Lake Michigan water level have played a significant role in sediment supply to Lake Michigan coastal dunes, and thus, have been a significant factor in the building of dunes (Arbogast and Loope, 1999). In order to understand the formation of the dunes within WDSP, a discussion of the geologic history of the Great Lakes is necessary.

The modern landscape of southwestern lower Michigan is mainly the result of geomorphic processes since the latter portion of the Late-Wisconsin glacial period. When the ice sheet advanced into the Great Lakes region, ice moved via the path of least resistance into old river valleys and divided into lobes. The ice lobes broadened and deepened these pre-existing valleys as the ice advanced over Michigan. The lobe that enlarged the Lake Michigan basin is known as the Michigan Lobe (Farrand, 1988).

Throughout most of the Late-Wisconsin glacial, Michigan was covered by several thousand feet of ice (Dorr and Eschman, 1970). The last readvance of ice into the study area occurred in approximately 14,000 B.P. and formed the Lake

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Border Moraine (Hansel et al, 1985). This moraine occurs just outside the study area, approximately 3.5 kilometers east (USGS, 1978) of the present Lake Michigan shoreline (Dorr and Eschman, 1970). From that time until the mid-Holocene, the lake levels of ancestral Lake Michigan fluctuated in response to glacial readvance and retreat and isostatic rebound (Eschman, 1985; Hansel et al, 1985; Farrand, 1988; Chrzastowski and Thompson, 1992).

The most prominent of these lake level stages relative to the WDSP study area is the Nipissing Phase, which peaked around 4,700 to 4,000 B.P. (Hansel et al, 1985). During the Nipissing phase of Lake Michigan intense wave action and currents were probable. The Nipissing phase persisted roughly 1,000 years before gradual outlet incision and differential uplift caused a lower lake stage, the Algoma, around 3,800 B.P. Lake-level continued to drop to modern elevation following the Algoma phase, with fluctuations attributed mostly to climatic variability during the late Holocene (Hansel et al, 1985).

Previous studies have linked the timing of dune building of the massive coastal dunes along the eastern Lake Michigan shoreline almost exclusively to the Nipissing transgression (6000 to 4000 years B.P.), when lake-level slowly rose to levels above the modern lake elevation (Dorr and Eschman, 1970 and Buckler, 1979). However, recent research (Arbogast and Loope, 1999; Loope and Arbogast, 2000; Van Oort et al., 2001; Arbogast et al, 2002) on Lake Michigan coastal dunes suggests that the dune building has been episodic and cannot be linked solely to one event.

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Van Oort et al. (2001) conducted research approximately 64 km (40 miles) north of WDSP on massive coastal dunes in Van Buren State Park. Their study area has dunes similar to those found in WDSP. As indicated by soils buried under eolian deposits, dune building at Van Buren State Park has been episodic and interrupted by periods of stability. The dunes at Van Buren State Park began to form during the Nipissing high stand, approximately 5,500 B.P (Van Oort et al., 2001).

A lengthy period of stability followed the initial, episodic dune building at Van Buren State Park, lasting approximately 1,500 years. This period of stability resulted in the formation of well-developed soil. Dune building was reinitiated approximately 500 B.P., burying the soil with eolian sand. The presence of alternating paleosols and eolian sand indicates that dune building has been interrupted by periods of stability. Dune building is presently active within Van Buren State Park (Van Oort et al., 2001).

Van Oort et al. (2001) concluded that dunes of the southeastern Lake Michigan shoreline might share a common geomorphic history. These findings remain untested on the dunes within WDSP. However, paleosols were observed on active, eroded dune surfaces during field surveys for this investigation. The presence of such paleosols buried within eolian sand indicates episodic periods of stability and dune growth. Radiocarbon dates collected from these buried soils may reveal a geomorphic history similar to that of Van Buren State Park.

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Climate

The climate within the study area is humid cold, with no dry season and hot summers (deBlij and Muller, 2000). Air temperature is moderated by prevailing south-southwest winds from nearby Lake Michigan (Larson et al., 1980). Humidity is also influenced by the lake, with average relative humidity in midafternoon at 63 percent. Average relative humidity is higher at night, with the average humidity reaching about 82 percent in the morning (Larson et al, 1980).

The closest coastal weather station to the study area is at Benton Harbor, MI (approximately 27.5 km north), which has been collecting temperature and precipitation data since 1881 (NOAA, 2001). Mean monthly precipitation values range from 110.74 mm in September to 44.96 mm in February, with a mean annual precipitation of 948.18 mm. (NOAA, 1999). Average seasonal snowfall for the study area is 170.18 cm (Larson et al, 1980).

Mean monthly temperature ranges from –4°C in January to 22°C in July, with a mean annual temperature of 10°C (NOAA, 2001). The lowest recorded temperature was on January 12, 1918 at –29°C. The highest temperature on record was on June 25, 1937 at 43°C (Larson et al., 1980). Sunny conditions are observed 67 percent of the time in summer and 37 percent of the time in winter (Larson et al, 1980).

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Soils

The soils within Warren Dunes State Park are categorized within the Spinks-Oakville-Oshtemo association. This association consists of well-drained sandy and loamy soils on moraines, till plains, outwash plains and beach ridges. A total of five soil series were identified by Larson et. al (1980) within the park: Oakville fine sand, Gilford sandy loam, Pipestone sand, Granby loamy fine sand, and Morocco loamy sand. However, the predominant soil series is Oakville, found on the forested dune areas. The other four soils are in the lowland areas of the park behind the dunes and outside the area of interest for this thesis.

Areas mapped as dune land by Larson et al (1980) are found adjacent to beaches and in blowouts (Larson et. al, 1980). This material was likely deposited within the late Holocene and is generally very pale brown (10 YR 7-8/4) to light gray (10 YR 7/2) (Stone, 2001). The dune land consists of actively shifting sand with little or no protective vegetative cover. Soils have not yet developed in these areas due to the actively blowing sand. Conversely, the stable, forested dunes are comprised of Oakville soils. Oakville fine sands are classified as mixed, mesic, Typic udipsamments (Larson et. al, 1980). The parent material for this soil is fine, yellow (10 YR 7/6) dune sand and is classified as a middle Holocene deposit, possibly related to Glacial Lake Nipissing (6000-4000 B.P) (Stone, 2001). These are weakly developed soils with A/E/B/C horizonation.

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These soils are well drained with rapid to very rapid permeability (Larson et. al., 1980).

Vegetation

Prior to settlement, natural vegetation upon the dunes consisted of central hardwood forest. These forested uplands were comprised of white oak (*Quercus alba*), black oak (Q. *velutina*) and hickory *(Carya species)*. The open dune areas were not noted in the original survey of 1830 (Corner et al., 1995). However, descriptions of massive expanses of open dunes in this area at the turn of the 20th century (e.g., Janette, 1919) may suggest that these open dunes were present during that initial survey but were neglected by the surveyors.

Current vegetation within the parkland is typical of that of Lake Michigan coastal dunes (Hoagman, 1994). Although the intent of this study was not to provide an exhaustive list of vegetative species found within the park, a minimal field survey was conducted on June 8 and 9, 2002 to present a general overview. Table 3:1 contains a list of vegetative species that were identified within the park, in addition to species commonly found upon Lake Michigan coastal dunes.

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Table 3:1

Vegetative species found within Warren Dunes State Park

GRASSES:	COMMON NAME:
* *Agrostis gigantea*	redtop grass
* *Ammophilia breviligulata*	American beachgrass (or marram grass)
* *Andropogon scoparius*	Little bluestem
* *Calamovilfa longifolia*	Sand reed grass
HERBACIOUS PLANTS:	**COMMON NAME:**
* *Arenaria stricta*	Rock sandwort
* *Artemisia campestris*	wormwood
* *Asclepias syriaca*	common milkweed
* *Cakile edentula*	Sea rocket
* *Equisetum arvense*	horsetail
* *Equisetum hyemale*	scouring rush
* *Lithospermum croceum*	hairy puccoon
* *Smilacina stellata*	starry false solomon's seal
* *Solidago sp.*	goldenrod
* *Toxicodendron radicans*	poison ivy
Vitis aestivalis	summer grape
* *Vitis riparia*	riverbank grape
SHRUBS AND TREES:	**COMMON NAME:**
* *Acer rubrum*	Red maple
* *Acer saccharum*	sugar maple
Arctostaphylos uva-ursi	bearberry
* *Cornus stolonifera*	Red-osier dogwood
* *Fraxinus americana*	white ash
Juglans cinerea	butternut
* *Juniperus communis*	common juniper
Juniperus virginiana	Red cedar
Larix laricina	tamarack
* *Liriodendron tulipifera*	Tulip tree
Pinus strobus	white pine
Populus balsamfera	balsam poplar
* *Populus deltoides*	cottonwood
* *Prunus pumilia*	Sand cherry
* *Populus tremuloides*	quaking aspen
* *Quercus alba*	white oak
Quercus rubra	northern red oak
* *Quercus velutina*	black oak
Salix syrticola	dune willow
* *Tilia americana*	American basswood
Tsuga canadensis	eastern hemlock
Ulmus americana	American elm

*** Denotes species identified in field**

Source: Developed from The Acorn, 1919; Olson, 1958a; Little, 1980; Marino, 1980; Hazlett, 1981; Businski, 1992; Hoagman, 1994; MDNR, 1996.

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Historic Land Use

Edward K. Warren, a prominent inventor and businessman from the village of Three Oaks (south of WDSP) purchased a 250-acre portion of the dune land in Lake Township, two miles north of Sawyer in Berrien county in 1919 (The Acorn, 1919). This purchase took place in an age when the railroad industry placed high demand on the sands quarried from coastal dunes. After witnessing the destruction of dunes near Michigan City, Indiana, Warren purchased the sand dune land to preserve it for future generations (Berrien Springs Era, 1917). As landowners reverted their agriculturally unproductive dune land back to the state, E. K. Warren purchased this land as a preservation measure (Galien River Watershed Project, 2002).

In the years prior to his death, Warren placed this dune land under the jurisdiction of the Warren Foundation. By Michigan law, a foundation allowed the land to be dedicated to public use and care while the landowner still held the title to the land (Janette, 1919). According to Alexander G. Ruthven, a professor at University of Michigan in 1919, this dune land had about 3,000 feet of Lake Michigan shoreline and had probably the largest dunes in the State of Michigan.

Professor Ruthven also had little doubt that the original vegetation prevailed in most areas of the property (The Acorn, 1919). Early visitors to the park describe in detail the bald sides and crest of the Great Warren Dune, providing evidence that the massive blowouts seen today were present even in

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1919. Visitors also describe tamaracks, elms and butternuts that were buried or threatened by moving sand.

George R. Fox, an early director of the Warren Foundation museum attempted to monitor this sand movement by placing a series of wooden stakes five feet apart at the foot of the Great Warren Dune. Fox estimated that the dune was moving inland at a rate of 1 foot per month (Janette, 1919).
Since 1938, the State of Michigan has continued to buy land adjacent to the Warren foundation land (Galien River Watershed Project, 2002). A small, northeastern portion of the parkland was owned by the Martin Marietta Corp., a sand mining operation, until the State of Michigan purchased it for Warren Dunes State Park in 1987 (Rockford Map Publishers, 1954, 1964, 1987).

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Chapter 4

Methods

In order to study the land cover changes on WDSP over time, historic and recent aerial photographs were digitized and orthorectified to create planimetrically correct images. The orthorectification was performed using ERDAS IMAGINE Orthobase and Orthobase Pro, version 8.5. Land cover was digitized from the orthophotos using ArcView GIS 8.2. Further data analysis and cartographic work was also produced using ArcView GIS 3.3 and ArcView GIS 8.2.

For the land cover change analysis, a period of at least 20 years of data covering at least three points in time was desired. This would provide starting and ending points, in addition to a middle point to compare whether rate of change was constant or varied. The time frame chosen for this investigation was from 1978-1999. This decision was made because supporting data for that time frame could be acquired. The following section describes the imagery and methods used to study land cover over this time frame.

Choice of Imagery

In the past, aerial photography has been the most commonly used method of remote sensing (Tueller, 1989). However, aerial photography has limited spectral sensitivity, which decreases its usefulness in the measurement of land cove

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cover (Tueller, 1989). Today numerous satellite platforms exist to collect remotely sensed data, including the SPOT series of satellites, the LANDSAT series of satellites, IKONOS and QuickBird to name a few.

The LANDSAT series of satellites collected imagery of the study area throughout the entire time period for this investigation (Lillesand and Kiefer, 2000). However, the ground resolution of LANDSAT imagery is limited to 79-meter for Multispectral Scanner data and 30-meter pixel size for the Thematic Mapper (Lillesand and Kiefer, 2000). Given that the changes within WDSP were hypothesized to be smaller than the resolution of the LANDSAT imagery, LANDSAT images were not chosen for this study.

Alternatively, the SPOT series of satellites offer better ground resolution at 20-meter ground resolution for multispectral imagery, and 10 m resolution for panchromatic imagery (Lillesand and Kiefer, 2000). However, because the first SPOT satellite (SPOT-1) was launched in 1986, SPOT series imagery has not been available throughout the desired period of study.

IKONOS and QuickBird offer high-resolution imagery and were launched in 1999 and 2000, respectively. Ground resolution for IKONOS imagery is 1-meter for panchromatic imagery and 4-meter limited multispectral imagery (Lillesand and Kiefer, 2000). QuickBird offers 0.61-meter ground resolution in panchromatic imagery and 2.5-meter resolution with limited multispectral data (DigitalGlobe, 2003). Although these satellite platforms offer high-resolution in

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imagery, both have been very recently launched and cannot be used for any long-term historical analysis prior to launch dates.

Given the difficulties with ground resolution and the questionable availability of long-term, repeat imagery within the study area, aerial photography was chosen as the image source for this investigation. In context of the goals of this study, aerial photography was chosen based upon several factors, including: scale, tonal quality, camera calibration report availability, and date of imagery. Scale was the overarching factor. Large-scale imagery is desired because it provides the most amount of detail. The scale should also remain constant, if possible, over the span of the imagery to minimize inconsistencies between the temporal datasets.

Aerial photography of the study area was available through a few different sources, with varying temporal coverage. In this context, the archives that were investigated were The Center for Remote Sensing and GIS Aerial Image Archive at Michigan State University; the MDNR, Land and Mining Resources Division; and the U.S. Army Corps of Engineers (USACE), Detroit District.

The Center for Remote Sensing and GIS Aerial Image Archive had historic aerial photography at varying scales, with a temporal coverage from 1938-1999. At the time this investigation began, documentation regarding orthorectification without the use of a camera calibration report was not available. The camera calibration report contains information critical to the orthorectification process.

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As a result, no imagery could be used that was older than 1967, the earliest available coverage year for which a calibration report was available. However, the 1967 photographic prints had poor tonal quality, with high reflectance from the open sand areas. The next available imagery from the Aerial Imagery Archive was captured in 1974. The scale of this photography is 1:40,000 and was ultimately not selected because larger-scale imagery was available elsewhere.

USACE had shoreline aerial photography coverage at various intervals between 1973 and 2001. The scale of this imagery is 1:6,000. Because this imagery showed an abundant amount of detail, this would have been a good imagery source. However, two factors made this imagery undesirable to the study. First, the camera calibration reports were unavailable for the early imagery. Second, the USACE area of interest during the aerial photography flights was the shore zone. Ultimately, the photographic coverage did not extend far enough inland to show some of the more interesting areas in WDSP.

The MDNR, Land and Mining Resources Division had aerial photography of the entire state flown in 1978, 1988, and 1999. This aerial photography was ultimately chosen because of the availability of camera calibration reports, the relatively even temporal spacing of the flights, and the minimal differences of scale among the photographs. Additionally, at least two of the dates collected (1978 and 1999) were available as diapositives. Diapositives (i.e. transparencies) are preferred over paper prints because they are less susceptible to distortions due to print degradation over long time periods (Brown and Arbogast, 1999).

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Lastly, the dates of the aerial photography flights provided an initial time frame (1978) and an ending time frame (1999) that spanned a period of approximately two decades. Because initial information regarding the movement of the dunes estimated a sand migration rate of 1 foot per month (Janette, 1919), it was hypothesized that twenty years would be an ample amount of time to observe landscape and land cover changes. Additionally, the middle time frame (1988) could be used to determine whether the changes were gradual or at varying rates. Information regarding the aerial photographs used in this investigation is summarized in Table 4:1.

Table 4:1. Summary of Aerial Imagery Used in the Investigation.

FLIGHT DATE	FILM TYPE*	SCALE	COMMENTS
9-11-1978	CIR	1:24,000	High reflectance from sand; diapositives; early- fall leaf-on conditions.
6-12-1988	BWP	1:24,000	Good tonal quality; paper prints; late-spring leaf-on conditions.
6-17-1999	BWIR	1:15,840	Fair tonal quality; diapositives; late-spring leaf-on conditions.

* CIR= Color Infrared; BWP=Black and White Panchromatic; BWIR= Black and White Infrared.

Overlapping pairs of images were selected in order to increase the accuracy of the orthorectification process (ERDAS, 2001). Only two overlapping images were needed to provide coverage for the study area for the 1978 and 1988 photography. Because the 1999 photography was at a larger scale, four images were needed to provide full coverage of the area.

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In order to process the imagery using softcopy photogrammetric techniques, the aerial photography was digitized with a UMAX Mirage II desktop scanner using Adobe Photoshop 5.0 software. Because scanning resolution ultimately determines the ground resolution covered by each pixel in a digital image, a desired ground resolution was determined before the imagery was scanned. In order to capture the detail needed to detect features on the digital imagery such as shrubs or small trees, a ground resolution below one meter was determined to be an appropriate pixel size.

When scanning aerial photography for orthorectification, additional considerations include the file size of the digital image and the pixel resolution measured in micrometers (μm). Höhle (1996) notes that pixel size will determine the size of the digital image file and thus, will determine processing time. Large files can have excessive processing times. Therefore, choosing pixel resolution is often a compromise between accuracy of the imagery and economy (Höhle, 1996).

Chandler (1999) recommends a scanning resolution of 40 μm for softcopy photogrammetry applications. Höhle (1996) used scanning resolutions of both 25 μm and 30 μm. Based upon this previous research, it was concluded that between 25 μm and 40 μm would be acceptable scanning resolutions. Accuracy and file size economy were considered while scanning the photographs used in this study. Scanning and ground resolutions for the imagery are summarized in Table 4:2.

Table 4:2. Scanning and ground resolution for imagery in the study area.

DATE OF IMAGERY	SCANNING RESOLUTION (dpi)	SCANNING RESOLUTION (μm)	GROUND RESOLUTION (m)
1978	1000	25.40	0.606
1988	1000	25.40	0.606
1999	800	31.75	0.503

The scanned images were saved as Tagged-Image File Format (TIFF) files and subsequently converted into the ERDAS IMAGINE native image format (*.img) using IMAGINE software.

Orthorectification methods

Orthophotos are photographs that have been corrected for distortions due to tilting of the camera during the photographic survey, distortions from the camera lens, and relief distortions (Lillesand and Kiefer, 2000). Orthophotos display all the valuable information of a photograph, but unlike a photograph, true distances, angles and areas can be measured directly (Lillesand and Kiefer, 2000). Today, orthophotos in digital format are widely used because they are ideal for image interpretation and feature encoding in a GIS environment (Lillesand and Kiefer, 2000).

Digital orthophotos are produced through softcopy photogrammetry. Photogrammetry is the science and technology of obtaining reliable spatial measurements of objects or phenomena from photographs (Lillesand and Keifer, 2000). Softcopy photogrammetry is applied to digital images that are stored and processed on a computer (ERDAS, 2001). This section of the investigation will discuss the softcopy photogrammetric methods used and tested to produce the digital orthophotos for this study.

Because ground conditions were most current in the 1999 imagery, two methods of orthorectification were tested upon this imagery. The first method used ERDAS IMAGINE Orthobase (version 8.5) to process and orthorectify the imagery using a USGS 30-meter DEM. The second method employed ERDAS IMAGINE Orthobase Pro (version 8.5) to process the imagery and to extract a localized digital terrain model (DTM) from the imagery. This extracted DTM was then applied to correct for relief distortion.

ERDAS IMAGINE Orthobase is a softcopy photogrammetry platform limited to producing orthophotos with the use of a pre-existing DEM to correct for relief distortion. ERDAS IMAGINE Orthobase Pro is a more sophisticated program that employs photogrammetric methods to extract a DTM from the input imagery. Therefore, orthorectification can be performed using a dataset that is customized to the imagery and study area location. Both methods employ the same initial steps until the DEM/DTM step of the process. Thus, the methods will be described as one and the same until that juncture. The 1978 and 1988 images were orthorectified using the method that demonstrated the greatest horizontal accuracy, as described later in this investigation.

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Interior and Exterior Orientation

In both Orthobase and Orthobase Pro, image orthorectification is performed within a "block file." Block files require overlapping pairs of photographs, information about the frame camera from the camera calibration report, the interior and exterior orientations of each image in the block file, ground control points, tie points and a DEM (Harrell, 2001).

The first step in building the block file was to add the four overlapping images from the 1999 image set. Next, the camera model was defined using information from the camera calibration report that establishes the interior and exterior orientation. The necessary data from the calibration report were camera type, calibrated focal length, calibrated principle point, fiducial mark coordinates, and radial lens distortion coefficients.

The calibrated principle point, calibrated focal length, and fiducial mark coordinates are used to define the image-space coordinate system (Thieler and Danforth, 1994). The image space is the geometry "within" the camera at the time of image capture (ERDAS, 2001). It is based upon a 3-dimensional Cartesian coordinate system, with the origin at the calibrated principle point (Thieler and Danforth, 1994).

Radial distortion can cause points on the images to be displaced from their true positions and is symmetric around the principle point (Thieler and Danforth, 1994). The effects of the radial distortion can be approximated using a polynomial function:

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where Δr is the change in radial distortion along a radial distance r from the calibrated principal point (ERDAS, 2001). Values for r and the three "kappa" coefficients were extracted from the camera calibration report.

Once these data were input to the block file, the interior orientation for each image in the block file was established. This procedure matched the image coordinates of the fiducial marks in each image with the fiducial mark coordinates given in the camera calibration report. Fiducial marks are features within the camera body that are exposed onto the photograph when the image is captured (ERDAS, 2001). Since the imagery was digitized using a scanner, a row and column coordinate system defined the position of each image pixel.

The calibration of fiducial marks was done manually by digitizing a point in the center of each image fiducial mark (Fig. 4:1). This digitized point indicated to Orthobase and Orthobase Pro the pixel coordinates associated with the corresponding fiducial mark coordinates (measured in mm) from the camera calibration report. Because fiducial marks from the camera calibration report are oriented according to the data strip position, the scanned images required a 270° rotation to match this orientation.

Once the fiducial marks were digitized from the images, Orthobase and Orthobase Pro performed an affine transformation to match each pixel on the image with its corresponding image-space coordinate (ERDAS, 2001). The quality of this transformation is measured by its root mean square error (RMSE).

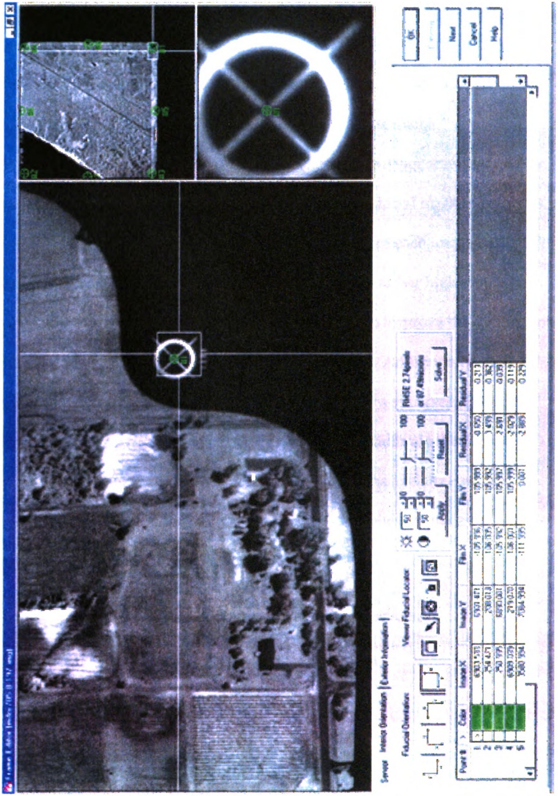

Figure 4:1. Illustration showing fiducial mark calibration in ERDAS IMAGINE Orthobase.

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The RMSE represents how well the image coordinates correspond to their respective calibrated fiducial mark coordinates (ERDAS, 2001). The ERDAS IMAGINE Orthobase manual (2001) suggests that RMSE for fiducial marks greater than 0.5 pixels indicates errors associated with the image.

These errors can be attributed to film deformation, poor scanning quality, mismeasured fiducial marks, or incorrectly calibrated fiducial mark coordinates. The RMSE associated with the fiducial mark calibration of each image in the 1999 block file are shown in Table 4:3. The error values were rather high, but I was unable to improve them. Repeated efforts were made to improve the digitization of the fiducial marks with no remarkable improvement. Additionally, the orientation of the imagery with respect to the data strip was triple-checked for accuracy. Because a great amount of care was taken to calibrate the fiducial marks, and the other imagery sets (1978 and 1988) also had relatively high RMSEs associated with fiducial mark calibration, it is believed that most of the errors can be attributed to scanning distortions.

Table 4:3. Fiducial mark calibration errors.

Image Number	RMSE (in pixels)
705-8-197	2.74
705-8-198	2.51
705-8-199	2.65
705-8-200	2.12

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Once the interior orientation was established for each image, the exterior orientation parameters were entered into the block file. Exterior orientation establishes the link between the image space and the ground coordinate system, and the angular orientation of the camera at the time of exposure (ERDAS, 2001). During image capture, the camera is subject to the roll, pitch and yaw of the airplane in flight (Thieler and Danforth, 1994). These measurements can be collected during modern flights using an airborne Global Positioning System (GPS) and Inertial Navigation System (INS) (ERDAS, 2001). However, during historic aerial photography flights, these tools were not available for use. Thus, the external orientation parameters are calculated during the block triangulation process, which will be described in more detail in subsequent sections (Thieler and Danforth, 1994).

The rotational information was defined during the block setup was Omega, Phi, and Kappa representing roll, pitch and yaw, respectively (Thieler and Danforth, 1994). Omega is rotation about the image-space x-axis, phi is rotation about the image-space y-axis and kappa is rotation about the image-space z-axis.

The positional orientation (latitude, longitude, and elevation) of the images was established through the use of ground control points. A ground control point (GCP) appears in one or more image and has known ground coordinates (X,Y,Z) (Thieler and Danforth, 1994).

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Ground Control Point Measurement

Before measuring GCPs, unrectified aerial photographs were printed as large, field-sized maps so that points could be easily identified. In order to compute the external orientation a minimum of two GCPs with X, Y, and Z positions are recommended per photograph. One additional point with at least a known Z position is also needed (Thieler and Danforth, 1994; ERDAS, 2001). Furthermore, when evaluating a strip of adjacent images, a minimum of two GCPs for every third image, with an additional three measurements at the corner edges of the strip is recommended (ERDAS, 2001).

The recommended arrangement of GCPs is depicted in Figure 4:2. Collecting more than the minimum number of GCPs is always advantageous to the quality and accuracy of the processing and is also recommended in order to perform an accuracy check (ERDAS, Inc., 2001; Höhle, 1996). With these recommendations taken into consideration, a total of 33 GCPs were selected from the photo maps for ground coordinate measurement.

Ideally, the network of ground control should be evenly distributed to ensure that the image space is accurately modeled (ERDAS, 2001). However, the ability to locate ground identifiable points, accessibility to points, and the sensitivity of the GPS equipment were considerations that limited where GCPs could be measured. The resulting ground control network with respect to the imagery is shown in Figure 4:3.

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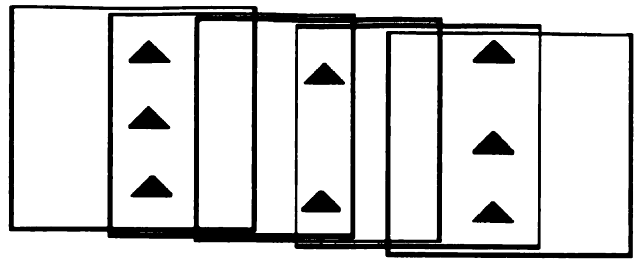

Figure 4:2. Recommended ground control point distribution (modified from ERDAS, 2001).

The GCPs selected for this investigation were primarily road intersections surrounding the area of study. The choice of these GCPs was mainly due to the difficulties in identifying isolated landmarks that were visible on the photos in the open dune and forested areas. However, some isolated trees and large bushes were available to be used as GCPs within the actual study area.

Ground control was measured using GPS. The GPS is comprised of a minimum constellation of 24 satellites in precisely monitored orbits, at an altitude about 20,200 km above the earth's surface (Lillesand and Kiefer, 2000). GPS signals are used to determine position by satellite ranging. Using a code correlation technique, the distance between a GPS satellite and a receiver can be calculated by measuring the amount of time it takes the signal to reach the receiver. The signals from at least four GPS satellites are needed to measure both horizontal and vertical position, and to correct for clock bias between each of the satellites and the GPS receiver.

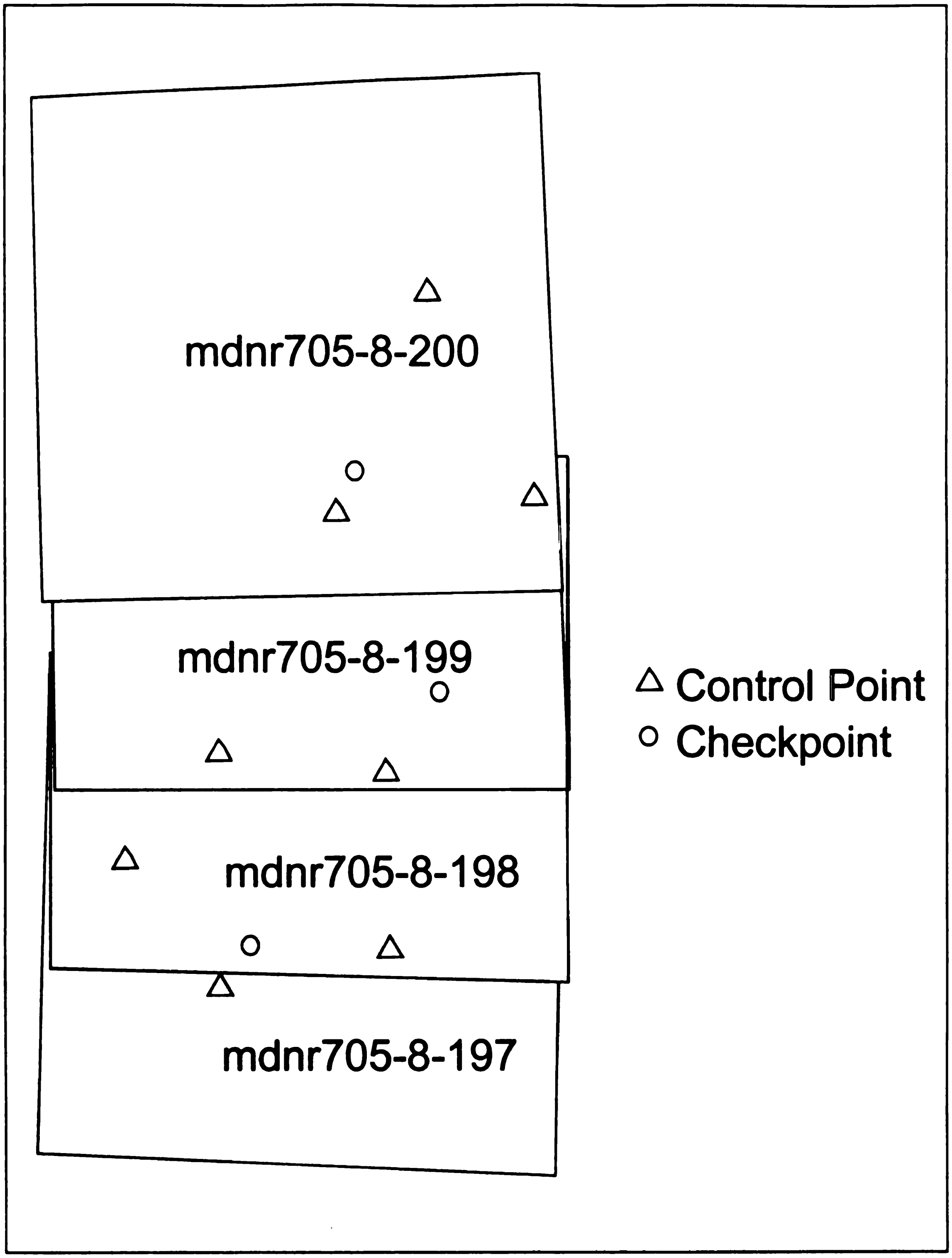

Figure 4:3. Control and checkpoint distribution with respect to 1999 imagery.

GPS measurements are subject to errors that include uncertainties in the satellite orbits, atmospheric conditions (differences in signal velocity depending on time of day, season, and the angular direction of the signal through the atmosphere), receiver errors (electrical noise), and multipath errors (the scattering and reflection of signals from objects not in a straight-line path between the satellite and the receiver). Differential GPS (DGPS) can be used to correct most of these errors (multipath errors usually persist). DGPS works by taking continuous position measurements at stationary base stations with known positions. Because the positions at the stationary base stations are known, errors can be measured and used to correct roving GPS receivers out in the field (Lillesand and Kiefer, 2000).

Trimble Pro XRS GPS receivers were used to collect the GCPs with either a TDC1 or a TSC1 datalogger. The Pro XRS is reported to have a horizontal accuracy better than 75 cm + 1 part per million (ppm) (Trimble, 2003). Because vertical accuracy is roughly 1.5 times the horizontal accuracy, vertical accuracy specifications for this receiver are about 1.1 m (Yao and Clark, 2000). The field accuracy of these instruments was not tested because at the time of GCP measurement, a nearby survey benchmark with known horizontal and vertical positions could not be located under forest litter. However, Schaetzl et al. (2002) tested a predecessor of the Pro XRS, the Trimble Pro XL, in northern Michigan and determined that this earlier model had a vertical RMSE of 1.34 m.

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Both units received real-time, differential corrections from OmniSTAR, a subscription service that uses a network of base stations to obtain differential correction information that is transmitted by communication satellite to the receiver. Before the points were measured in the field, mission planning was conducted using Trimble Quick Plan mission planning software. The mission planning provided time windows when the overall dilution of precision (PDOP) was predicted to be less than 4.0. Yao and Clark (2000) suggest that using a low PDOP filter (in the 2-4 range) in the field may improve the accuracy of elevation measurements made with the Pro XRS. The receivers were subsequently set with a PDOP mask of 4.0, and GPS measurements were only conducted during time windows pre-determined to have PDOP of less than 4.0.

At each pre-selected GCP, position fixes were taken at one-second intervals for two minutes, resulting in 120 positions (WI DNR, 2001). The positions were recorded in geographic, decimal degree coordinates on the WGS 1984 ellipsoid. When a GCP was located at a tree, the positions were offset by a measured distance and direction (Brown and Arbogast, 1999). Each recorded GCP was saved in the datalogger as an individual point feature file. The point was then marked on the image photomap to aid in subsequent identification in ERDAS IMAGINE Orthobase.

The data were downloaded from the datalogger using Trimble GPS Pathfinder Office software. Each GCP was opened and decomposed into the 120 individual position fixes associated with that point. The measurements were evaluated for multipath errors, changes in PDOP, and number of satellites. If multipath errors showed an obvious trend, extreme outliers were deleted from the point cloud. A majority of the GCPs had standard deviations less than 0.5 meters in horizontal precision.

Once the GCPs were examined, the multiple position fixes were averaged to create one X, Y, Z coordinate per GCP (Rees, 2000). The GCPs were then exported in ArcView GIS shapefile format after being projected into Michigan Georef, with the horizontal datum set to the North American Datum of 1983 (NAD 83), and the vertical datum set to the North American Vertical Datum of 1988 (NAVD 88).

Exterior Orientation

With ground control measured, the GCPs were imported into the ERDAS IMAGINE Orthobase blockfile as a text file with X, Y, and Z measurements. In order to determine the unknown exterior orientation parameters, the measured ground coordinates needed to be paired with the corresponding pixels on the images. This was facilitated in Orthobase by the Point Measurement Window (Fig. 4:4) that displayed the images and the GCP coordinate text file. A GCP record was selected from the text file, and a cross-hair cursor was used to create a point on the image that corresponds to the point listed in the text file. GCP positions marked on the image photomaps taken into the field and field notes aided in the process of correctly locating the GCPs in the Point Measurement

Window. For the 1999 imagery, a total of 11 GCPs were used, with three selected for use as checkpoints to test the accuracy of the camera model (Fig. 4:3).

After the GCPs were digitized in the Point Measurement Window, tie points were collected. Tie points are distinct features that appear on two or more images but their ground coordinates are unknown. They commonly include features such as road intersections, buildings, or trees. Ground positions of the tie points are solved in latter steps (during block triangulation) and thus extend the ground control network to improve the accuracy of the camera model (ERDAS, 2001). Tie points also establish the relative orientation of photos to each other (Thieler and Danforth, 1994).

A total of 200 tie points per image were collected to produce the most accurate solution to the model. This number increases data redundancy and distributes the error throughout the images (ERDAS, 2001). The first ten tie points were manually collected throughout the block of images in the Point Measurement Window, which can show two images at a time. This allowed a tie point to be digitized on one image and then the matching pixel could be digitized on other overlapping images.

Because tie point collection can be time-consuming, the remaining tie points were measured using the "Automatic Tie Point Collection" feature in Orthobase. This procedure uses image matching, which analyzes the

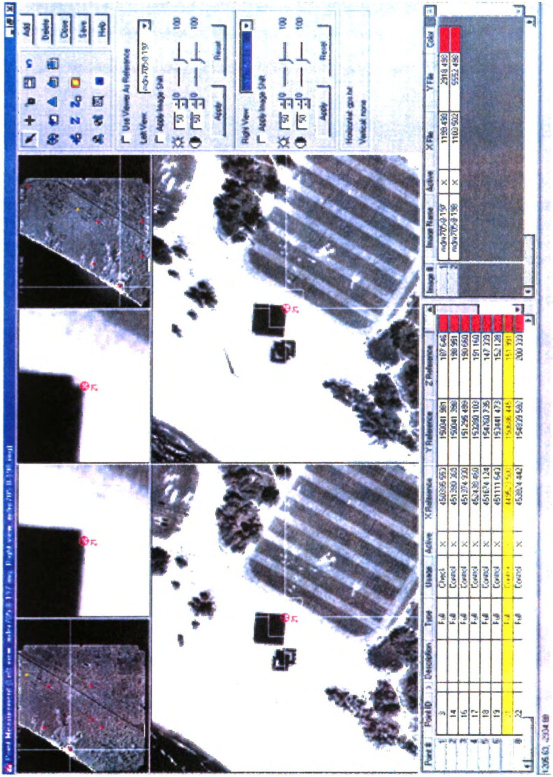


Figure 4:4. Illustration showing point measurement window in ERDAS IMAGINE Orthobase.

correspondence of pixel brightness values between the manually placed tie and control points in two or more images. Additional tie points are then created based upon these correspondence values (Thieler and Danforth, 1994; ERDAS, 2001). Once the tie points were automatically generated, the quality of each was visually inspected in order to discard poorly matched tie points. A total of 367 tie points were used in the 1999 imagery.

Block Triangulation

ERDAS (2001, p. 80) defines block triangulation as "the process of defining the mathematical relationship between the images contained within a block, the camera or sensor model that obtained the images, and the ground." This process simultaneously calculates the exterior orientation of each image in the block at the time of image capture, the ground coordinates of the tie points (thus adding more ground control points to the model), and the interior orientation parameters associated with the camera (ERDAS, 2001).

In Orthobase and Orthobase Pro, block triangulation is facilitated through bundle block adjustment (ERDAS, 2001). Because the exterior orientation parameters and the ground coordinates of the tie points are derived through the same equations, they are derived as a "bundled" solution. The entire "block" of images is processed simultaneously, using a least squares "adjustment" to calculate the bundled solution for the entire block (ERDAS, 2001). Block bundle adjustment uses the collinearity condition to establish the exterior relationship of each image (ERDAS, 2001). The collinearity condition is met when the camera position at time of image capture, any point on the ground, and its corresponding point on the image all lie in a straight line. The collinearity condition is expressed for each image through a series of collinearity equations (Lillesand and Kiefer, 2000).

The block bundle adjustment also incorporates a least squares adjustment. Least squares adjustment is a statistical method used to determine the unknown parameters in the photogrammetric solution while simultaneously distributing and minimizing error (ERDAS, 2001). The least squares adjustment is an iterative process where a solution is obtained when the errors have been minimized. The least square adjustment integrates the solutions from the collinearity equations (ERDAS, 2001).

In Orthobase and Orthobase Pro, the block triangulation can be optimized by using statistical information pertaining to the quality of input data. For the 1999 imagery, some of these optimizations were employed in an effort to improve the results of the block triangulation. These optimizations are specified in the "Aerial Triangulation" dialog box in Orthobase. An image point standard deviation of 0.33 pixels for both x and y was selected based on the recommendation of ERDAS (2001). This specified the amount of fluctuation the image coordinates could have during the iterative bundle block adjustment process.

A statistical weight was also assigned to the GCPs before the bundle block adjustment was performed as recommended by ERDAS (2001). Weighted standard deviation values were the same for all GCPs: 0.5 m X, 0.5 m Y and 2.0 m Z. These values were chosen based upon an informal examination of the standard deviations provided from the GPS measurement of the GCPs. The values are representative of the standard deviations in X, Y, and Z associated with the GPS measurement.

Because the exterior orientation parameters were unknown, no statistical weights were applied to these parameters (ERDAS, 2001). However, statistical weights were applied to the interior orientation parameters because information was available from the camera calibration report. The "Same Weighted Values" option was used on the interior orientation parameters because the number of GCPs was limited (ERDAS, 2001). The standard deviation weights were: 0.003 μm for focal length, 0.003 μm for principal point x, and 0.003 μm for principal point y. These values were obtained from the camera calibration report, which reported the standard deviations in the measurements of these input parameters.

With these statistical weights applied, the block triangulation was performed with the "No Additional Parameters" and "Advanced Robust Checking" options selected. An initial run was executed to solve for the unknown exterior orientation parameters and to provide ground coordinates for the tie points. The residual errors for the tie points were examined and points were repositioned if the errors were high. The block triangulation was performed once more with the updated exterior orientation parameters for each image and the estimated ground coordinates for the 367 tie points. The overall RMSE of the block triangulation for the 1999 imagery was 0.6120 pixels.

With the triangulation completed, the remaining distortion in the images that needed correction was relief displacement. The final step in orthorectification requires the use of a DEM. The remainder of the orthorectification discussion will be separated into two different subsections to represent the two methods tested. Both methods use the results obtained from the aforementioned bundle block adjustment.

Orthorectification using USGS 30-meter DEM

This method combines the results of the bundle block adjustment, the imagery and a USGS 30-m DEM of the area covered by the imagery using ERDAS IMAGINE Orthobase. The DEM was obtained from the National Elevation Dataset (NED), a seamless raster product that provides data in a geographic coordinate system. The horizontal datum for the NED is NAD 83, the vertical datum is NAVD 88 and the elevation units are reported in decimal meters (Gesch et al., 2002). The vertical accuracy of the NED for the study area is five meters.

In Orthobase, the NED DEM was applied to the bundle block adjustment results and the imagery through a process called ortho resampling. This process matches each pixel in the DEM to its corresponding position on the imagery and assigns each location a brightness value based upon a resampling of surrounding pixels. The brightness value is then combined with the elevation value and the exterior orientation parameters to determine the relief-corrected ground location on the imagery (ERDAS, 2001).

The method of ortho resampling chosen was bilinear interpolation. Bilinear interpolation is a distance weighted technique that incorporates the brightness values of the four nearest pixels (Lillesand and Kiefer, 2000). Bilinear interpolation is the recommended ortho resampling technique in Orthobase (ERDAS, 2001). The two other methods of resampling are nearest neighbor and cubic convolution. Nearest neighbor resampling can cause pixel offsets of up to one-half pixel (Lillesand and Kiefer, 2000) and cubic convolution is computationally intensive (ERDAS, 2001).

The output cell size for the orthophotos was equivalent to the imagery pixel size (0.5 meters). Once the individual orthophotos were generated, they were mosaicked together to produce one full image of the study area, as opposed to a few, disjointed images of the study area. Only two of the orthophotos were chosen for use in the final image mosaic (images 705-8-198 and 705-8-199), because the outlying photographs (images 705-8-197 and 705-8-200) were far outside the area of interest for this investigation. The final image mosaic was saved in the native IMAGINE file format (*.img) for analysis.

DTM Extraction and Orthorectification

DTM extraction is based upon the principal of parallax, the apparent change in relative positions of stationary objects that is caused by imaging the objects from two different positions (Lillesand and Kiefer, 2000). Elevation can be derived by measuring the parallax between corresponding image points and triangulating a solution using the parallax measurement and the interior and exterior orientations of the camera and imagery (Lillesand and Kiefer, 2000).

Orthobase Pro allows for the extraction of a DTM from the results of the bundle block adjustment and the imagery. For the 1999 imagery, a DTM cell size of 3 meters was chosen. This decision was based upon the DEM resolution chosen by Brown and Arbogast (1999) to analyze coastal dunes at Ludington, MI. The output DTM type selected was DEM, as this format produces a file in the native IMAGINE file format (*.img), which is useful when orthorectifying imagery. The *.img file displays the DEM in gray scale, with brighter pixels representing higher elevations and darker pixels representing lower elevations (ERDAS, 2001). A single DTM mosaic was chosen as the output form to be used later in ortho resampling. The output coordinate system of the DEM was the same as that used in the bundle block adjustment (Michigan Georef, NAD 83, NAVD 88, with units measured in meters).

The "Area Selection" tab in Orthobase Pro allows the user to digitize areas of the imagery that will be included in the DTM extraction and the associated "region strategies" with these areas, in addition to allowing the user to exclude some areas from the DTM extraction. Region strategy refers to parameters and methods that are used to optimize the performance of the DTM extraction.

In the case of the 1999 imagery, the portions of the image that captured Lake Michigan were excluded from the DTM extraction by digitizing them using the area selection feature of Orthobase Pro. This area was then assigned a constant value of 176.2 meters, which corresponds to the average elevation of Lake Michigan in 1999 (USACE, 2003). The areas of the imagery that featured dunes were also digitized and a "rolling hills" strategy was used for DTM extraction in these areas. This strategy incorporates a 15 X 3 pixel search window to find corresponding image points within the overlapping areas of the imagery. The Y-value of the search window is reduced in this strategy. This is due to smaller parallax between points located on more than one image. Lower elevations result in smaller Y-parallax (ERDAS, 2001).

To analyze the accuracy of the extracted DTM, the block GCPs and check points were used. The accuracy of the resultant DTM will be discussed in the Results and Discussion section of this thesis. Once the extraction was successfully completed, the output DEM was smoothed in an effort to compensate for artifacts. For example, subtle differences in elevation between adjacent pixels were detectable in the forested regions of the photographs, most probably due to differences in canopy height of the trees. Additionally, pits and hummocks resulted that were not observable in the field or on topographic maps. In order to compensate for these errors, the DEM was smoothed using a 9 X 9 averaging filter (as in Brown and Arbogast, 1999).

With the DEM preparation complete, the extracted and processed DEM was used to ortho resample the block of imagery via bilinear interpolation as recommended by ERDAS (2001). The output cell size for the orthophotos was equivalent to the imagery pixel size (0.5 meters). Once the individual orthophotos were generated, they were mosaicked together according to the aforementioned methods.

Processing the Remaining Imagery

The remaining imagery sets from 1978 and 1988 were processed according to the DEM-extraction method. This method produced orthophotos with higher positional accuracy, as explained in the Results and Discussion section of this investigation.

The parameters and inputs to the photogrammetric models for the 1978 and 1988 imagery were the same used for the 1999 imagery, with a few exceptions. The number of GCPs varied slightly in the 1978 and 1988. This was because the images were a smaller scale than the 1999 imagery and thus, covered more ground area. Ultimately, this meant that fewer images were used in the photogrammetric solution, and it also allowed the addition of more GCPs into the models used in the 1978 and 1988 image processing. Only two images were used in the 1978 and 1988 bundle block adjustments. Table 4:4 shows the fiducial calibration errors associated with each imagery set.

Table 4:4. Fiducial mark calibration error for the 1978 and 1988 imagery.

Imagery Year	Image Number	RMSE (in pixels)
1978	69-124-42	3.64
1978	69-124-43	2.89
1988	426-294-43	3.55
1988	426-294-44	3.63

Figures 4:5 and 4:6 show the 13 GCPs and 4 checkpoints used in the 1978 and 1988 imagery relative to the image coverage areas. The number of tie points used to process the 1978 imagery was 211 and the number of tie points used to process the 1988 imagery was 190.

The accuracy of the bundle block adjustments for the 1978 and 1988 imagery were 1.934 pixels and 3.7120 pixels, respectively. Lastly, extracting the DTMs from the 1978 and 1988 imagery differed slightly from the 1999 imagery. The image areas depicting Lake Michigan were excluded from the DTM extraction, with constant lake elevations set to 176.6 meters, the approximate average lake elevation for both time periods (USACE, 2003).

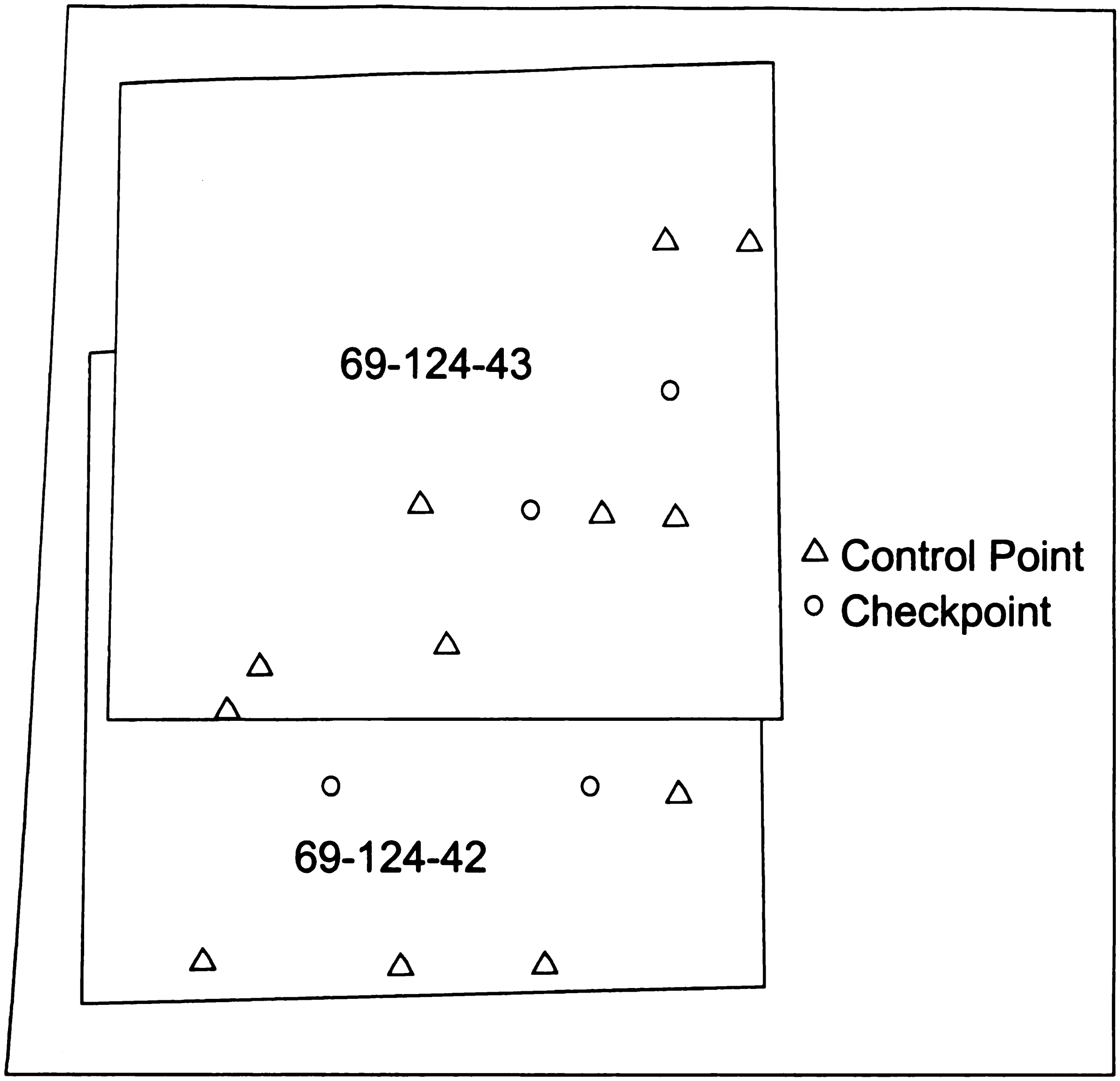


Figure 4:5. Control and checkpoint distribution with respect to 1978 imagery.

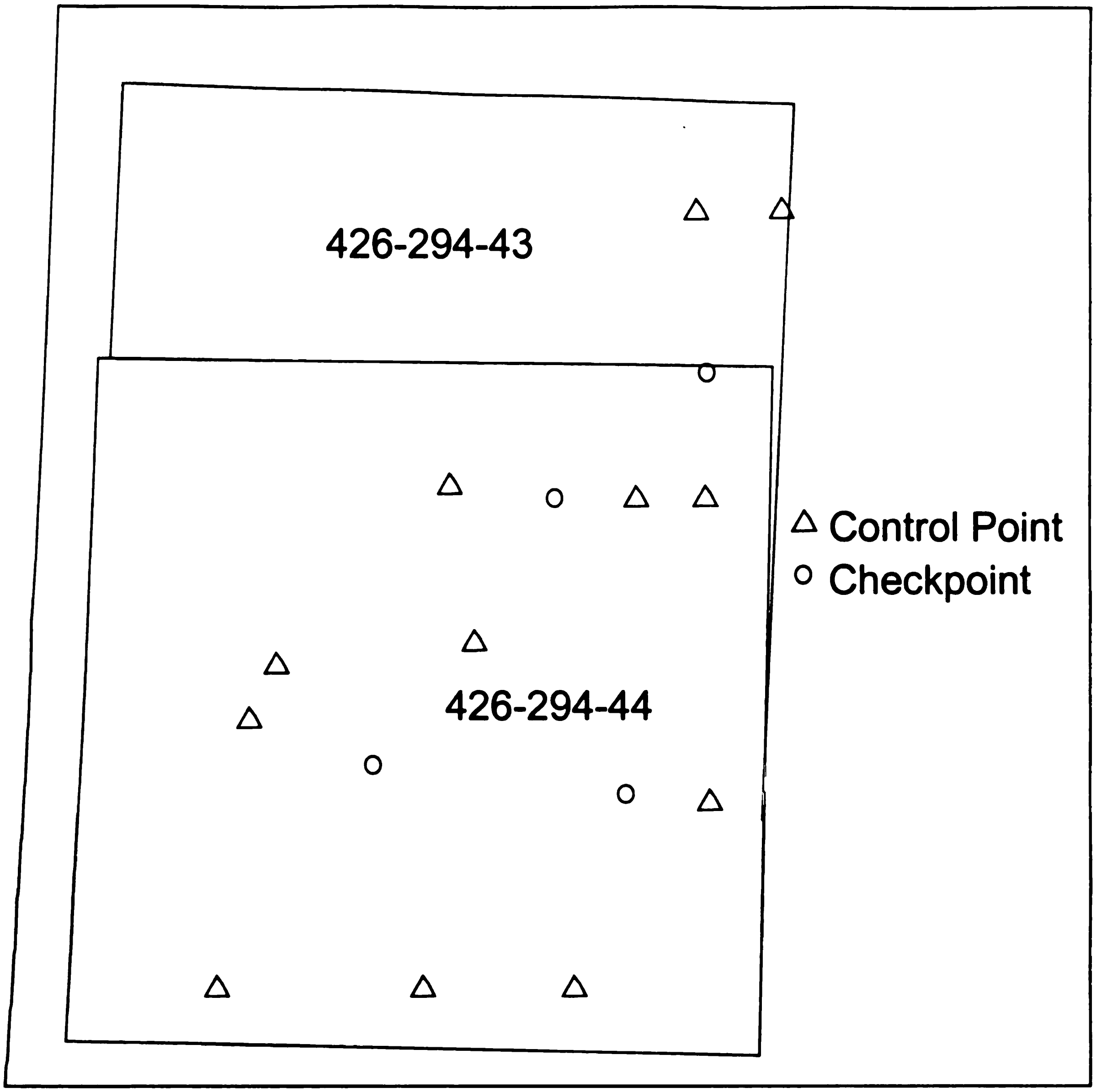


Figure 4:6. Control and checkpoint distribution with respect to 1988 imagery.

Classification System

According to Lachowski et al (1995), a well-defined classification system should be able to accomplish the goals of the project using the technology and resources available, and simplify all further processing. With those goals in mind, a classification scheme was chosen that would meet the objectives of this investigation, be appropriate for the imagery available, and reflect vegetation conditions within WDSP. Businski (1992) created a classification scheme for Lake Michigan dunes at Sleeping Bear National Park that fit the context of Olson's (1958a; 1958c) research. This classification system recognizes the successional evolution of vegetation upon coastal dunes, ranging from barren sand with little or no vegetation to the successional climax represented by closed-canopy.

There are also geomorphological implications in Businski's classification scheme. Olson (1958c, p. 351) suggests that vegetation "can be useful to the geomorphologist who would translate its language." The presence of different types of vegetation can be associated with differing rates of sand deposition and the disappearance of vegetation over time can be associated with erosion. Consequently, different classes of land cover are associated with varying levels of dune stability. For example, areas identified as barren sand represent geomorphically active surfaces, where rates of erosion or sand deposition are too high for vegetation to take root.

Because Businski's classification system fit so eloquently into the goals of this investigation, a modified version of this system was chosen. Ground photographs of each of the six classes are used to illustrate the field conditions represented in each class.

Barren Sand

This land cover class bares no stabilizing vegetation; therefore, the surfaces are exposed to high winds with sufficient energy to entrain sand particles. Due to the absence of vegetation, these areas have unstable surfaces and can be reshaped readily by wind, water, and human foot traffic. These areas are found near the lake and in active blowouts. Figure 4:7 illustrates the Barren Sand classification.

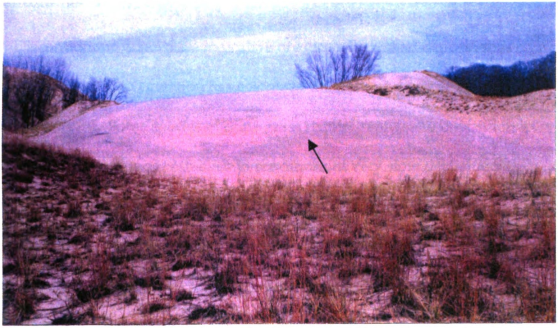


Figure 4:7. Unvegetated dune depicting the barren sand classification (at arrow) with discontinuous grasses in the foreground.

Barren with Isolated Plants

The Barren with Isolated Plants classification is slightly ambiguous because it could possibly represent two conditions in the field. The first is barren sand that has begun to be colonized by pioneer vegetation. However, the vast majority of this class represents vegetation that is actively being buried by sand. It represents an unstable environment, where the surface was once stable enough to support vegetation, but has since destabilized. This class was developed from an initial analysis of the imagery, which showed a trend in some areas with stable, vegetated dunes in the older imagery, to isolated trees or shrubs surrounded by barren sand. Figure 4:8 shows an example of the barren with isolated plants class.

Discontinuous Grass

Discontinuous grasses are indicative of areas where sand deposition is actively occurring, but vegetation has colonized the dune and acts as a stabilization agent. Some species of dune grass require rapid sand deposition to grow, whereas other species establish in conditions of very slow deposition (Olson, 1958c). Regardless of the specific grass species, discontinuous grass cover represents low dune stability. Most grasses growing in these environments reproduce through rhizomes, as seeds may be buried too deeply to germinate with such rapid deposition rates.

Figure 4:8. Photograph depicting the barren with isolated plants class.

These areas may have some humus at the surface, but no fully developed soils or continuous land cover to entirely stabilize the dune surface. These areas may also be mixed with herbaceous annuals and perennials that can tolerate varying levels of sand deposition. Additionally, dune grasses are particularly sensitive to even low levels of human disturbance (Roethele, 1985), making these areas especially susceptible to destabilization in the "High Use Area" area of WDSP. Discontinuous grass cover is illustrated in Figure 4:9.

Figure 4:9. Photograph depicting the discontinuous grass classification.

Grass and Shrubs

These areas possess grass species, annual and perennial plants, woody shrubs, and some small trees that grow as shrubs (such as cottonwoods) that tolerate at least some sand deposition. Shrub species growing here may be remnants from a time of rapid sand deposition, or may have seeded once sand deposition slowed to a few millimeters per year (Olson, 1958a). Species that reproduce through seed can be found in these areas, since sand deposition has slowed enough to allow sufficient time for seed germination. These areas are older and have been stable or nearly stable for a longer time than areas represented by discontinuous grass. This land cover is illustrated in Figure 4:10.

Figure 4:10. Grass and shrubs land cover class.

Grass, Trees, and Shrubs

Shrubs, isolated trees, and continuous grass cover become established rapidly when sand deposition has stopped or decreased to a few millimeters per year (Olson, 1958c). Vegetation has become dense enough in these areas that a well-defined humus layer has formed and a weakly developed soil can be observed. These areas are similar to areas covered by grass and shrubs, with the exception that the rate of sand deposition has stopped or slowed for a long enough time that tall trees with large canopies are discernable in both the field and on the aerial imagery.

As a precursor to forest development, these types of vegetation also act as stabilization agents in dune environments. However, it should be noted that this land cover is less stable and more sensitive to disturbance than forest cover. This land cover is depicted in Figure 4:11.

Figure 4:11. Photograph illustrating the grass, trees, and shrubs vegetative cover class.

Forest

Forests establish on dunes after other plant communities have thoroughly stabilized the surface (Olson 1958a). Once closed canopies of forest develop on dunes, vegetation and soil anchor the sand in place and prevent eolian transport. As compared to the other land cover classes, areas covered by forest are the oldest surfaces because sand deposition has ceased long enough for communities of large trees with undergrowth to develop. The forest land cover is illustrated by Figure 4:12.

Figure 4:12. Photograph depicting the forest land cover class.

One additional class, unclassified, was used to mask out areas that were outside the area of study or areas that had been urbanized. These areas included the inland areas that were not covered by dunes, but were still inside the park boundaries and the road, parking lot, and beach houses. From the images, it was apparent that the paved areas and beach houses have remained the same dimensions and in the same location. The unclassified areas were not analyzed as part of this investigation.

Interpretation Factors

According to Lillesand and Kiefer (2000), an image interpreter examines aerial imagery systematically, often referring to additional materials such as maps and field observations to assist in the interpretation process. The success of image interpretation relies heavily upon the experience of the interpreter, the nature of the objects or phenomena under examination, and the quality of the imagery used. It is important for the interpreter to be familiar with the objects or phenomena under observation, in addition to having knowledge of the geographic region under examination. Additionally, the interpreter must also be able to evaluate several image characteristics to interpret features or phenomena on the imagery. Factors important to this study include shape, size, tone, texture, shadows, site, resolution, and image quality.

Shape refers to the general form of an individual object. This factor was not exceptionally important to distinguish between land cover classes in this study since it refers to individual objects (Lillesand and Kiefer, 2000). However, the shapes of individual trees and bushes were helpful in discerning when a particular area might be referred to as grass and shrubs versus discontinuous grasses.

The size of objects is always considered in the context of image scale. Additionally, relative sizes of objects to each other on the imagery are also an important consideration (Lillesand and Kiefer, 2000). This factor was important to this study, especially when classifying cover types with trees and shrubs.

Tone and texture were perhaps the most useful interpretation factors in this study. Tone is the relative brightness or color of features on an image (Lillesand and Kiefer, 2000). Tone helped distinguish between areas of barren sand and areas of vegetation. Barren sand is bright white or light gray on the black and white imagery and bright white to light cyan on the color infrared imagery, whereas vegetated areas are darker shades of gray on the black and white imagery and magenta to deep red on the color infrared imagery.

The aggregation of smaller features, some too small to be individually discernable on an image, produces texture on an image (Lillesand and Kiefer, 2000). Tree leaves, branches, and twigs, in addition to tree shadows are examples of features that produce texture. Texture can be defined according to the overall coarseness and smoothness of image features. Discontinuous grass cover presents a coarser texture than barren sand due to the aggregated blades of grass, and forest cover represented the coarsest texture on the film from the leaves or branches.

Shadows can both aid and hinder the interpreter. The shape and outline of a shadow can help the interpreter recognize features. Alternatively, objects within shadows are obscured and become difficult to interpret (Lillesand and Kiefer, 2000). Shadow was also an important factor in interpretation in that it helped distinguish between trees and shrubs. Shadows are also a limitation to this investigation; especially adjacent to forest cover where canopy shadows obscure the margins between land cover classes.

The geographic and topographic location of features is also a useful aid in interpreting imagery. This factor is referred to as "site" (Lillesand and Kiefer, 2000). Site played a minor role in interpretation in this study. Field observations indicated a loose trend that the topographically low blowout areas had no vegetation and that the higher crests were usually vegetated, very often with trees. Additionally, relatively little forest cover was found directly adjacent to the beach.

Resolution is the most limiting factor. At the scale of this imagery, individual species of plants could not be discerned. Additionally, the resolution at which the imagery was scanned limited the recognizable features to an approximate size of one-half meter. Identification of individual species of plants would likely provide a stronger link between this investigation and Olson's research (1958a; 1958c).

The quality of the film was also influential on the results of the interpretation. In the 1988 and 1978 imagery, the areas with barren sand were overexposed. This could have lead to some misinterpretation in these areas, especially if small clumps of discontinuous grasses were obscured due to the brightness of the surrounding pixels. Because the quality of the 1999 imagery is slightly better than the other imagery, it is suspected that the interpretations of the 1999 imagery could be more accurate.

Analysis and Mapping Procedures

Digitizing

Land cover polygons were head's-up digitized from the *.img format image mosaics using ArcView GIS 3.3. The images were contrast stretched to compensate for areas where barren sand was overexposed. A minimum mapping unit area of 4 meters^2 was used based upon the resolution of the imagery, and the lack of necessity for any smaller unit in this study. The land cover classifications were saved in the native ArcView GIS shapefile format. As each polygon was digitized, the associated land cover class was recorded in the database file associated with the land cover shapefile in an attribute field named "VegCover."

By copying the data, two shapefiles of land cover for each time period were created. One shapefile in each set represented the entire study area so that the general trends in land cover in the park could be analyzed. The second shapefile for each set divided the park into the "High Use Area" and the "Natural Area" so a comparative analysis could be performed.

Once each time period of imagery was completely digitized, the shapefiles were converted to ArcInfo coverages using ArcInfo Workstation 8.2. Once the shapefiles were converted to coverages, the area of each polygon in each coverage was automatically calculated in square meters. The "clean" and "build" commands were performed on the land cover coverages in order to build topologically correct polygon files. To eliminate errors in the digitization process known as sliver polygons, the "eliminate" command was utilized. The coverages were then converted back into shapefile format in ArcView GIS 3.3 for further analysis.

Positional Accuracy Assessment

It was hypothesized that:

H_1: The DTM-extraction method of orthorectification will be the best method to create digital orthophotos of the study area.

It was believed this method would be superior to the method that employs a USGS 30-m DEM because the DTM is created from GPS measurements collected at points visible on the orthophotos. Therefore, the DTM was localized to the study area. The method used to test this hypothesis was to assess the positional accuracy of the orthophotos produced by both methods.

Reporting positional accuracy supplies a measure of how well the spatial relationships on the imagery model those in the real world. To measure positional accuracy, the Geospatial Positioning Accuracy Standards from the National Standard for Spatial Data Accuracy (NSSDA) were used as a guideline.

The NSSDA is intended for use with digital geospatial data derived from a variety of sources and stored in raster, vector or point format (FGDC, 1998). The NSSDA uses RMSE to report positional accuracy. To measure accuracy in accordance with the NSSDA, a minimum of twenty, well-defined checkpoints should be collected from an independent source of higher accuracy (FGDC, 1998). Well-defined checkpoints may be small isolated shrubs and bushes, or right angle intersections of roads or buildings. These points may be surveyed using a GPS to function as the independent source of higher accuracy. Additionally, these points should not be included in the aerial triangulation model used to produce the orthoimages (FGDC, 1998).

Several factors limited the number of both GCP and independent checkpoints that were identifiable both on the imagery and in the field. These factors included: terrain, property ownership, land cover, and a relatively low number of road intersections in and around the study area. Therefore, collecting 20 independent checkpoints to test each set of imagery was not feasible. In lieu of this, the largest feasible number of checkpoints was collected for each set of imagery. In addition, the accuracy at ground control points used in the model was reported to provide supplementary information about the positional accuracy of the imagery.

The checkpoints were collected is the same manner as the GCPs, using Trimble Pro XRS GPS receivers. The checkpoints were located at road intersections, large isolated trees or shrubs, and building corners. The points were marked on a photomap of the area for easy recognition during the accuracy assessment process. Ten checkpoints were used to test the 1999 imagery, eight checkpoints were used to test the 1988 imagery, and 12 checkpoints were used to test the 1978 imagery.

In ArcView GIS 3.3, the imagery was added, and a new point shapefile was created. Using the field photomaps as reference, the positions of the checkpoints were head's-up digitized, zooming in at the points to assure accurate placement of the points. The "Add X,Y coordinates" script was run on the point shapefile to add horizontal positions of the checkpoints, as displayed by the orthophotos. These positions were then compared to the GPS positions of the checkpoints.

Additionally, coordinates at GCPs were collected from the digital orthophotos in the same manner as the checkpoints and compared to the GPS coordinates measured in the field, providing nine additional points from the 1999 and 1988 imagery, and 10 additional points from the 1978 imagery.

Errors were calculated by subtracting the GPS coordinates (actual) from the orthophoto coordinates (measured). The results of the positional accuracy assessment are reported in the Results and Discussion section of this thesis. The results are reported in RMSE in accordance with the NSSDA, with supplementary information including: minimum error, maximum error, range of error, mean error, and standard deviation.

Thematic Accuracy Assessment

Reporting thematic accuracy establishes the level of confidence within the results of the land cover class interpretation. For thematic accuracy, standards used by the USGS-NPS Vegetation Mapping Program were used to test the 1999 imagery only. Because the field conditions had changed greatly in some areas since the 1978 and 1988 imagery had been acquired, it was deemed unfeasible to assess the accuracy of these imagery dates. The landscape may also have changed from the image capture date in 1999 to the field observation date in 2003, which is a limitation in this investigation. However, an independent orthophoto of the study area from 1999 was available from the Michigan Center for Geographic Information to assist in the accuracy assessment.

These USGS-NPS Mapping Program standards were deemed appropriate for use in this investigation because they were specifically designed for vegetation classification schemes and the methods were supported through pre-existing research. Stratified random sampling was used for thematic accuracy assessment, with vegetation class as the stratifying variable. This method of sampling performs well and can be used when small, yet important, areas need representation in the sample (Congalton, 1988).

When a study area has classes that are extremely abundant and classes that are not very abundant, the USGS-NPS Vegetation Mapping Program accuracy assessment standard recommends a stratified random sampling strategy based upon number of polygons and total area covered. Under this scheme, the maximum number of points sampled in abundant classes is 30, while the minimum number of points sampled in rare classes is 5. The most abundantly present land cover class would cover greater than 50 hectares and consist of at least 30 polygons. This class would have 30 randomly chosen sample points. Less abundant classes may also cover greater than 50 hectares but consist of less than 30 polygons. These classes would have 20 randomly chosen sample points. The rare classes would have greater than five but fewer than 30 polygons, and cover less than 50 hectares. These classes would have five randomly chosen sample points (The Nature Conservancy and ESRI, 1994).

In order to determine the area in hectares per class, an attribute field was added to the land cover class shapefiles called "Hectares." The area in hectares for each polygon in each class was determined by using the "calculate" command in ArcView GIS 3.3. The total area of each class was determined by first using the "query" tool to select out each class, then using the field "statistics" command. This also determined the number of polygons per land cover class. The land cover classes and number of sampling points per class is summarized for the entire study area in Table 4:5.

With the necessary number of sampling points determined, the positions of the sample points needed to be acquired randomly. This was facilitated in ArcView GIS 3.3 using a random point generator extension that used a polygon theme to generate a desired number of randomly determined points. Decimal degree latitude and longitude for a total of 140 randomly generated points were output to a text file that could be input into a GPS as waypoints for accuracy assessment.

The sample points were also plotted against a 1999 color infrared, orthorectified image of the park, obtained from the Michigan Center for

Geographic Information. This procedure produced a field map to assist in identification of the points in the field.

Table 4:5. Summary of vegetation class, area, number of polygons per class, and number of sampling points per class.

Class	Area	Number of Polygons	Number of Sample Points
Barren Sand	>50 hectares	106	30
Barren With Isolated Plants	<50 hectares	75	20
Discontinuous Grass	>50 hectares	76	30
Grass and Shrubs	<50 hectares	63	20
Grass, Trees, and Shrubs	<50 hectares	36	20
Forest	>50 hectares	8	20

The sample point file was loaded as waypoints into a Trimble Pro XRS GPS unit so that each point could be navigated to. As each point was visited, the observed land cover was recorded. In areas of dense forest cover, the terrain and tree cover made it extremely difficult to navigate to sample points in these areas. Thus, the orthorectified image provided by the Michigan Center for Geographic Information was used to check the accuracy of these points, in addition to a small portion of points that were inaccessible due to the terrain. This orthophoto of the study area has an accuracy of +/-33 feet (10.06 meters). Although the positional error is greater than the imagery produced in this investigation, it was the best available independent source to aid in the accuracy assessment.

Once the data wer collected from the field and the independent 1999 orthophoto, the sample point data was inserted into an error matrix to compute the thematic accuracy results.

Measurement, Comparison and Presentation Procedures

One of the research objectives of this investigation was to determine if land cover change occurred at a constant or a variable rate throughout the period of study. It was hypothesized that:

H_2: Given that coastal systems are constantly changing in response to various factors, the rate of land cover change would not be the same from 1978 to 1988 as it was for 1988 to 1999.

To explore this hypothesis, an overlay function was used to analyze any changes in land cover in the study area. Overlays are used to detect differences between categorical data on two or more time periods in the same region (Chrisman, 1997). In ArcView 3.3, an "intersect" was performed between the 1978 and 1988 land cover classifications, the 1988 to 1999 land cover classifications, and the 1978 and 1999 land cover classifications. New fields were created in the shapefile databases to categorize the type of overlay change category and the area of the overlay polygons in square meters.

The overlay categories were divided into three classes to simplify the discussion: successive, regressive, and unchanged. Table 4:6 breaks down these three categories into their component land cover change classifications. For analysis purposes, the regressive, successive, and unchanged areas are presented as a percentage of the entire classified area. Individual cover changes within each of these three categories are discussed as a percentage of total regressive, successive, or unchanged area, depending on which category they belonged to.

An additional research objective of this study was to determine if management strategies had an effect upon land cover change over the period of study. It was hypothesized that:

H_3: Given that the southern end of the park is more intensely used by people than the northern end of the park, degradation of land cover would be more apparent in the High-Use Area than in the Natural Area.

This hypothesis was explored by splitting the land cover interpretations into a Natural Area and a High-Use Area. These areas were shown on Figure 3:1 in the Study Area section. This division was made so a comparison could be drawn between an area under heavy recreational use and an area under light recreational use. The determination of the boundary between the two approximates the designation of the natural area according to the MDNR.

The Natural Area is used primarily by hikers and nature enthusiasts. It is located north of the beach and therefore away from the main activities there. The High-Use Area is subject to heavy recreational use, especially in the summer when temperatures are favorable for swimming. The campground is also to the east of the High-Use Area, and campers must hike through the area in order to reach the beach by walking. This area is subject to trampling of the land cover, in addition to disturbances that could lead to sand mobilization.

Table 4:6. Land cover change categories and overlay classifications.

Regressive Land Cover Changes	Successive Land Cover Changes	Unchanged Land Cover
BWI to BS	BS to BWI	BS
DG to BS	BS to DG	BWI
DG to BWI	BS to F	DG
F to BS	BS to GS	F
F to BWI	BS to GTS	GS
F to DG	BWI to DG	GTS
F to GS	BWI to F	
F to GTS	BWI to GS	
GS to BS	BWI to GTS	
GS to BWI	DG to F	
GS to DG	DG to GS	
GTS to BS	DG to GTS	
GTS to BWI	GS to F	
GTS to DG	GS to GTS	
GTS to GS	GTS to F	

*BS, barren sand; BWI, barren with isolated plants; DG, discontinuous grass; F, forest; GS, grass and shrubs; GTS, grass, trees, and shrubs.

Maps, tables, and graphs were used to present the results and aid in the discussion of the section. Some images and maps presented in this thesis are presented in color.

Limitations

This study has several limitations that will be discussed in this section. Limitations within the study arise primarily from to the imagery used. Ideally, photo scale, timing of the image capture, type of film, and the quality of the images should have been the same for each time frame. However, when utilizing historic aerial photography, it is difficult to control for all of these factors. Often whatever is available must be used. Differences in photo scale, month the imagery was captured, the type of film, and the differing quality of the photographic prints undoubtedly had some impact upon both the orthorectification of the images and the interpretation of the land cover from these orthoimages.

Additionally, the temporal scale of this study is too coarse to be able to do any correlative studies. Many of the possible factors influencing the results (such as park visitor numbers, lake levels, wind, precipitation, and storms) are collected at much finer temporal frequencies. In order to do any true correlative studies, the images would need to have a finer temporal frequency, possibly one photo every one to three years and over a longer time period than 20 years.

Moreover, because this is a historical study, no field measurements were available regarding erosion or deposition rates in the dune field during the period of study. Although the vegetation cover may be used as a means to detect erosion or sand deposition, the relationship between vegetation and eolian sand movement can only be speculated about using existing literature.

Positional and thematic accuracy also limit the results of this study. Although quantitative results regarding land cover change are presented in this study, it is difficult to say that these numbers are accurate. That being said, most of the results discussed in this thesis were limited to the land cover classifications that produced the best thematic accuracy values (user's accuracy).

Lastly, experience of the interpreter is a limitation upon the results. Image interpretation is a skill that can be improved through practice. Although I had done land cover interpretation prior to this study, I would not deem myself an expert in land cover interpretation. However, I spent extensive amounts of time in the field using aerial photographs as maps to become familiar with the landscape. This gave me a solid base knowledge of the vegetation in existence at present day and how the vegetation correlated with landscape features.

Chapter 5

Results and Discussion

Accuracy

In this section, the accuracy of the orthoimagery and the data derived from the orthoimagery will be discussed. Reporting vertical accuracy provides a statement regarding the quality of the data used to prepare the orthoimages. Measuring the positional accuracy of the resultant orthoimages alludes to the quality of the measurements taken from the orthoimages. Describing thematic accuracy of the land cover interpretation presents an estimate of how well a sample of land cover interpretations matched conditions in the field.

Vertical Accuracy of the 1999 Input DEM and DTM

The vertical accuracy of the USGS 30-m DEM was reported in RMSE as five meters within the study area. This was considerably better than the accuracy of the DTM extracted from the 1999 imagery, which had an RMSE of 13.2 meters (measured from checkpoints and ground control combined). Based upon the quality of the input DEM and DTM alone, it was believed that the orthoimagery processed with the USGS 30-m DEM would have better positional accuracy as a result. However, this was not the case as described in the following section.

Positional Accuracy of the 1999 Test Imagery Sets

Positional accuracy describes how well the coordinates of features on the digital orthoimagery match their true horizontal location. Positional accuracy can be used, amongst other measurements of accuracy, to assess the quality of data derived from the orthoimagery. If the positional accuracy of the orthoimagery is high, then confidence can be placed in measurements collected from the orthoimagery. Thus, positional accuracy was used to determine which method of orthorectification should be used to interpret land cover in WDSP. This section compares the positional accuracy of the 1999 imagery orthorectified using a USGS 30-m DEM and the orthorectified images produced using a DTM extracted from the imagery itself.

X and Y errors were calculated by subtracting the GPS coordinate measurements of ten independent checkpoints (actual) from the image coordinate values of those checkpoints (observed). This process was repeated for the GCPs used in the orthorectification process. The checkpoint errors for both datasets are shown in Table 5:1, and GCP errors are shown in Table 5:2.

Summary statistics of error are provided for both sets of 1999 imagery. Table 5:3 presents the descriptive statistics and positional accuracy of the two test imagery sets for both the checkpoints and the ground control points. It is clear from these statistical measures that the orthoimagery produced by the DTM extraction method had a smaller range of error in X and Y than the orthoimagery produced by the USGS 30-m DEM method, indicating higher accuracy in the DTM extraction-produced imagery.

Table 5:1. Calculated differences between images and surveyed values at checkpoints (1999 imagery).

Checkpoint ID	1999 DTM Extraction Method: Error X (meters)	1999 DTM Extraction Method: Error Y (meters)	1999 USGS 30-m Method: Error X (meters)	1999 USGS 30-m Method: Error Y (meters)
2	-0.50	0.89	-9.64	2.74
15	2.48	2.52	3.22	9.05
20	-4.42	-0.68	6.13	6.19
24	1.11	0.87	4.20	5.71
27	-2.70	2.49	3.40	13.82
28	-2.34	1.15	14.58	18.27
31	2.64	-3.41	-2.37	2.01
32	0.92	-0.79	-0.06	4.92
34	-4.73	-0.86	8.11	9.45
35	0.04	-1.08	-5.12	3.17

Table 5:2. Calculated differences between images and surveyed values at ground control points (1999 imagery).

GCP ID	1999 DTM Extraction Method: Error X (meters)	1999 DTM Extraction Method: Error Y (meters)	1999 USGS 30-m Method: Error X (meters)	1999 USGS 30-m Method: Error Y (meters)
21	-4.83	0.01	11.94	13.56
14	0.31	1.32	2.14	0.15
16	1.66	0.30	1.79	2.40
17	1.05	2.65	-18.15	4.76
29	-0.54	-1.15	8.78	3.58
30	-0.47	-2.32	-6.38	-3.95
3	-1.28	9.49	0.59	13.77
26	-1.36	1.23	-4.08	2.63
33	3.48	-4.76	-6.75	-11.46

Table 5:3. Summary Statistics for Error Data of the 1999 imagery.

		1999 DTM Extraction Method: Error X (meters)	1999 DTM Extraction Method: Error Y (meters)	1999 USGS 30-m Method: Error X (meters)	1999 USGS 30-m Method: Error Y (meters)
Checkpoints	Minimum	-4.73	-3.41	-9.64	2.01
	Maximum	2.64	2.52	14.58	18.27
	Range	7.37	5.93	24.22	16.26
	Mean	-0.75	0.11	2.24	7.53
	Standard Deviation	2.54	1.73	6.91	5.22
	RMSE	2.65	1.73	6.93	9.02
GCP	Minimum	-4.83	-4.76	-18.15	-11.46
	Maximum	3.48	9.49	11.94	13.77
	Range	8.31	14.25	30.09	25.23
	Mean	-0.22	0.75	-1.12	2.83
	Standard Deviation	2.32	3.95	9.00	7.88
	RMSE	2.20	3.80	8.56	7.95

The mean error in X was slightly negative (west-biased) in the DTM-produced imagery, whereas the mean of Y errors was slightly positive (north-biased). However, both values (-0.75 and 0.11) were very close to zero. For the USGS 30-m DEM produced imagery, the means for both X and Y were farther from zero (2.24 and 7.53, respectively). The X errors had an eastward bias, whereas Y errors exhibited a northward bias that was greater in magnitude than the eastward bias. Because all Y errors were positive in the USGS 30-m DEM produced orthoimagery (Table 5:1), a northward bias can be confirmed.

Standard deviation and RMSE were smaller in both X and Y in the orthoimagery produced by the DTM extraction method than the orthoimagery produced by the USGS 30-m DEM method. This pattern implies that the dispersion and magnitude of errors were lower in the imagery produced by DTM extraction than in the imagery corrected with the USGS 30-m DEM.

Overall, the summary statistics show that the errors in X and Y on the DTM Extraction-produced imagery were less than the errors in X and Y on the USGS 30-m DEM-produced imagery. This trend was also evident at ground control points (Table 5:3). The statistical summary also shows that ground control error was greater in both orthoimagery sets than checkpoint error. This result was most likely due to the manner in which GPS measurements were collected.

The first of these limitations is that the GPS surveys for GCPs and checkpoints were conducted on different dates. Second, the GCP network was more evenly distributed over the entire image surface than the checkpoints. Some extreme positional outliers were located towards the edge regions of the orthophotos, whereas nearly all the checkpoints were in the interior portions of the images, near the dunes. The sampling distribution of the checkpoints could have biased the positional accuracy, making it appear better than the GCP accuracy.

Once the errors had been determined, a RMSE was calculated to describe positional accuracy in accordance with NSSDA guidelines (FGDC, 1998). RMSE is determined by the following equation:

$$RMSE_r = sqrt[\square((Xdata\ i - Xcheck\ i)^2 + (Ydata\ i - Ycheck\ i)^2)/n],$$

where Xdata i , Ydata i are the coordinates of the i-th check point in the dataset, Xcheck i , Ycheck i are the coordinates of the i-th check point in the independent source of higher accuracy, n is the number of check points tested, and i is an integer ranging from 1 to n. The NSSDA (FGDC, 1998) also states that the RMSE should also be reported to a 95-percent confidence interval, determined by this equation:

$$Accuracy_r \sim 2.4477 * 0.5 * (RMSE_x + RMSE_y).$$

Table 5:4 shows the results of the RMSE and accuracy calculations for both imagery sets. Checkpoint and GCP accuracies were better in the orthoimagery produced by DTM extraction than in the orthoimages produced using the USGS 30-m DEM. Therefore, this method was chosen to produce the remaining imagery sets (1978 and 1988).

Positional accuracy could have varied between the two test imagery sets for a few reasons. Shortridge and Clarke (1999) concluded that reprojection of square raster cells may alter elevation data. The USGS 30-m DEM was reprojected from geographic to Michigan Georef, using a nearest neighbor resampling strategy. Although Shortridge and Clarke (1999) concluded that nearest neighbor and cubic convolution preserve spatial characteristics in elevation data to a greater degree, these methods still change the data.

Table 5:4. Positional Accuracy of the 1999 orthoimagery.

		1999 Orthoimagery produced by DTM Extraction Method (meters)	1999 Orthoimagery produced by USGS 30-m Method (meters)
Checkpoints	$RMSE_r$	3.17	11.37
	$Accuracy_r$	5.36	19.51
GCP	$RMSE_r$	4.39	11.68
	$Accuracy_r$	7.33	20.20

Additionally, raster cell size may have played a role in the resultant accuracy of the orthoimagery. The USGS DEM had a cell-size of 30 m X 30 m, whereas the extracted DTM had a cell size of 3 m X 3 m. The terrain becomes more generalized with large cell sizes because the same elevation value is applied over a large area. It is likely that the 3 m DTM more closely represented the shape of the landscape than the 30-m DEM, despite the large errors in elevation values.

Vertical and positional accuracy: 1978 and 1988 imagery

Extracted DTMs for the 1978 and 1988 imagery had vertical accuracies in RMSE of 12.4 m and 12.9 m, respectively (as determined from GCPs and checkpoints). These DTMs were used to produce the 1978 and 1988 orthoimagery.

The summary statistics for positional error in 1978 and 1988 imagery are displayed in Table 5:5. Positional accuracy of the imagery sets is summarized in Table 5:6. These results show that the 1978 and 1988 orthoimages were less accurately positioned than the 1999 imagery. The images may be less accurately positioned due to the difference in scale between the 1999 imagery and the 1978 and 1988 imagery.

Table 5:5. Summary statistics for error data (1978 and 1988 imagery).

		1978 Error X (meters)	1978 Error Y (meters)	1988 Error X (meters)	1988 Error Y (meters)
Checkpoints	Minimum	-2.64	-7.86	-4.13	-1.06
	Maximum	9.82	11.64	7.27	11.54
	Range	12.46	19.49	11.40	12.60
	Mean	1.74	1.56	0.38	3.79
	Standard Deviation	2.49	2.31	3.27	4.11
	RMSE	3.57	4.79	2.91	4.70
GCP	Minimum	-8.93	-21.07	-8.07	-20.88
	Maximum	4.03	7.26	4.29	4.27
	Range	12.96	28.33	12.36	25.15
	Mean	-0.22	0.98	1.00	-0.33
	Standard Deviation	3.85	7.97	4.04	7.78
	RMSE	3.66	7.62	3.94	7.34

As was the case for the 1999 orthoimagery, the checkpoints were more accurately positioned than the ground control points. This was most likely due to a biased distribution of the checkpoints similar to that of the 1999 imagery. Additionally, some shrinkage and/or curling may have occurred on the paper prints of the 1988 images. Shrinkage or expansion of paper prints by even 1-2 mm can result in errors of from 24 m to 48m on 1:24,000 scale aerial photographs. The 1978 diapositive imagery was on stable polyester material that resist expansion and shrinkage. However, the quality of the 1978 imagery appeared to be the worst of the imagery sets. This was possibly due to slightly overexposed areas in and around barren sand. The reduced quality in this imagery set could have hindered the image matching techniques used by ERDAS IMAGINE Orthobase to create the orthophotos.

Table 5:6. Positional Accuracy of the 1978 and 1988 orthoimagery.

		1978 Orthoimagery (meters)	1988 Orthoimagery (meters)
Checkpoints	$RMSE_r$	6.60	5.87
	$Accuracy_r$	11.37	9.31
GCP	$RMSE_r$	8.45	8.33
	$Accuracy_r$	13.80	13.80

Thematic Accuracy

A classification error matrix is one of the most common methods of presenting thematic accuracy. An error matrix compares ground truth to the results of image classification on a category-by-category basis. Table 5.7 shows the classification error matrix for the interpretation of the 1999 imagery. Each column of errors represents omission errors (areas excluded from a category), whereas the rows represent errors of commission (areas included in the category, but are incorrectly classified).

Table 5:7. Error Matrix for 1999 Land Cover Classifications.

	Reference Data (Field)						
	BS	BWI	DG	GS	GTS	F	Row Total
Classification Data							
BS	28	0	2	0	0	0	30
BWI	1	14	2	1	1	1	20
DG	2	0	26	2	0	0	30
GS	0	0	4	16	0	0	20
GTS	0	0	1	2	14	3	20
F	0	0	0	0	2	18	20
Column total	31	14	35	21	17	22	140

Producer's Accuracy		**User's Accuracy**	
BS	90%	BS	93%
BWI	100%	BWI	70%
DG	74%	DG	87%
GS	76%	GS	80%
GTS	82%	GTS	70%
F	82%	F	90%

Overall Accuracy = 83%
KHAT = 0.79

*BS, barren sand; BWI, barren with isolated planted; DG, discontinuous grasses; GS, grass and shrubs; GTS, grass, trees and shrubs; F, forest.

Producer's accuracy indicates the percentage of each category in the sample set that was correctly classified and is a measure of omission errors (Congalton, 1991). User's accuracy refers to the probability that a point in the sample set actually represents that category in the field and is a measure of commission errors (Congalton, 1991). Overall accuracy indicates the percentage of sample points that were correctly classified.

The error matrix reveals that the barren with isolated plants and the grass, trees, and shrubs categories presented the most difficulties in the land cover interpretation. The producer's accuracy for barren with isolated plants was 100%, meaning there were no areas that were incorrectly classified as barren with isolated plants during the interpretation that should be of another category. However, the user's accuracy for the barren with isolated plants classification was only 70 %. This indicates that there is only a 70% chance that an area interpreted as barren with isolated plants will be of that category in the field.

Likewise, the grass, trees, and shrubs classification had a fairly high producer's accuracy (82%), meaning that points from this classification were correctly classified as grass, trees, and shrubs 82% of the time. However, this classification had a user's accuracy of only 70%, meaning, again, that there is only a 70% chance that an area interpreted as grass, trees, and shrubs will be of that category in the field. In terms of user's accuracy, the most accurately identified land cover classes were barren sand (93%) and forest (90%), meaning that these categories had the highest probabilities of being that category if visited in the field.

The overall accuracy of the sample set (83%) meets the USGS-NPS Mapping Program standard of 80%. However, overall accuracy is a limited measure of accuracy because some, or many, classifications may be correct due to random chance. The KHAT statistic is used to determine the percentage of correctly classified locations that are due to actual agreement and not random chance agreement (Lillesand and Kiefer, 2000). The KHAT statistic is calculated as:

$$\text{KHAT}=\frac{N\sum_{i=1}^{r} x_{ii}-\sum_{i=1}^{r}(x_{i+} * x_{+i})}{N^2-\sum_{i=1}^{r}(x_{i+} * x_{+i})},$$

where r is the number of rows in the matrix, x_{ii} is the number of observations in row i and column i, x_{i+} and x_{+i} are the marginal totals of row i and column i, and N is the total number of observations (Congalton, 1991). The KHAT value for the sampled set of classified data is 0.79. This indicates that the land cover class interpretation was 79% better than a random classification.

Once the accuracies for the sample set were determined, this information was used to reclassify areas that were misclassified according to field verification during the accuracy assessment. The accuracy assessment also aided in a re-evaluation of the classifications over the entire study area. Special attention was given to troublesome categories that presented the most confusion. With the information gained from the classification of the 1999 imagery, the 1978 and 1988 images were classified.

Some factors may have influenced the thematic accuracy assessment. Firstly, some of the sampling locations may have been incorrectly classified due to the positional accuracy of the imagery, and not as a fault of the interpretation itself. This is especially a concern when samples were drawn at or near land cover polygon boundaries. Additionally, GPS navigation rarely led to the precisely desired sampling location. A small fraction of the classification errors may be attributed to sampling in the wrong location. The difference between the date of image capture and the date of field verification could also have skewed the results of the thematic accuracy assessment. For example, an area classified as barren sand in 1999 may have appeared to be barren from the photograph, but by the time of field verification in 2003, grasses had grown into the area.

Land Cover Analysis

Maps of land cover interpreted from the digital orthophotos of the entire park area for 1978, 1988, and 1999 are shown in Appendices A, B, and C respectively. These maps are presented to demonstrate the land cover at each of the studied time periods and to demonstrate the general trends in land cover. It is important to note that although specific locations are discussed throughout this section, the quantitative measures are displayed on a park- wide scale. At this scale, a variety of geomorphic and ecological conditions are detectable and it is difficult to discern whether a pattern is dominant or not.

To place the land cover in context of landscape features, observations in the field and a topographic map aided in the interpretation of the land cover trends. To quantify these results, Table 5:8 shows the total number of polygons and total area mapped for every land cover class in each time period for the entire park area.

1978 Land cover: General Discussion

As demonstrated on the 1978 map of land cover, massive areas of barren sand covered the blowouts in all areas of the park at this time. Within the blowouts, vegetated areas were small and fragmented. The high number of polygons interpreted from the imagery is evidence of the high amount of land-cover fragmentation in 1978. For example, the barren with isolated plants, discontinuous grasses, and grass, trees and shrubs classifications each have over 100 polygons (Table 5:8).

The majority of these fragmented areas of vegetation were found at the lakeward throats of the blowouts, and mostly likely corresponded with foredunes. More dense areas of vegetation existed within depressions, probably where moisture was collecting. Recent field observations have determined that these areas are deflation hollows on the present landscape.

Deflation basins are wind-eroded hollows formed by erosion of sand (Hesp and Thom, 1990). According to Olson (1958a), deflation hollows are damp because they are often located at or near the water table. The damp conditions at deflation hollows are effective areas for initial vegetation development on dunes. The presence of dense, more mature vegetation at areas A, B, and C (Figure 5:1) suggests that the deflation hollows were protected from erosion in 1978.

Despite the general trend of fragmented vegetation in 1978, some rather dense, contiguous areas of vegetation existed at areas D, E, and F (Figure 5:1). At areas D and E, field surveys and examination of a topographic map show that these areas correspond with the limbs of parabolic dunes. Thus, in 1978, vegetation was growing up the slopes of the limb ridges.

Area F also had dense, contiguous areas of vegetation. Field observations at F revealed that the topography at this site was unusually flat. Further examination of this area on aerial photographs taken prior to 1978 provides evidence that the flat area at F was previously mined. Observations in the field suggest that the mined area was most probably the southern limb of a parabolic dune. Just to the north of this flat area is a ridge of sand that is normal to the lake and gradually rises toward the east in a manner similar to that of the limbs of parabolic dunes found elsewhere in the park. Although the area had been disturbed prior to 1978, vegetation had colonized the flat, mined area and the ridge to the north by 1978. It is uncertain if the vegetation naturally colonized the mined area, or if vegetation had been planted in an attempt to reclaim the previously mined land.

With respect to specific classifications of land cover, barren sand and forest account for the largest percentages of the total classified area in 1978, with approximately 29.5% and 62.2%, respectively (Table 5:8). The vast majority of forest cover was located on large, inland dunes to the east of the blowouts. Field observations have shown that these are mature forest communities as described by Olson (1958a) and thus, it is estimated that these dunes have been stable for at least several hundred years. Areas of barren sand include the beach and massive, open blowouts that are connected to the beach system. Because the blowouts were still connected to the beach system in 1978, sand could still move into the back dune areas with few obstacles provided that winds were strong enough to support sand transport. Additionally, the large amount of barren surfaces meant that the blowouts were very susceptible to erosion in 1978.

The remaining land cover classes represent much smaller percentages of the total classified area. Grass, trees, and shrubs cover is the most prominent of the remaining classes, representing approximately 2.8% of the total classified area. The largest areas of grass, trees, and shrubs cover were located at areas A, B, C, and F (Appendix A). As previously stated, the locations of areas A, B, and C correspond with present day deflation hollows and area F was located at an area that was previously mined.

Because the surface at area F is extremely low, it may be near the water table. Mining could have created conditions similar to the deflation hollows, producing a low, moist area. According to Olson (1958c) most tree and shrub species require moist conditions for their seeds to germinate. It would appear that in 1978, these low, moist areas were favorable for the growth of shrubs and trees. Being near the water table, these areas would have been more favorable for vegetation growth than the dry, sun exposed areas on windswept slopes of the blowouts, especially if the rainfall and snow accumulation was low at that time. Additionally, the moisture in these areas would have protected the sand from eroding, thus creating a stable surface for the growth of plants.

1988 Land cover: General Discussion

In 1988, several of the large spans of barren sand found in blowouts in 1978 had been colonized by pioneer vegetation in accordance with Olson's (1958a) model of sand dune ecological succession. Discontinuous grasses or grass and shrubs (Appendix B, areas A, B, F, E) clearly represented a bulk of the pioneer growth in these formerly barren areas. The throats of the blowouts also grew over with stabilizing vegetation, the majority of which was grass and shrubs (areas C and D, Appendix B).

Compared to 1978, the land cover in 1988 was less fragmented and covered larger, more contiguous areas. Field surveys and examination of a topographic map suggested that the vegetated areas on blowouts spread from the slopes of ridges into the interior of the blowouts from 1978 to 1988. Because most pioneer grass species require at least some burial to grow more vigorously (Olson, 1958 a, 1958c) this suggests that sand deposition was quite active from 1978 to 1988. Although some grass species tolerate low rates of erosion, the majority of grass species need sand deposition to support vigorous growth (Olson 1958a). Thus, the dense areas of grass growth suggest that erosion rates were low from 1978 to 1988.

Present day field surveys show that area E is located on the slope of a blowout limb. This area saw marked growth of discontinuous grass from 1978 to 1988. This would suggest sand deposition was active, conditions might have been moist, and that erosion in the area was low or not present. At area G there was a large area covered by barren with isolated plants that was adjacent to barren sand on the lakeward boundary and forest to the west, indicating possible burial of the forest cover by actively blowing sand.

Barren sand, discontinuous grasses, and forest accounted for the largest percentages of the total classified area in 1988, with 17.7%, 11.1% and 63.2%, respectively (Table 5:8). Barren sand decreased greatly between 1978 and1988 from 29.5% to 17.7% of the total classified area, while discontinuous grasses increased sharply from 1.6% to 11.1% (Table 5:8). This sharp decrease in barren sand cover and simultaneous sharp increase in discontinuous grass cover may signify that erosion was occurring at a slower in 1988 than it was in 1978 and/or that conditions were moister and more favorable for vegetative growth during the years leading up to 1988 than the years prior to 1978.

Grass and shrubs also increased slightly for a difference of 1.5% (Table 5:8). Though the change was small, it suggests that a small percentage of the total classified area progressed through succession from 1978 to 1988 in a manor congruent with Olson's (1958a) model on coastal dunes. Barren with isolated plants, and grass, trees and shrubs showed little or no change between 1978 and 1988.

Table 5:8.

Total Number of Polygons and Total Area for Each Class: 1978, 1988, and 1999

Class	Total Number of Polygons			Total Area (m^2)			Percent of Classified Area		
	1978	1988	1999	1978	1988	1999	1978	1988	1999
Barren Sand	85	89	102	921310	547438	499881	29.5	17.7	16.0
Barren with Isolated Plants	163	87	74	51087	44290	49338	1.6	1.4	1.6
Discontinuous Grasses	100	62	72	50027	342483	386588	1.6	11.1	12.4
Grass and Shrubs	110	69	59	69653	113717	154855	2.2	3.7	5.0
Grass, Trees, and Shrubs	79	53	35	86430	87483	102085	2.8	2.8	3.3
Forest	7	11	7	1940955	1952018	1930749	62.2	63.2	61.8
Unclassified	4	4	4	1378390	137056	1375040			
Total	**548**	**375**	**353**	**4497852**	**4466484**	**4498535**			

Total Classified Area = 1978, 3119461; 1988, 3087428; 1999, 3123495.

The total number of polygons has decreased from 548 to 375 between 1978 and 1988 (Table 5:8). This decrease verifies that in 1988, land cover was less fragmented than in 1978. More specifically, nearly all the land cover classifications with vegetation decreased with regard to number of polygons, while barren sand increased only slightly. This means that vegetative cover expanded from 1978 to 1988 (Table 5:8).

In 1988, it is interesting to note that the total area was smaller than in the 1978 and the 1999 interpretations. This was due to higher lake levels recorded on the 1988 imagery. The high lake level decreased the size of the beach, therefore decreasing the total area of the park. Though 1978 and 1988 had approximately the same average annual lake level, the 1988 imagery may have been captured just after a storm, explaining why the lake level might have been higher than what was captured in the 1978 imagery.

1999 Land cover: General Discussion

Land cover in 1999 was even less fragmented than in 1978 or 1988. Present day field studies showed that area A (Appendix C) is located within a blowout, thus, in 1999 must have also been within a blowout. This blowout was nearly filled in with vegetation in 1999. Grasses and shrubs dominated the lakeward throats of these blowouts, a possible indication that these blowouts are healing. The blowouts at areas B and C (Appendix C) also have extensive areas of grass and shrubs or discontinuous grasses at the lakeward throats, implying that these blowouts may also be healing as described in Gares and Nordstrom (1995).

At area D (Appendix C) there was a very large area covered by the barren with isolated plants class, with an open area of barren sand to the west. Field investigations show that this area is currently the slip face of a parabolic dune. Slip faces undergo sand deposition if the dune is active. Barren with isolated plants cover at D suggests that in the years leading up to 1999, this dune was active. As sand slipped down the lee slope of this dune, it buried forest cover behind it. However, field evidence showed that while this dune may have been migrating over pre-existing forest cover, new, pioneer species of trees were taking root on the slip face as well. Olson (1958a, 1958c) noted that trees such as cottonwoods are often pioneer tree species, especially on the steep lee sides of dunes and can tolerate moderate rates of sand deposition.

The area of barren with isolated plants cover at area E (Appendix C) is also adjacent to a lakeward area of barren sand, but is abutted by forest to the east. However, field investigations of this area show that this area corresponds with the windward slope of a dune. Exposed tree roots and fallen trees observed during present day field studies are a testament of the severe erosion in this area. Thus, in 1999, the large area of barren with isolated plant cover here indicates that the area was most likely undergoing erosion in 1999 also. Sand was eroding away at a high rate, exposing tree roots and undermining trees.

At area F (Appendix C), a large area of grass, trees and shrubs cover existed, though this area was still rich with trees. Field studies showed that this area also corresponded with the slip face of a large parabolic dune. A likely scenario here was that sand had been sliding down the slip face of the dune at a slow rate, buried some of the more sensitive understory vegetation and made the vegetation less dense in 1999 than in the 1988 and 1978 imagery.

Field surveys concluded that discontinuous grasses at area G (Appendix C) were located on a ridge that gradually rises running from west to east (as in Appendix A, area F). Grasses and shrubs dominated the flatter, previously mined topography to the south of the ridge. The presence of grasses and shrubs in this area indicates a slow rate of sand deposition and erosion. It also indicates a maturing plant community at this location in accordance with Olson's (1958a) model of ecological succession.

Barren sand, discontinuous grasses, and forest accounted for the largest percentages of classified area in 1999, with 16.0%, 12.4% and 61.8%, respectively (Table 5:8). Barren sand decreased only slightly between 1988 and 1999 for a difference of 1.7%, while discontinuous grasses increased slightly from 11.1% in 1988 to 12.4% in 1999 (Table 5:8). This suggests that over a park-wide scale, very little of the most stable and mature cover (forest) regressed to other, less mature land cover. However, at specific regions within the park, changes from forest cover to less mature cover are noted.

Grass and shrubs also increased from 3.7% in 1988 to 5.0% in 1999 (Table 5:8). Additionally, grass, trees and shrubs increased slightly from 2.8% in 1988 to 3.3% in 1999 (Table 5:8). The expansion of these more mature vegetation covers suggests some ecological succession had occurred in a manner similar to that described by Olson (1958a).

Overlay Discussion

Overlay maps of the land cover changes from 1978-1988 and 1988-1999 are presented in Appendices 4 and 5, respectively. These maps are included to show and compare the change in land cover for each time period studied. The maps have been simplified into three categories of land cover changes in context of Olson's (1958 a, 1958c) research on the ecological succession of Lake Michigan sand dunes. The three categories are successive land cover changes, unchanged, and regressive land cover changes.

The presence of plant cover can provide a relative measure as to the geomorphic conditions of dunes (Olson, 1958c). Land cover changes from a less mature or barren stage in an earlier time to a denser, more mature form of vegetation cover in a latter time period indicate a successive land cover change had occurred. If vegetation communities had progressed forward through ecological succession, erosion rates may have decreased to a rate to support the succession of vegetation communities. Additionally, some land covers indicate moderate rates of sand deposition (discontinuous grasses, grasses and shrubs for example), while others are dominant when deposition has slowed or is non-existent (such as grasses, trees, and shrubs cover or forest). Regardless of deposition rates, an increase in vegetation density indicates succession has occured. Areas undergoing succession are progressing towards dune stabilization in accordance with Olson's model of ecological succession (1958a; 1958 c).

In unchanged areas, land cover had not changed during the indicated decade of study. Conditions in these areas were not suitable for vegetation to succeed and mature, nor for pioneer vegetation to establish. Alternatively, not enough time had passed for vegetative cover to mature to the next stage (Olson, 1958a). Additionally, conditions in unchanged areas did not allow for the degradation of the existing vegetation.

Regressive land cover signifies that vegetation that had existed at an earlier time period had been reduced. Conditions at these areas had caused vegetation communities to degrade to a less mature state or to disappear. Erosion or deposition rates in these areas may have increased to reflect this reversal in the ecological succession as described by Olson (1958a). Thus, because stabilizing vegetative cover had been lost, these areas were destabilizing and geomorphic processes that cause the migration of sand were activated.

To quantify the results, figures and graphs are provided along with the discussion of each time frame of the study. The changes from one land cover type to another are discussed in terms of whether the change was successive, unchanged or regressive. The breakdown of these categories is listed in Table 4:6, of the methods section, for review. Unless stated otherwise, percentages of change from one classification to another are reported as a percent of total successive, regressive or unchanged land cover, and not as a percentage of the total park classified area. Land cover changes from 1978 to 1988 are discussed first, followed by changes from 1988 to 1999.

1978 – 1988 Visual Overlay Analysis

Appendix D shows the changes in land cover for the 1978-1988 overlay analysis. During this time frame, the northernmost blowouts at area A (Appendix D) had filled in with vegetation cover. The majority of species were most likely pioneer vegetation such as *Ammophilia breviligulata* (American beach grass; Olson, 1958a). Field investigations suggest that these areas were either the limbs of parabolic dunes, topographically lower areas near blowout hollows, or flatter, interior dune regions.

The regressive land cover found at area B (Appendix D) corresponds to a slip-slope of a parabolic dune, according to field investigations at that site. Here, sand was being deposited along the forest margin, burying pre-existing trees. However, some pioneering species of trees invaded the slope from 1978, to 1988, explaining the presence of some small trees seen on the slope in the 1988 imagery that were undetectable on the 1978 imagery. This suggests that while the dune is migrating and burying over pre-existing, mature forest cover, conditions here are still favorable for the growth of new, pioneering trees (Olson 1958a, 1958c). Perhaps the new trees on the slope will be able to stabilize the movement of this dune in the future.

Thin, linear bands of regressive land cover at areas C, D, and E (Appendix D) corresponded with the present day locations of foredunes. Because the land cover changes were regressive and not successive, the rate of sand deposition may have greatly increased from 1978 to 1988 to exceed the tolerance level of the vegetation species located there. Alternatively, the regression of vegetative cover may indicate the rate of erosion on these foredunes increased from 1978 to 1988. Upon closer examination, it was evident that the majority of these foredunes had regressed from grass, trees, and shrubs in 1978 to grasses and shrubs in 1988. The relatively quick loss of trees during this decade suggests that this area was most likely undergoing erosion.

In the southernmost blowouts at areas F and G (Appendix D) successive land cover changes occurred. Field investigations suggest that these areas corresponded with the limb slopes of parabolic dune and the flatter, interior areas of the blowouts. The presence of successive cover here suggests that these limbs were progressing towards stabilization.

The large areas of regressive land coverthat surrounded area H (Appendix D) are in an area of flat topography. Field investigations suggest that area H was at a windward slope of a dune. A small band of regressive land cover at H was abutted by barren sand to the west, and forest to the east. This pattern suggests that pre-existing mature forest cover was being destroyed by erosion on the windward slope (Baurer and Sherman, 1999).

Field studies show that Area I coincides with the slip face of a parabolic dune. In 1978, the regressive land cover here suggests that sand was actively burying pre-existing forest cover at area I. In the 1988 imagery, extremely large, tall trees were notably surrounded by barren sand at this spot. No new growth appeared to have occurred from 1978 to 1988, suggesting that this area was experiencing high rates of sand deposition.

At area J (Appendix A), a large area of successive land cover occurred in an area that corresponds with the flatter, interior region of a blowout and also up the northern slope of a limb. The presence of successive vegetation at this location suggests that the area was progressing towards stabilization from 1978 to 1988.

1978 – 1988 Overlay Analysis: Quantitative Results

Although the former section discussed qualitative results in land cover change in specific areas around the park, this section details the quantitative results of land cover change from 1978 to 1988 for the entire park. From 1978 to 1988, the largest percentage of classified land was in the unchanged category and amounted to 82%. The breakdown by land cover classification is displayed in Figure 5.1. The classifications that held the largest percentages of unchanged areas from 1978 to 1988 were forest (75.1%) and barren sand (20.0%).

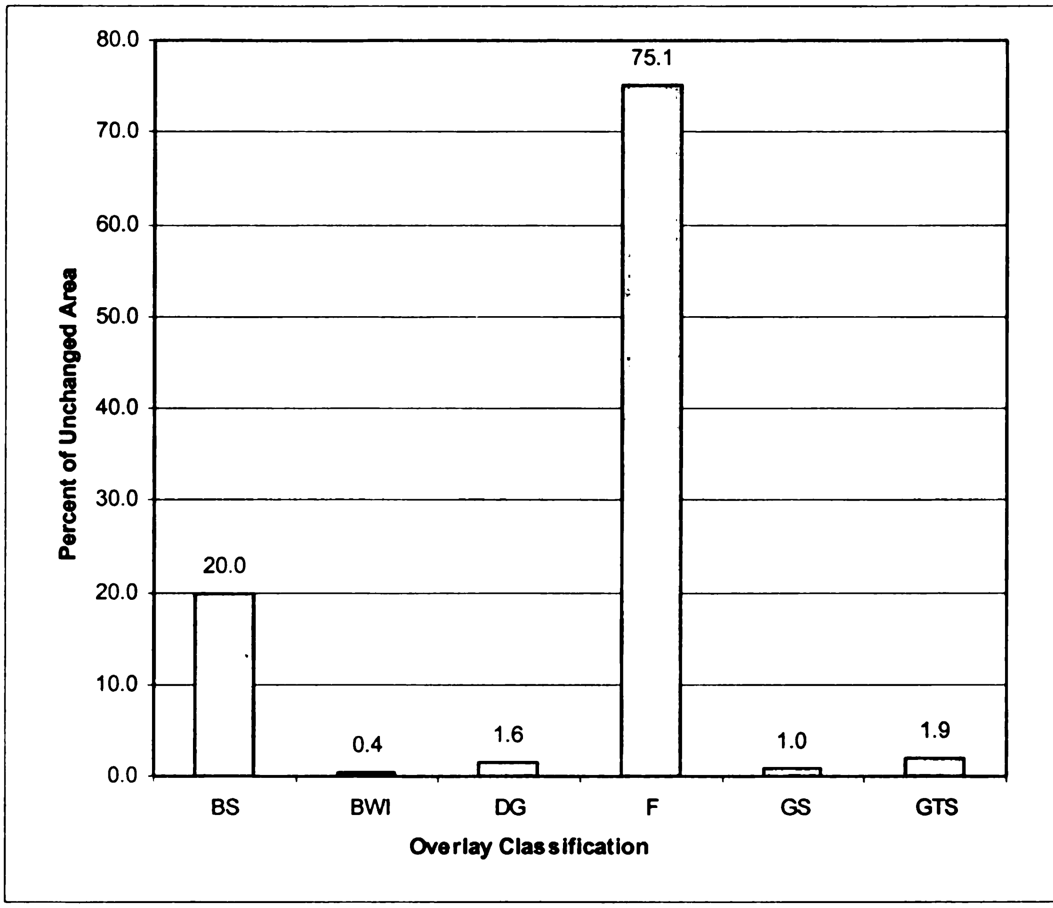


Figure 5.1. Graph showing overlay percentage of unchanged land cover by overlay classification, 1978-1988. *BS: barren sand, BWI: barren with isolated plants, DG: discontinuous grasses, F: forest, GS: grasses and shrubs, GTS: grass, trees, and shrubs.

The percentage of classified area that was covered by successive land cover was the next largest portion of the study area, accounting for 13.8% of the total classified area. Within the successive land cover changes category, the four largest changes were from barren sand in 1978, to vegetated land in 1988 (Figure 5.2). Barren sand to discontinuous grasses was the most common type of successive land cover change from 1978 to 1988, accounting for 59.1% of all the areas that experienced ecological succession.

This value is distinctly higher than changes from barren sand to grasses and shrubs, which accounted for the next largest percentage of the total area covered by successive land cover (14.6%). The high percentage of barren sand to discontinuous grasses suggests that grasses were most likely to colonize barren sand before other plant species and that ecological succession was proceeding as described by Olson (1958a).

Many dune grasses require sand deposition for vigorous growth (Olson 1958 a, 1958c). The large percentage of barren sand to discontinuous grasses implies that this decade was marked by a rate of sand deposition that did not exceed the growth rate of the grasses, and even favored this growth. It also implies that the rate of sand deposition was too rapid in most areas to allow the growth of larger plants, such as shrubs.

It is interesting to note that barren sand to forest accounts for 5% of the successional land cover changes (Figure 5:2). It is highly unlikely that within 10 years barren sand cover would convert to forest. The majority of this conversion is most likely explained by changes in tree canopy. A small portion of the areas that changed from barren sand in 1978 to forest in 1988 was at the margins of blowouts where sand abuts forest cover. Tree canopy changes add a small amount of bias to the results only where the changes are from very immature ecological stages (barren sand or discontinuous grasses) to forest and the areas are at the margins of dense forest cover.

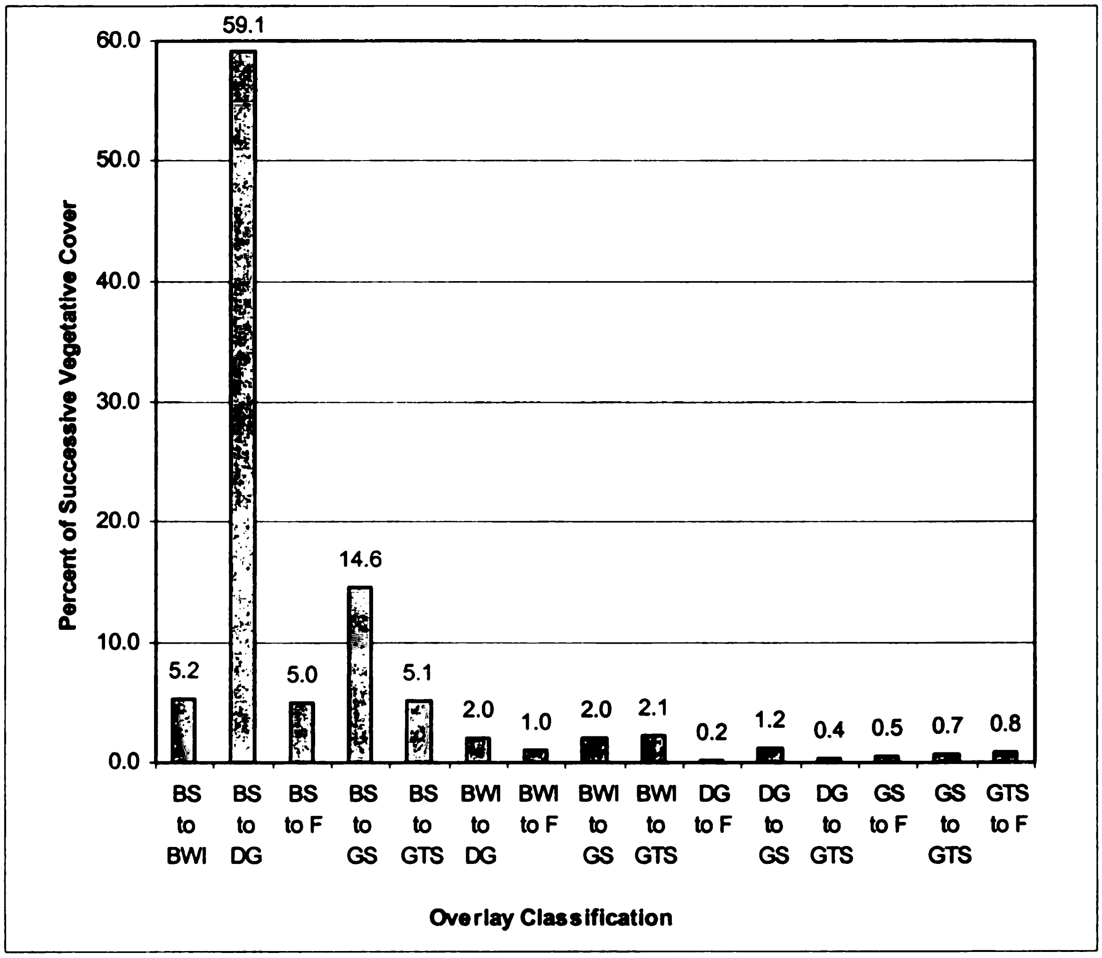


Figure 5.2. Graph showing overlay percentage of successive land cover by overlay classification, 1978-1988. *BS: barren sand, BWI: barren with isolated plants, DG: discontinuous grasses, F: forest, GS: grasses and shrubs, GTS: grass, trees, and shrubs.

Regressive land cover changes account for 3.5% of the total classified area from 1978 to 1988. The largest portion of regressive land cover was from grasses and shrubs in 1978 to discontinuous grasses in 1988 (26.0%; Figure 5.3). This suggests that in a majority of the areas undergoing degradation, the rate of sand deposition or erosion exceeded the tolerance of some shrub species.

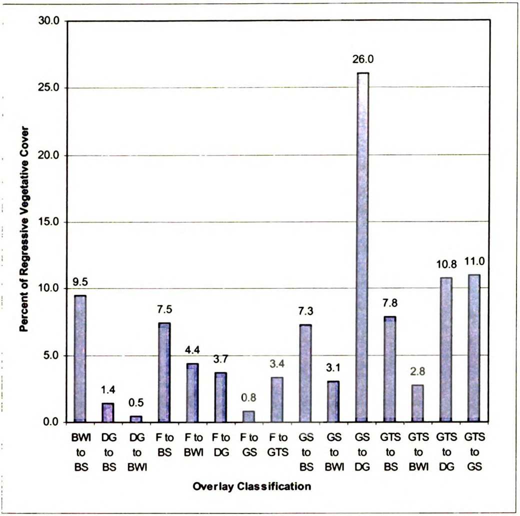


Figure 5.3. Graph showing overlay percentage of regressive land cover by overlay classification, 1978-1988. *BS: barren sand, BWI: barren with isolated plants, DG: discontinuous grasses, F: forest, GS: grasses and shrubs, GTS: grass, trees, and shrubs.

The next largest portion of regressive land cover was from grass, trees, and shrubs in 1978 to grass and shrubs in 1988. It is likely that this type of change implies erosion in these areas. When compared to the digital orthophotos, a majority of these areas were found on windswept slopes of blowouts, suggesting that the sand was being swept from under the roots of very small, immature trees, thus undermining the trees until they fell over. Some of the grasses and shrub species that may have accompanied these trees in 1978 were more tolerant to erosion than the small trees that had disappeared by 1988 and thus, were still detectable in 1988.

Another interesting pattern is the amount of change from forest cover in 1978 to barren sand in 1988. A small portion of this type of degradation was biased by changes in tree canopy, but the bias was only detectable in small bands at the margins of the forest. As noted before, Appendix D shows an area at H and at I where sand was burying forest. Qualitatively, this recession of the forest boundary is detectable on the digital orthophotos at these areas (Figure 5:4). Additionally, field observations revealed that dead wood littered the barren sand near the forest boundary, suggesting that sand is being eroded away from the root systems of large trees.

1988 – 1999 Visual Overlay Analysis

Appendix E shows the changes in land cover for the 1988-1999 overlay analysis. Long, linear regions of successive land cover occurred in the majority of foredunes within the park at A, B, and C (Appendix E). Sand deposition probably occurred at a moderate rate from 1988 to 1999 to support the growth of vegetation on these foredunes (Olson, 1958 c; 1958d).

However, the foredunes at area D (Appendix E), which also corresponds with the High-Use Area, have regressed from 1988 to 1999. This would suggest that the foredunes at area D had experienced erosion during this decade, possibly from the presence of beach visitors in this area.

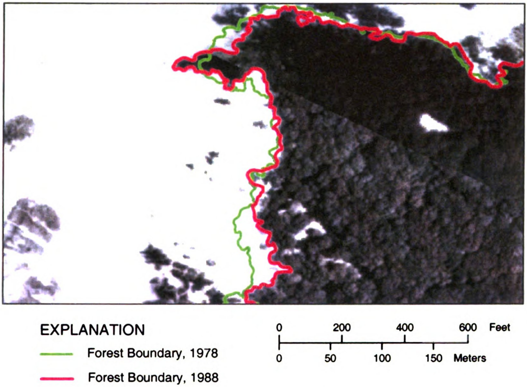


Figure 5.4. Recession of forest cover as seen at areas H and I (Appendix D).

In the northernmost blowouts at area E (Appendix E), some large areas of regressive land cover occurred in the central region of these blowouts. Modern field investigations suggest these areas corresponded with a windward slope. The regressive land cover implies that erosion occurred in this blowout between 1988 and 1999. According to Baurer and Sherman (1999) a blowout undergoing erosion has not yet reached it's deflation limit and will continue to erode and migrate until it does.

The small blowout at area F (Appendix E) shows a large area of successive land cover in the backdune area, suggesting that for the most part, sand deposition or erosion decreased from 1988 to 1999 in the backdune area of this blowout. However, degradation of the land cover occurred through some of the interior, windswept slope of this blowout and near the lake.

Within the southern blowout at area G (Appendix E), were large areas of successive land cover. Field studies show that these areas coincide with the slopes of blowout limbs. Vegetation plays a role in the formation of parabolic dunes by stabilizing the limbs while allowing the central part to advance with the wind (Livingstone and Warren, 1996). This finding suggests that the dunes here behave in a matter consistent with other dunes.

Some of the successive land cover at area G (Appendix E) also corresponds to an area of flat topography. As previously stated, field investigations and examination of historic aerial photography suggest this area had been mined. The surface here is in a topographic low and may collect moisture. This low, moist area would encourage the growth of trees that need moisture and lengths of time to germinate from seed (Olson, 1958a).

To the west, at area H (Appendix E), is a pronounced area of regressive land cover. Field investigations suggest that this area coincides with the slip face of a parabolic dune. On slip faces of dunes, sand particles get deposited near the crest. When the amount of deposited sand exceeds a critical angle, slope failure occurs, resulting in a flow of sand down the slip face (Livingstone and Warren, 1996). At area H, sand deposition and slope failure from 1988 to 1999 was high enough to bury massive trees.

At area I (Appendix E), an additional, massive area of regressive land cover was observed. This was located on the main, windward slope of a high dune and therefore was experiencing erosion (Livingstone and Warren, 1996). The erosion here was strong enough to undermine trees and therefore the land cover regressed.

Lastly, area J was another large area of regressive land cover. This area, like I, was on the slip face of a dune. However, the rate of sand deposition was not apparently high enough to constantly bury large trees. The area had actually converted from forest cover in 1988 to grass, trees and shrubs cover in 1999, suggesting that sand may have buried understory vegetation, making the cover less dense in this area.

1988 – 1999 Overlay Analysis: Quantitative Results

From 1988 to 1999, the largest percentage of total classified land was in the unchanged category, amounting to 86.2%. The breakdown of the unchanged category by land cover classification is displayed in Figure 5:5. The land cover classifications that held the largest percentages of unchanged areas were forest (71.3%) and barren sand (15.0%).

The percentage of total classified area that was covered by successive land cover represented the next largest portion at 8.6%. Within the successive land cover areas, barren sand to discontinuous grasses was the most common change from 1988 to 1999, accounting for 36.2% of the total area covered by successive

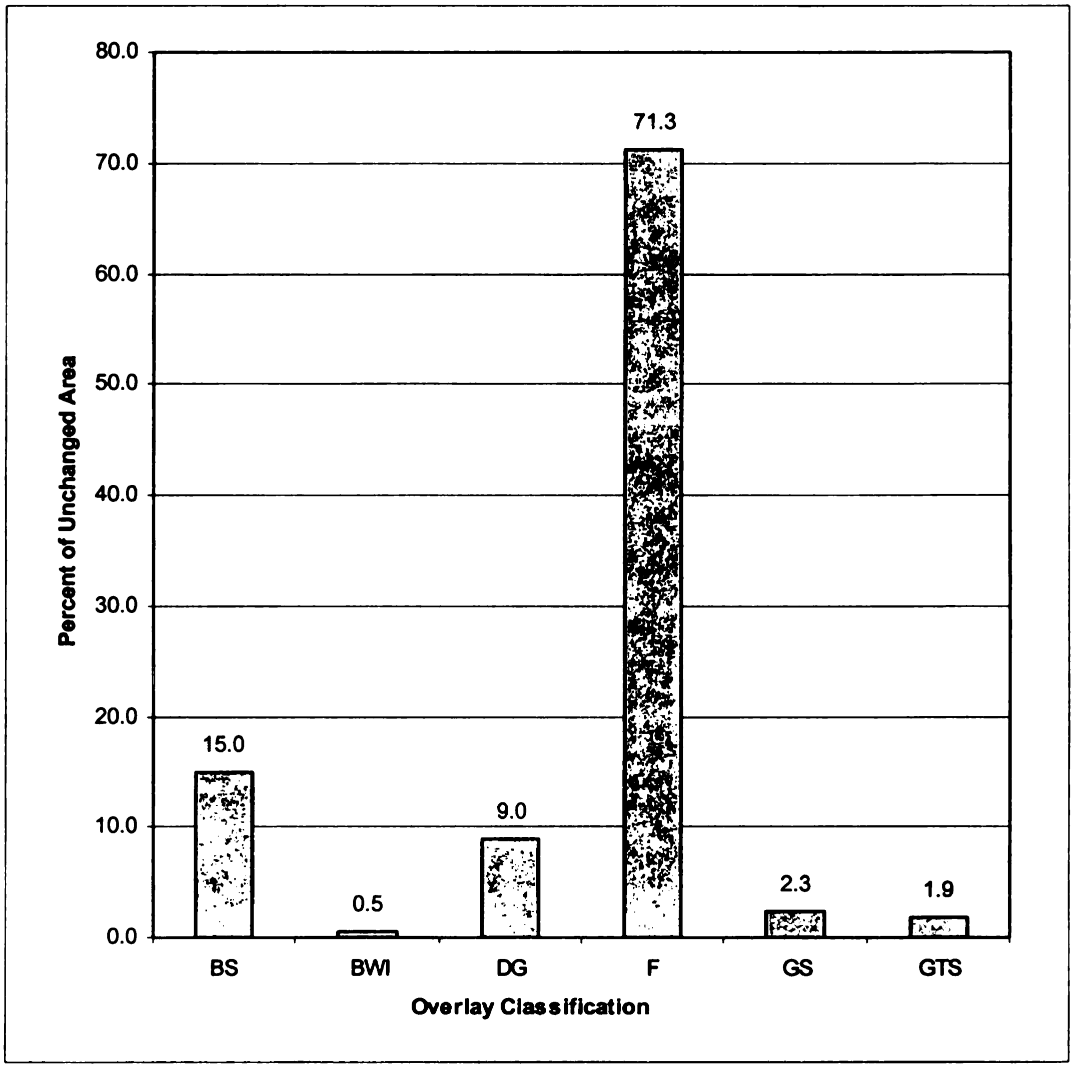


Figure 5:5. Graph showing overlay percentage of unchanged land cover by overlay classification,1988-1999. *BS: barren sand, BWI: barren with isolated plants, DG: discontinuous grasses, F: forest, GS: grasses and shrubs, GTS: grass, trees, and shrubs.

vegetation (Figure 5:6). This value was considerably higher than the next highest type of successive land cover change, from discontinuous grasses in 1988 to grasses and shrubs in 1999 (19.3% of the total area experiencing succession).

Therefore, in areas where successive land cover was found, conditions were more favorable for grasses to colonize barren sand than they were for shrubs to grow into areas already stabilized by grasses. In accordance with Olson's (1958a) model of ecological succession on Lake Michigan dunes, the dominance of grass as pioneer vegetation suggests that sand deposition occurred in a majority of the areas where succession had occurred.

The third highest percentage of successive land cover changes was from barren sand to grasses and shrubs (7.7% of the total area undergoing succession). This finding suggests that within the cumulative areas that had successive land cover changes from 1988 to 1999, there was a modest percentage of area where ecological succession happened at a faster rate than for example, areas that had progressed from barren sands to discontinuous grasses. This is evident from the growth of both grass species and shrubs on barren sand within a decade.

Regressive changes in land cover account for 5.3% of the total classified area from 1988 to 1999. Therefore, over the entire park area, degradation of the vegetation was occurring at a slower rate than vegetation could mature. The largest change in regressive cover was from discontinuous grasses in 1988 to barren sand in 1999, which accounted for 14.6% of the cumulative areas undergoing degradation (Figure 5:7).

However, grasses and shrubs in 1988 to discontinuous grasses in 1999 was a nearly equivalent type of land cover change (14.5% of the cumulative areas undergoing degradation; Figure 5:7). This suggests that from 1988 to 1999, the most likely types of vegetation to be lost were pioneers. This could imply that in this decade, the rate of sand deposition within some areas of the park was too high to support plant growth, or, conversely, that the rate of erosion was too high for these pioneering species to grow.

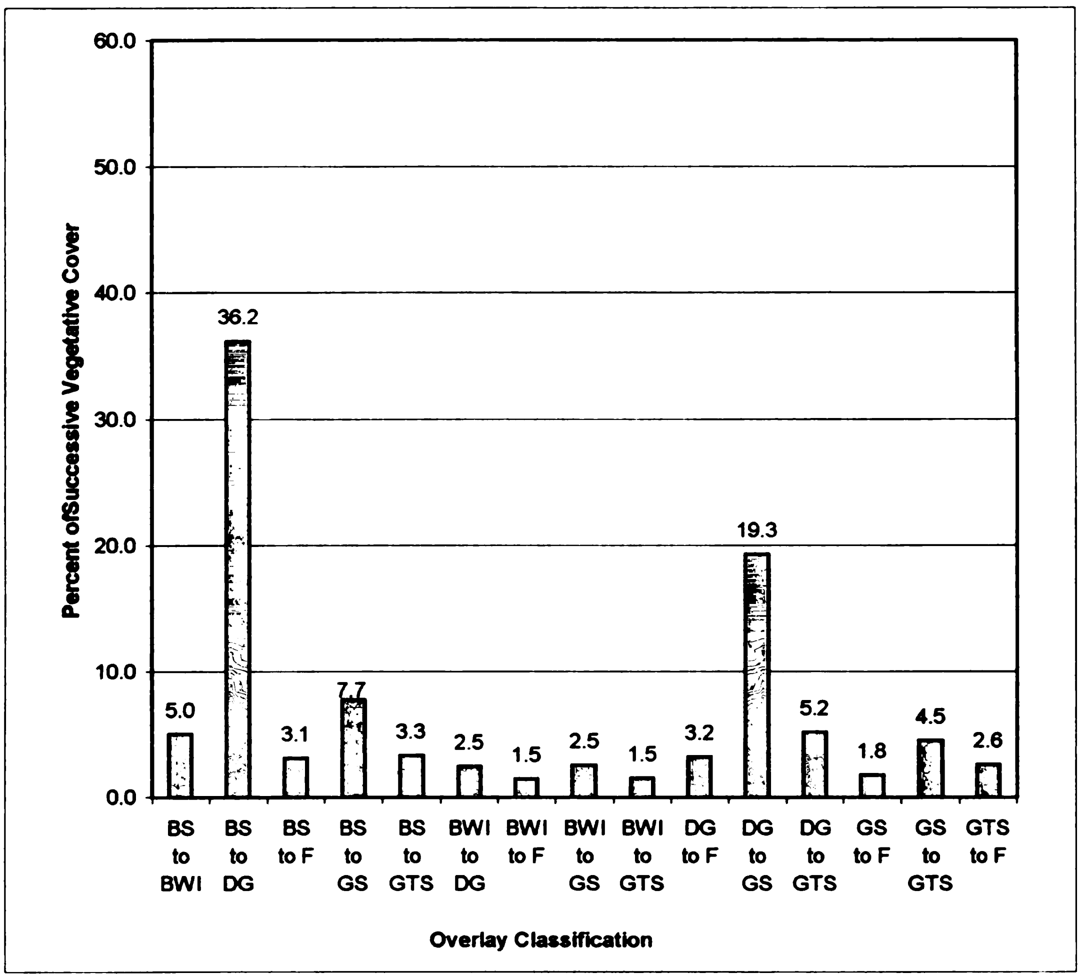


Figure 5:6. Graph showing overlay percentage of successive land cover by overlay classification, 1988-1999. *BS: barren sand, BWI: barren with isolated plants, DG: discontinuous grasses, F: forest, GS: grasses and shrubs, GTS: grass, trees, and shrubs.

The next common types of recessive land cover changes were both from forest in 1988 to a less dense vegetative cover in 1999. Forest in 1988 to grass, trees and shrubs in 1999 occurred in 8.6% of the total regressive area, while forest in 1988 to barren sand in 1999 occurred in 8.5% (Figure 5:7). Two large areas of these types of changes were found at areas I and J (Appendix E). As explained earlier, area I was on the windward slope of a high dune and is undergoing rapid erosion.

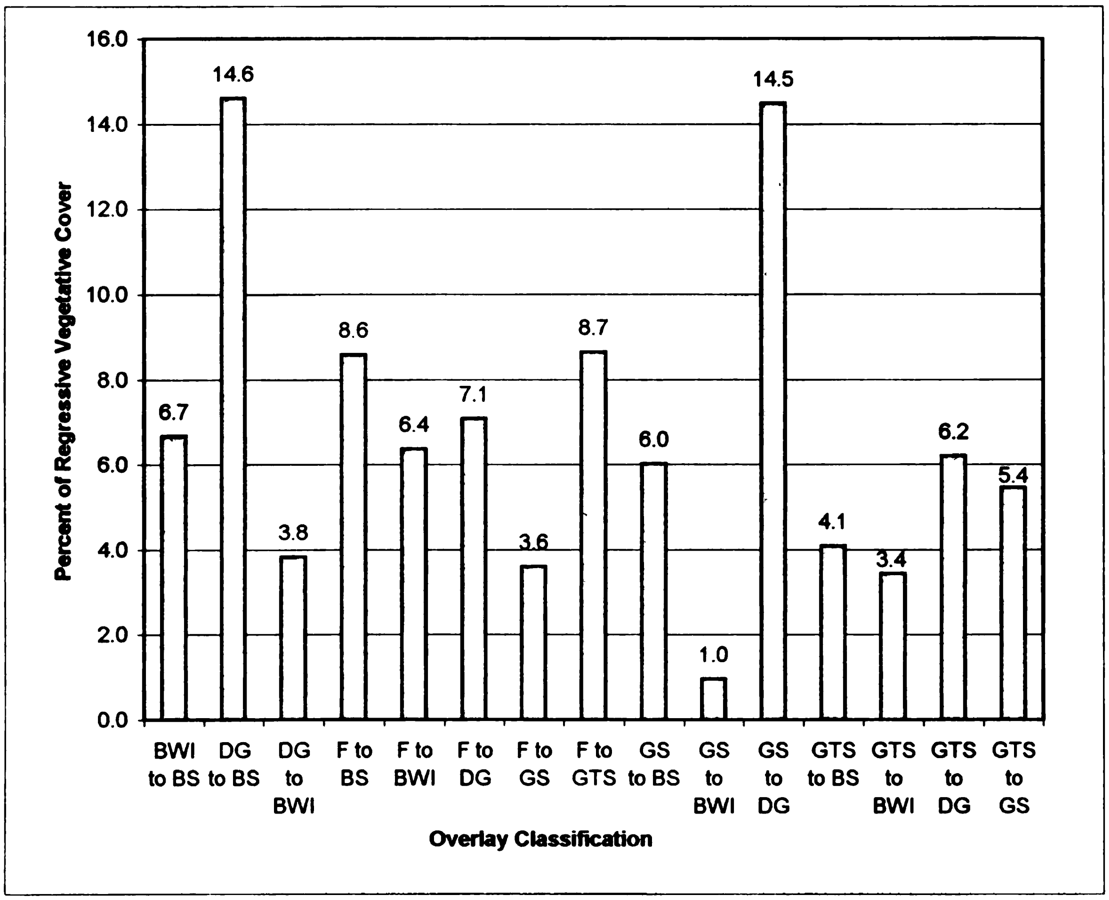


Figure 5:7. Graph showing overlay percentage of regressive land cover by overlay classification, 1988-1999. *BS: barren sand, BWI: barren with isolated plants, DG: discontinuous grasses, F: forest, GS: grasses and shrubs, GTS: grass, trees, and shrubs.

Figure 5:8 shows the forest boundary at each time period studied and depicts the rapid rate of forest recession at this area. Area J, as mentioned previously, was on the slip face of a dune. Because this area had converted from forest cover in 1988 to grass, trees, and shrubs in 1999, there is the implication of some possible deposition of sand over understory vegetation. However, the rate of burial on this slope is probably moderate, given that the land cover degradation has not been dramatic.

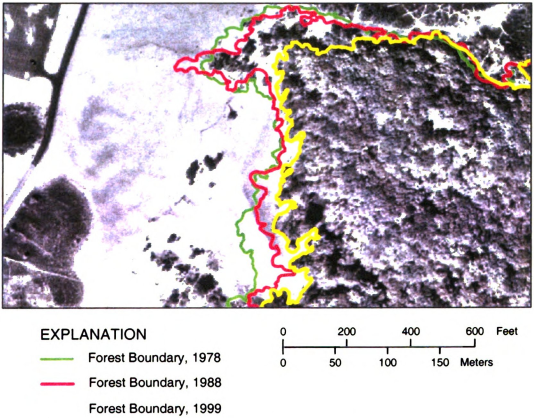


Figure 5:8. Forest recession 1978-1999 at (area I, Appendix E).

A comparison: 1978-1988 and 1988-1999

The intent of this section is to compare the rates of land cover change over the entire study area from 1978 to 1988 and 1988 to 1999. The middle time frame, 1988, was included to determine whether changes in land cover occurred evenly over the period of study or if change had occurred at different rates. Comparing results on a decadal scale, as opposed to the entire period of study, provides insight as to whether land cover changes in the park are over the short term or long term. Generalized land cover changes (successive, unchanged, or regressive) for each decade are shown in Figure 5:9 as a graph comparing percentage of total classified area.

The results of this study suggest that the rate of change was not constant throughout the period of study. Figure 5:9 shows that from 1978 to 1988, 13.8% of the total classified area was successive land cover, while 3.5% of the total classified area was regressive land cover. From 1988 to 1999, the amount of successive land cover had decreased to 8.5% of the total classified area, a difference of 5.3% from the previous decade. Regressive land cover increased slightly from 1988 to 1999 to 5.3%. The percentage of land cover remaining unchanged (on a decadal scale, not over the entire period of study) also increased from 82.8% of the total classified area in 1978-1988 to 86.2% in 1988-1999.

These results indicate that in both decades, successive land cover changes covered a greater area than regressive land cover changes. However, a greater percentage of successive land cover changes occurred from 1978 to 1988 than from 1988 to 1999. Additionally, both decades saw some regression of land cover, though the percentages of land cover regression were relatively low in both decades. The findings of this study suggest, however, that degradation of land cover occurred at a greater rate in 1988 to 1999 than from 1978 to 1988.

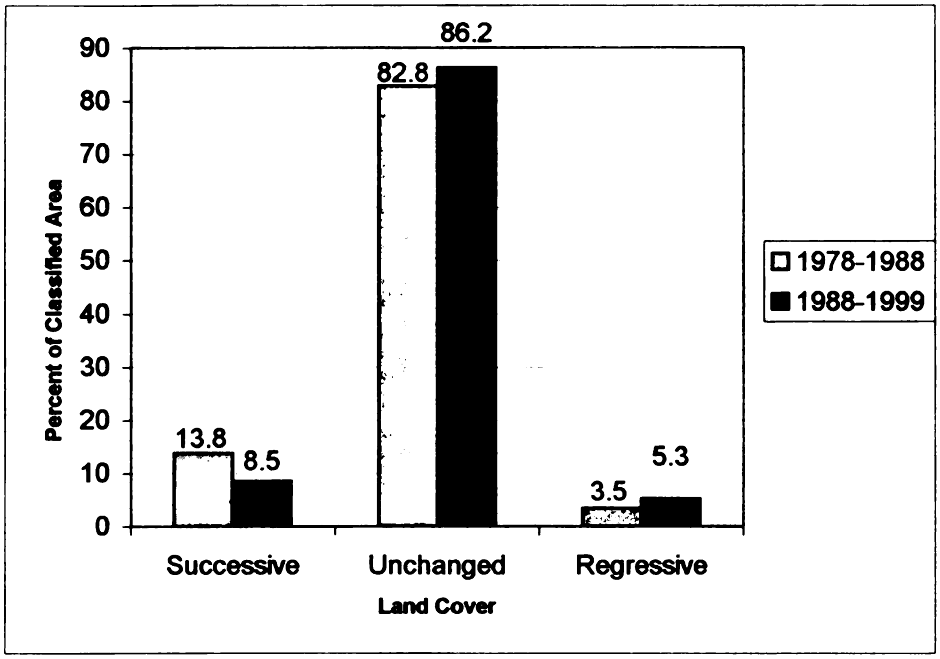


Figure 5:9. Land cover change as percent of entire classified area: 1978-1988 vs. 1988-1999.

Possible Factors Influencing Land Cover Changes

This section offers some environmental and cultural factors that could explain the apparent differences in land cover change between 1978 to 1988 and 1988 to 1999 for the entire park. Vegetative growth or degradation may be impacted by climatic factors such as precipitation or intense storm winds, or indirectly affected by cultural factors such as the number of visitors who contribute to disturbance of the vegetative cover. Additionally, since vegetation responds to sand deposition and erosion, the succession or regression of vegetation can also be attributed to geomorphic factors such as lake level changes and sand nourishment.

Climate

The extent and type of vegetation can result from the amount of precipitation in the region. Extremely wet years can encourage very vigorous vegetative growth, while dry years can inhibit or discourage the growth of stabilizing vegetation. Precipitation values used in this study were collected from the Benton Harbor or Eu Claire stations, located near the study area.

As seen from Figure 5.10, though average precipitation values vary from year to year, the general trend in average precipitation is steadily falling over the entire period of study. Within the region, the first time frame of the study (1978-1988) had a slightly higher average precipitation value (100.51 mm) than the later time frame, 1988 to 1999 (92.04 mm). Additionally, precipitation was at a relative peak within the study area in 1981. This could, in part, possibly explain the greater percentage of successive vegetation from 1978 to 1988 than from 1988 to 1999.

Storms may also have an impact upon vegetation. The high winds during storms can destroy vegetation on sand dunes. Patches of sand that are laid bare by high storm winds may lead to the development of blowouts (Livingstone and Warren, 1996). Thus, storms, especially those accompanied by high winds, may initiate erosion in some areas of the dunefield.

During the period of study, storms were classified as thunderstorms with high winds, hail storms, winter storms, flood events and tornadoes. The intensity of winds measured during these storm events was generally over 74 km/h (46 mph).

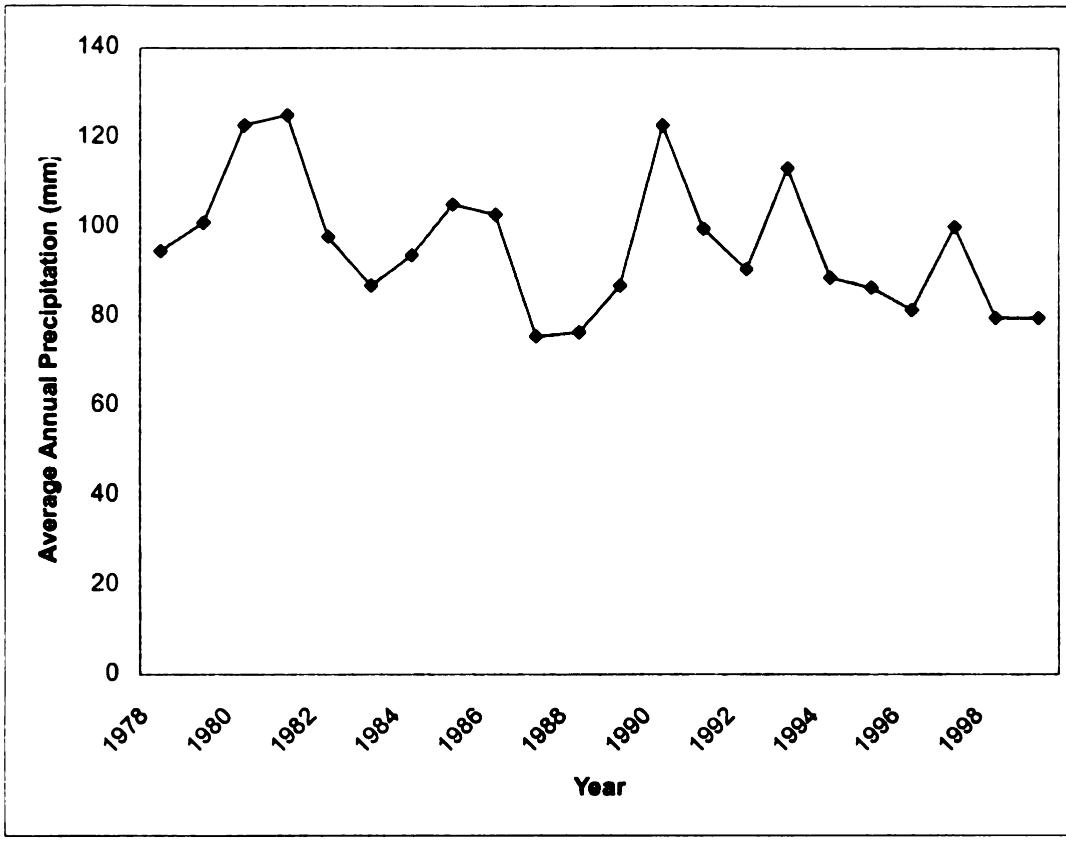


Figure 5.10. Average annual precipitation near the study area, 1978-1999. Source: National Oceanic and Atmospheric Administration, 1978-1999.

Over the entire period of study, it is evident that amount of storms in Berrien County had increased rapidly (Figure 5:11). In the later time frame (1988 to 1999), the number of storms had more than doubled from 56 in the first decade (1978-1988) to 126 from 1988 to 1999 (NCDC, 2003). The increase in storms during the latter decade may be partially accountable for the increase in regressive land cover observed from 1988 to 1999.

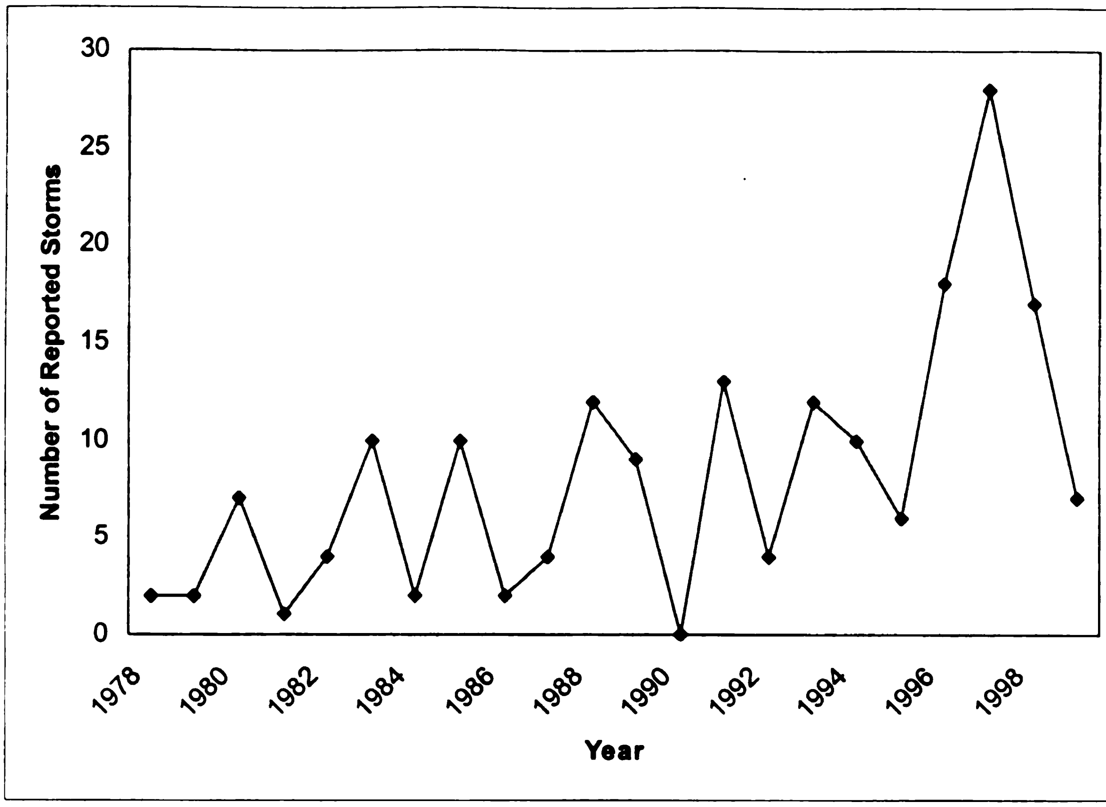


Figure 5:11. Number of reported storms in Berrien County, 1978-1999. Source: NCDC, 2003.

Lake-level Fluctuations and Sand Nourishment

As discussed in the literature review of this thesis, lake level is one of several factors that control sand supply to dune systems of Lake Michigan. As lake levels fall, the widened beach supplies sand to the foredunes (Olson, 1958d). Thus, foredunes receive sand from the beach and build when lake levels fall. Because some plant species require sand deposition to thrive, an increase in pioneering types of vegetation, especially grass species (Olson, 1958a, 1958c), on dunes may be a response to the increased sand deposition as lake levels fall. Additionally, while sand is deposited in the foredunes and at the beach, the foredunes act as a sand trap, preventing sand nourishment into the inland areas (Arens et al., 1995). This would create an environment where the blowouts are sediment starved, and thus, gradually degrade (Livingstone and Warren, 1996).

Conversely, when lake levels are high, waves erode beach ridges and/or foredunes, forming a lakeward facing bluff. Dunes may migrate inland as sand dislodged from the bluff is blown on the leeward side (Marsh and Marsh, 1987; Loope and Arbogast, 2000). In turn, as foredunes erode, the vegetation cover will degrade in response to the high rates of erosion. Furthermore, sand can deposit further inland during high lake levels, thus feeding the large, open blowout areas. Therefore, in response to this sand nourishment, pioneer species that require sand deposition for vigorous growth (such as grasses) may colonize these areas.

Figure 5:12 shows the trends in lake level for Lake Michigan during the period of study. Lake level rose throughout most of the first decade of the study (1978-1988) and peaked at record levels in 1986. After that peak, lake levels began to fall. As described earlier, marked regression of land cover occurred at foredunes between 1978 and 1988 (areas C, D, and E, Appendix D). This suggests that the foredunes were possibly being eroded during the high lake levels before the image in 1988 was captured, thus, degradation of the land cover occurred in response.

Additionally, this decade of the study (1978 to 1988) was marked by a higher percentage of successive land cover than the later time frame (1988 to

1999; Figure 5:9), especially with regard to changes from barren sand in 1978 to discontinuous grasses in 1988. Most of these areas were inside blowouts (as in area A, Appendix D). Because pioneer species of grasses require some amount of sand deposition for vigorous growth (Olson 1958a, 1958c), this finding suggests that inland sand deposition may have increased in a manner described by Marsh and Marsh (1987) and Loope and Arbogast (2000) as a response to the high lake levels during this decade of study.

Conversely, the later time frame of the study was characterized by low lake levels (Figure 5:12). After the record high in 1986, lake level fell off rapidly until 1991. Lake level then began a gradual rise, but the peak did not reach the high levels of the earlier decade, nor was it long lived. Because lake levels were lower from 1988 to 1999 than in 1978 to 1988, beaches would have been broader as discussed in Olson (1958d) and Loope and Arbogast (2000).

The broad beaches would have supplied sand to the foredunes and initiated foredune growth (Olson 1958d). Growth of the foredunes is detectable through changes in land cover that show succession of vegetation (areas A, B, and C on Appendix E). The majority of these land cover changes were from barren sand in 1988 to discontinuous grasses in 1999. The growth of grass species in these areas would imply moderate rates of sand deposition because these species are dependent upon sand deposition for growth (Olson, 1958a; 1958c).

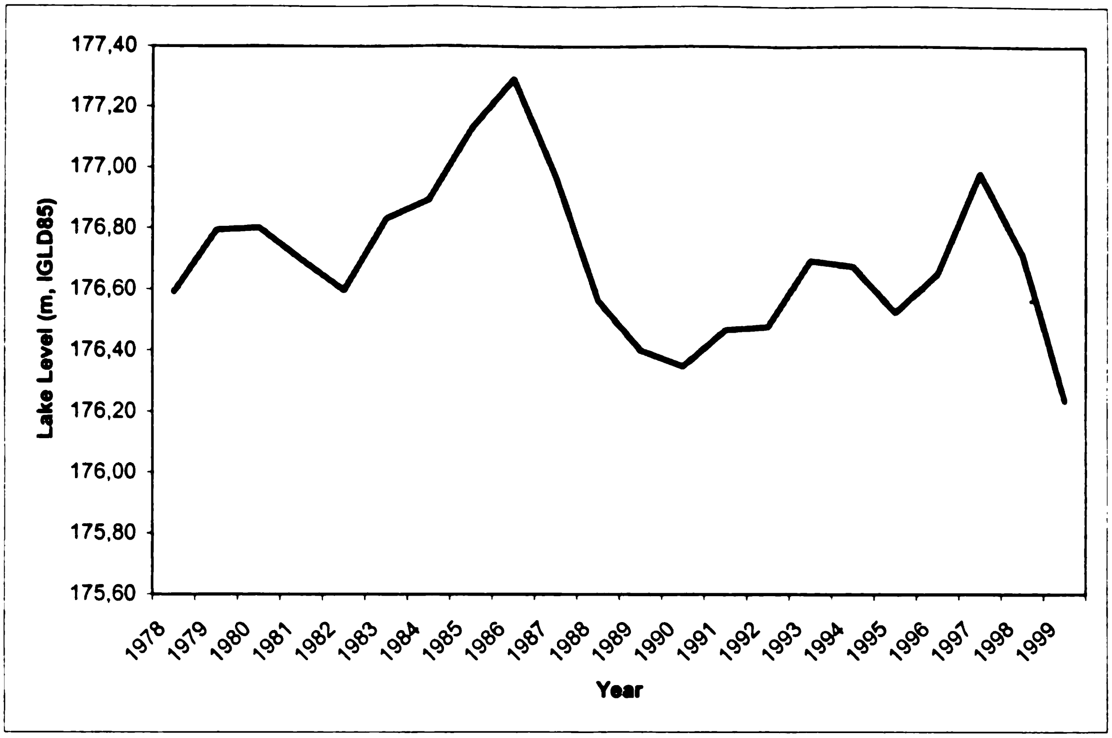


Figure 5:12. Average annual lake levels for Lake Michigan, 1978-1999. Source: USACE, 2003.

Because the sand was being stored within the foredunes, this would have created a negative sand budget in the throats of the blowouts. A negative sand budget on blowouts causes erosion on the windward slopes. This time frame of study saw increased rates of land cover degradation over the earlier decade, especially on windward slopes of blowouts and on leeward slopes where sand was burying mature vegetation cover. This suggests that during the lower lake levels from 1988 to 1999 the blowouts underwent rapid rates of erosion on windward slopes, with sand depositing in the lee.

Park Visitor Numbers

Park visitors can contribute to changes in land cover by trampling vegetation, therefore causing degradation of vegetative cover and erosion. The presence of recreational users can also prevent the growth of vegetation in areas that are barren and unstable, thus preventing the stabilization of dunes.

As seen in Figure 5:13 average number of park visitors increased from 1,346,978 within the first decade of study (1978-1988) to 1,317,082 in the later decade of study (1988-1999). Thus, park visitor numbers increased slightly over the entire period of study, taking a slight drop in 1986, but working up to a peak in 1999 of 1,827,025 (Herta, Harold, personal comm., 2002).

Although visitor numbers increased over the period of study, it is difficult to establish a link between number of park visitors and land cover change at park-wide level. Additionally, it is difficult to make any solid correlations between park visitor numbers and land cover changes at the temporal scale of this study. To make correlative studies, a finer temporal scale would be desirable, possibly at a scale of 1-3 years between image capture dates to provide more data for land cover change.

However, the possibility human impact on land cover may still be explored by examining the area where park visitors are concentrated. The area of high recreational use can be compared with the area managed as natural area. The intent of the following section is to employ this method to further explore the relationship between human impact and land cover changes.

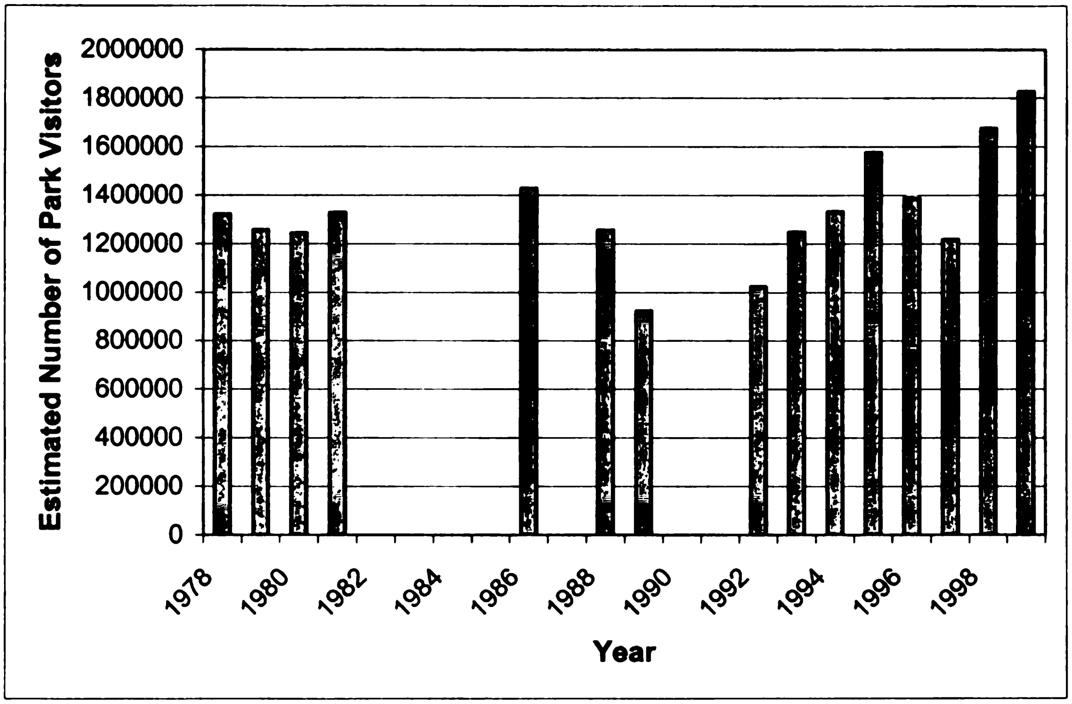


Figure 5:13. Estimated Park Visitor Numbers, 1978 to 1999. (No bar indicates data unavailable for that year). Source: Herta, Harold, personal comm., 2002.

High-Use Area Versus Natural Area

As stated previously in the methods section of this thesis, the study area was divided into a High-Use Area and a Natural Area to determine if recreational use had any impact on the land cover changes within the park over the period of study. For simplification of the results, only the overlay from 1978 to 1999 was compared with regard to the High-Use and Natural Areas. Appendix F demonstrates how these two areas compare visually.

In the Natural Area (Appendix F), it is clear that successive land cover changes were extensive over the northern blowout complex. Comparison with the original imagery and field studies show that these areas that had undergone succession coincide with north-facing slopes of ridges that extend eastward through the blowout complex, backdune areas, swales between dune ridges near the mouth of the blowout and blowout hollows.

Because the sun shines more intensely upon southern slopes in Michigan, southern slopes are hotter and drier than northern slopes. The presence of denser vegetation might suggest that conditions on the northern slopes were moister and cooler, thus, favoring vegetative growth on these slopes. Additionally, the initial growth of vegetation in swales and blowout hollows conforms to Olson's (1958a) research.

The northernmost blowout area appears to have been progressively healing throughout the study interval. Figure 5:14 demonstrates this pattern. In 1978, large areas of barren sand were apparent in the throat region and were interconnected with the beach area. Scattered discontinuous grasses and grasses and shrubs provided some stabilizing land cover. By 1999, these areas had filled in with denser vegetation. Thus, as vegetative cover expanded over the study period, areas of barren sand within the blowout interior were progressively cut off from the beach system and sand supply.

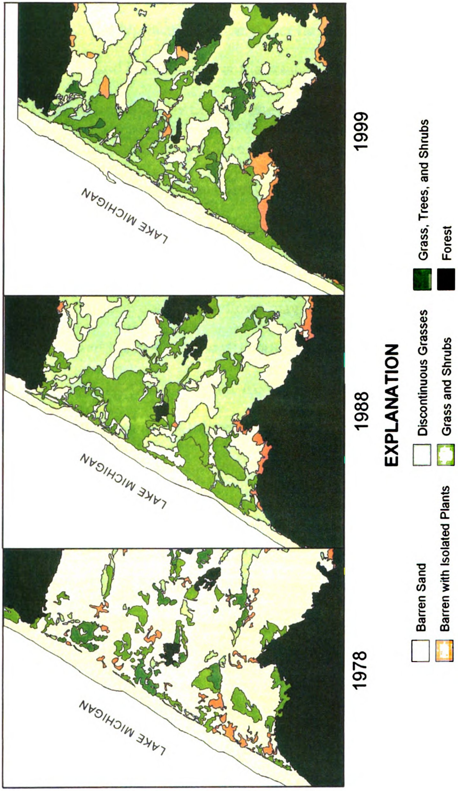


Figure 5:14. Blowout healing from 1978 to 1999.

Area A on this map (Appendix F) is a large area of regressive land cover that corresponds with the slip face of a dune. Over the two decades of study, a substantial amount of sand has blown over the crest of this dune and deposited on the leeward side, as described by Livingstone and Warren (1996). When sand deposition reached a threshold, slope failure occurred and progressively buried the abutting forest on the lee side of the dune (Figure 5:15).

However, further examination of this area in the field and on the original imagery shows that new trees have taken root upon this slope. According to Olson (1958 a, 1958c) cottonwoods and willows may act as pioneer species if conditions are moist and the rate of sand deposition does not impede seed germination. Although it is not discernable from the aerial photography, these small trees may be cottonwoods or willows. This would suggest that although sand deposition was active on this slope, the surrounding tree cover may have provided cooler, moister conditions for pioneer tree species to grow.

Area B (Appendix F) also corresponds with the slip slope of a dune, where sand blown over from a high ridgeline is burying land cover located on the leeward side of the ridge. There was no evidence of pioneer tree species on this slip face. This would suggest that sand deposition is too rapid and/or conditions are to dry for tree seeds to germinate. This same pattern occurred at areas C and D (Appendix F) in the High-Use Area.

A smaller extent of the blowouts within the High- Use Area was marked by successive land cover changes. Thus, from a qualitative standpoint, it appears that ecological succession was retarded in the High-Use Area relative to the Natural Area.

The successive land cover at area E (Appendix F) appears to be most dense on the north-facing slope of a ridge that elevates as it runs eastward. As discussed previously, vegetation growth was probably favored on this slope because it receives less sun than the southward-facing slopes; therefore more moisture is retained in here.

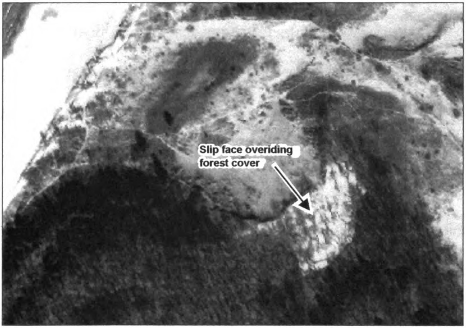


Figure 5:15. Ikonos image showing slip face of dune (Area A Appendix E).

The successive land cover found at area F (Appendix F)was in a previously mined, topographically flatter region between limb ridges. Though previously disturbed by industrial activity, this area grew in with stabilizing vegetation fairly quickly. It is uncertain, however, whether vegetation was planted in an attempt to reclaim the mined land, or whether the ecological succession that occurred in this area was a natural phenomenon. As previously mentioned, the low topography in this area may have created a cooler, edaphic environment where vegetation thrived.

Unlike the Natural Area, extensive areas of regressive land cover are observable in the High-Use Area. Large areas of regressive land cover at areas G, I, and J (Appendix F), are located on the slip faces of parabolic dunes, which are associated with depositional environments. Figure 5:16 is a present day photograph of the slip face at area G. Small trees can be seen growing upon the slip face. Upon further examination of the imagery, grasses also once coexisted with these trees (in 1978 and 1988).

However, by 1999 and until present, the grasses had nearly completely died away. This would suggest that sand deposition had increased enough over the period of study to prevent the growth of grasses and to bury trees rooted in the slip face. Figure 5:17 is a modern photograph of the slip face at area I. Here, tall trees are being buried by sand, and the dune encroaches upon a picnic area. It is evident that this area is undergoing rapid rates of sand deposition.

At area H (Appendix F), the large area of regressive land cover is most likely under an erosional environment due to its location on a windward slope of a dune (Livingstone and Warren, 1996). This is also an area that gets heavy human foot traffic in the summer, due to the location of the dune with respect to the beach area. Figure 5:18 is a modern photograph taken on this slope. It is evident from the photograph that erosion is very high in this area. The roots of living trees are exposed as sand is eroded away from the surrounding area.

Figure 5:16. Slip face of a dune (Area G, Appendix E).

Figure 5:17. Slip face of a dune (Area I, Appendix E).

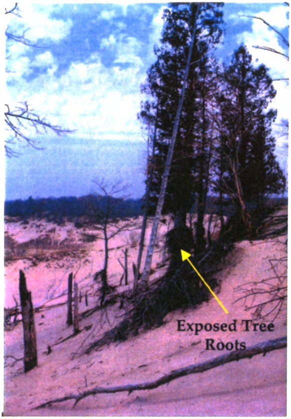


Figure 5:18. Slope at Pike's Peak showing erosion. Note exposed roots (Area H, Appendix E).

Figure 5:19 quantifies the differences between the High-Use Area and the Natural Area. Within the Natural Area, land cover had undergone succession in a manner described by Olson (1958a) over 19.0% of the total classified area. In contrast, 14.8% of the total classified area had progressed into a more ecologically mature state within the High-Use Area.

These changes are less than the successive land cover changes found in the Natural Area. Thus, successive land cover changes are greater in the Natural Area than in the High Use Area by 4.2% from 1978 to 1999. Because successive land cover changes are a sign that dunes are progressing towards stabilization (Olson 1958a), it could be stated that a greater percentage of the dunes in the Natural Area are progressing toward stabilization than in the High-Use Area.

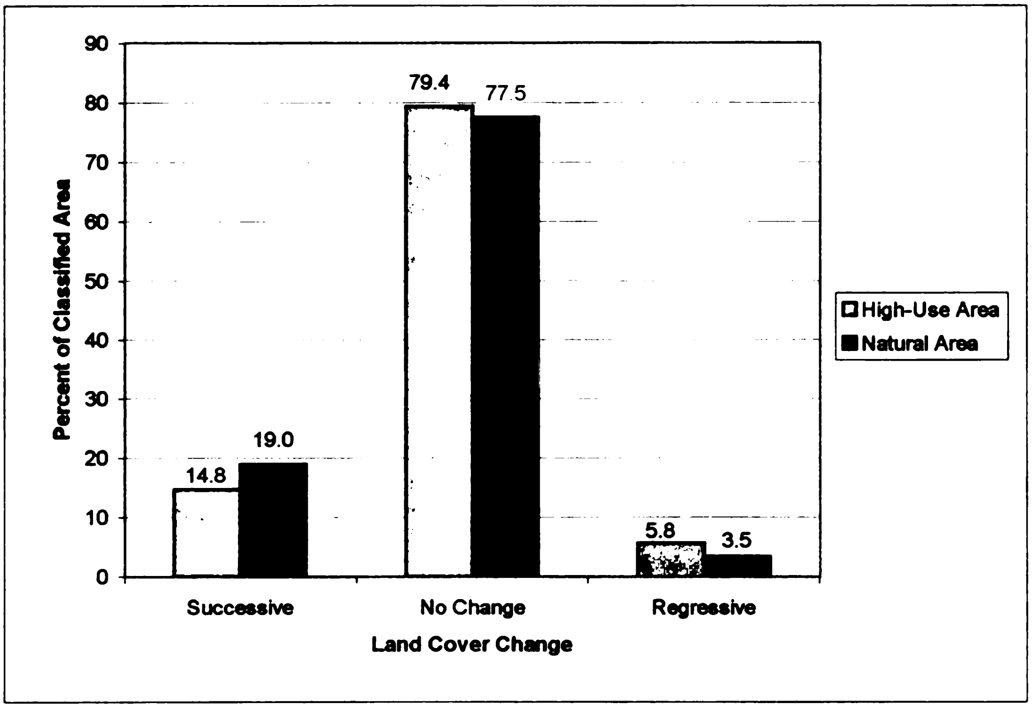


Figure 5:19. Land cover change as percent of entire classified area: High-Use Area vs. Natural Area.

When considering regressive land cover changes, the High-Use Area has a higher percentage of total classified area than the Natural Area by a margin of 2.5% (Figure 5:19). Thus, a larger percentage of the dunes in the High-Use Area are progressing towards destabilization. Additionally, the area remaining unchanged in the High-Use Area is also slightly higher than the Natural Area (by 1.9 percent).

Table 5:9 provides a summary of the greatest percentage of land cover changes within each area of the park from 1978 to 1999. Forest in 1978 to barren sand in 1999 accounted for the highest percentage of the total area undergoing land cover regression in the High-Use Area (16.3%). Because this type of change is so dramatic, it implies that areas that had undergone degradation in the High-Use Area had rapid rates of erosion, sand deposition, or both. As described before, a large area of regressive land cover changes experiences high recreational activity and is located on windward slopes (Area H, Appendix F). Thus, erosion (both naturally occurring and human induced) may be the most dominant process that causes land cover degradation than sand deposition in the High-Use Area.

Table 5:9. Summary of Largest Percentage Land Cover Changes by Area.

	High-Use Area	Natural Area
Percent of Regressive Area	F>BS 16.3%	GS>DG 22.6%
Percent of Successive Area	BS>DG 44.0%	BS>DG 67.6
Percent of Unchanged Area	F 68.5% BS 26.1%	F 86.5% BS 9.8%

*BS: barren sand, DG: discontinuous grasses, F: forest, GS: grasses and shrubs.

Conversely, the largest percentage of regressive land cover changes in the Natural Area was from grass and shrubs in 1978 to discontinuous grasses in 1999. This type of land cover change accounted for 22.6% of the total regressive area in the Natural Area. The environmental changes were great enough that within regressing areas, shrubs could not sustain growth. However, grasses, which are especially tolerant to sand deposition, could maintain growth (Olson, 1958a). This suggests that in the Natural Area, sand deposition may be the most dominant process causing land cover regression in the Natural Area.

With regard to successive types of land cover changes, discontinuous grasses in 1978to barren sand in 1999 was the largest percentage of total successive land cover area in both the High-Use and Natural Areas (Table 5:6). However conversion occurred over a greater amount of area in the Natural Area than in the High-Use Area (by 23.6%). The higher percentage suggests that conditions were more favorable for grasses to colonize barren sand in the Natural Area than in the High-Use Area. The reasons could be two-fold. First, because grasses grow vigorously during active sand deposition (Olson 1958a, 1958c), this may suggest that sand deposition is a dominant process in the Natural Area. Second, it may also suggest that the area is less disturbed by foot traffic than in the High-Use area, since grasses are sensitive to trampling (Roethle, 1985).

With respect to unchanged land cover, forest accounted for the highest percentage of total unchanged area in both the Natural Area and the High-Use Area. However, only 68.5% remained forest in the High-Use Area, as compared to 86.5% in the Natural Area. This suggests that the most mature and therefore most stable land cover type changed to a greater extent in the High-Use Area than in the Natural Area.

Barren sand covered the second greatest amount of unchanged area in both regions of the park. In the High-Use Area, barren sand covered 26.1% of the unchanged areas as compared to 9.8% of the unchanged area in the Natural Area. This suggests that greater areas of unstabilized sand were exposed in the High-Use Area than in the Natural Area from 1978 to 1999. Therefore, more land cover was vulnerable to mobilization and erosion in the High-Use Area than in the Natural Area.

Human Impact in the High-Use Area

Human impact is an explanation for at least some of the higher percentage of regressive land cover changes in the High-Use Area. Recurrent trampling of plant species by park visitors may have destroyed stabilizing plant species, thus leaving sand exposed to eolian transport. Additionally, as dune climbers scoured the face of Pike's Peak (see H on Appendix F) and the surrounding areas, each footstep would have caused at least a small amount of slumping along the windward face of the dune. This process would easily expose sand to eolian mobilization.

Perhaps the greatest area of interest in terms of human impact upon the High-Use Area was adjacent to the park beach and the beach parking lot. Aerial photography reveals that in the early 1970's, the parking lot was expanded from one to include three parking areas. With this construction, foredunes that had once existed on the beach were destroyed. Since foredunes store excess sand provided by the beach, there was no longer an area to store excess sediment. Recreational use of the beach inhibits new foredune formation, as does the presence and maintenance of the beach parking lot. Without foredunes to capture the influx of sand from the beach environment, the sand movement to the blowout areas east of the parking lots is virtually unchecked.

Most of the recreational activity on the beach is focused upon the central parking lot and beach house (Figure 5:20). The concession stand is at this central beach house and draws many people towards this central area. This central beach house contains a restroom that is also open more often during the year than the southern and northern beach houses. Additionally, the northern parking area is closed for a large part of the year, centralizing recreational activities. The massive areas of regressive land cover changes (Figure 5:20) lie just to the east of this central parking area. Heavy recreational activity focused in this area may have contributed to regression of land cover.

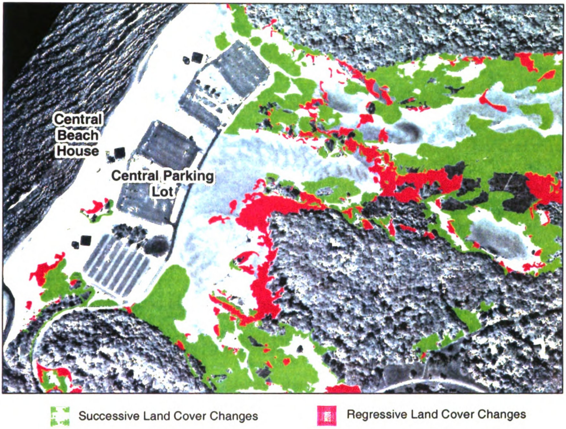


Figure 5:20. Central parking lot and beach house in relation to areas of regressive and successive land cover.

Chapter 6

Conclusions and Recommendations

This study had several goals. The first goal was to determine which method of orthorectification produced imagery with the best positional accuracy for use in land cover change analysis of Lake Michigan coastal dunes. In this thesis, two methods to orthorectify historic aerial photography were tested. One method was to use a USGS 30 m DEM to produce the orthoimagery. The second method was to extract a 3 m DTM from the imagery once it had been block triangulated and to use the extracted DTM to orthorectify the imagery.

Results from this study suggest that extracting a DTM from the imagery and using it to produce the orthoimages produced the most positionally accurate results. Therefore, the DTM extraction method was used to produce orthoimages for the land cover interpretation analysis. Although this method produced superior results in terms of positional accuracy, it should be noted that this method required extensive amounts of time to collect GPS measurements in the field. The terrain makes it physically challenging to collect GPS measurements. Additionally, some GPS measurements were impossible to collect due to terrain difficulties, signal scatter from forest cover or surrounding ridges, or land ownership issues.

If this method were to be implemented to monitor land cover change in additional parks with massive coastal dunes, careful mission planning would need to be utilized before GPS measurements are made. Furthermore, ample amounts of time and funding would be required to allow field personnel to obtain the GPS measurements.

The second goal of this study was to determine where change had occurred on a coastal dunefield and what types of change have occurred in context of previous work conducted by Olson (1958a; 1958c). The results of this study suggest that the major areas where land cover changes had occurred over the period of study were on foredunes, windward slopes of blowouts, and the leeward slopes of parabolic dunes and blowout crests.

Land cover changes essentially followed the model of ecological succession on Lake Michigan sand dunes suggested by Olson (1958a). That is, pioneer grasses were usually the first to colonize barren sand when conditions were suitable, followed by pioneer tree species that are small enough to appear as shrubs on the photographs, or shrub species that grow when sand deposition or erosion has greatly decreased or stopped. As land cover progresses through succession, vegetation density increases.

In the context of literature regarding the ecology of Lake Michigan coastal dunes, the vegetation cover on coastal dunes can be an indicator of the relative rates of sand deposition (e.g. Olson 1958a, Olson 1958c; Olson 1958d). Likewise, regression from a more mature state of land cover in one time period to a less mature state of land cover can indicate increases in the rate of sand deposition or erosion. Because of the apparent link between geomorphic activity and vegetation growth, observations in land cover change between time frames placed the results of this study in the context of research that links dune building to lake level fluctuations (Olson, 1958d; Marsh and Marsh, 1987; Arbogast and Loope, 1999; Loope and Arbogast, 2000; Arbogast et al., 2002).

Overlaying land cover interpretations between time periods addressed the third goal of this thesis: to determine whether change occurred at a constant rate or was variable over the period of study. The results of this study suggest that rates of land cover change were variable over the period of study and may be tied to changes in lake level.

The first period of the study (1978 to 1988) experienced a greater percentage of successive land cover changes than the later time frame (1988 to 1999), especially with regard to changes from barren sand in 1978 to discontinuous grasses in 1988. The appearance of grass species indicates an increase of deposition in areas of successive land cover. The majority of these areas were within blowouts. Additionally, from 1978 to regressive of land cover changes were observed in foredune areas. This time period also coincided with a period of record lake level highs. These observations suggest that the foredunes were probably being eroded during the high lake levels. While the foredunes were eroded during the high lake levels, sand was transported inland to nourish the blowout areas, as evident by the increase in vegetation that requires sand deposition for vigorous growth.

The second time frame of the study (1988 to 1999) had a greater percentage of regressive land cover changes than the first decade, with a majority of the regression occurring on windward slopes of blowouts and on slip faces of dunes. Additionally, the latter time frame also saw successive land cover changes in the foredunes as opposed to regression in the earlier decade. This time frame was characterized by lower lake levels than the earlier decade.

Low lake levels created broader beaches and sand deposition was directed into the foredunes from 1988 to 1999. As a response, pioneer species that thrive during sand deposition colonized the foredune areas. Because foredunes trap sediment, the blowout areas became sediment starved, thus the blowout areas underwent erosion. Degradation of forest cover on windward slopes and burial of vegetation on slip faces is evidence of this erosion from 1988 to 1999.

The last goal of this thesis was to determine how land cover changes compare between the High-Use Area and Natural Area over the entire study interval. Within each region, succession and regression were both observed, while most of the areas remained unchanged.

However, from the data collected from the land cover interpretation and overlay analysis, it would appear that the Natural Area experienced a greater percentage of successive land cover changes from 1978 to 1999 than the High-Use Area. Moreover, the High-Use Area saw greater percentages of regressive land cover changes than the Natural Area.

Evidence from historic newspapers suggests that these areas were active prior to the foundation of the park. However, the results from this investigation suggest that recreational use of the dunes may be promoting the destruction of stabilizing vegetation in these areas. Land cover regression was focused at a location east of the central beach house and parking lot, on the windward slope of Pike's Peak. Ultimately, these areas will probably continue to degrade so long as the slopes are open for recreational use.

Erosion will continue to occur on the windward slopes and sand deposition on the leeward slopes will cause burial of mature forest cover to the east of these intensely used areas. At present, the only park infrastructure and services in danger of being buried on the opposite side of this erosion is a small picnicking area and small access road to the picnic area.

Although there may not be many structures in danger of burial at this park, the results of this study may have implications in other parks where coastal dunes attract high numbers of visitors. For example, in Petoskey State Park, active, unstable dunes have been encroaching upon a campground in the park (Lepczyk, 2001). Remotely sensed land cover change studies could be used by the MDNR to monitor the succession or regression of vegetation on coastal dunes and thus, serve as a proxy measurement for the movement of sand. By understanding the natural and human induced processes occurring on coastal dunefields, the MDNR can prevent loss of infrastructure and property, such as at what may occur at Petoskey State Park.

An immense amount of potential exists for further studies within WDSP, and for future research upon other dune fields of the Lake Michigan coastline. Observations in the field revealed several exposed paleosols in blowouts around the park. At least one of these paleosols appeared to have strong development, as evident by a thick, organic-rich A-horizon and brownish colored B-horizon. This paleosol appears to be consistent in development with the well-developed soil in the upper part of dunes in the Holland area (Arbogast et al., 2002). Sedimentological studies of the dunes and radiocarbon-dates obtained from the paleosols could provide better insight as to how and when these massive dunes evolved. Additionally, this type of research would place the dunes at WDSP within the context of other dunefields on the Lake Michigan coastline, thus providing a better understanding of coastal dune evolution in the region.

For future remote sensing studies of coastal dunefields, it is recommended that the imagery be captured at a less coarse time interval, possibly yearly, to do correlation or regression studies with quantitative data that may explain changes in the dune environment (such as lake levels, precipitation, wind, temperature, number of visitors, storm events, fires, sediment supply, and erosion and sand deposition rates). With advances in satellite technology, it is now easy to obtain very high-resolution images without the need of ordering costly aerial photography flights.

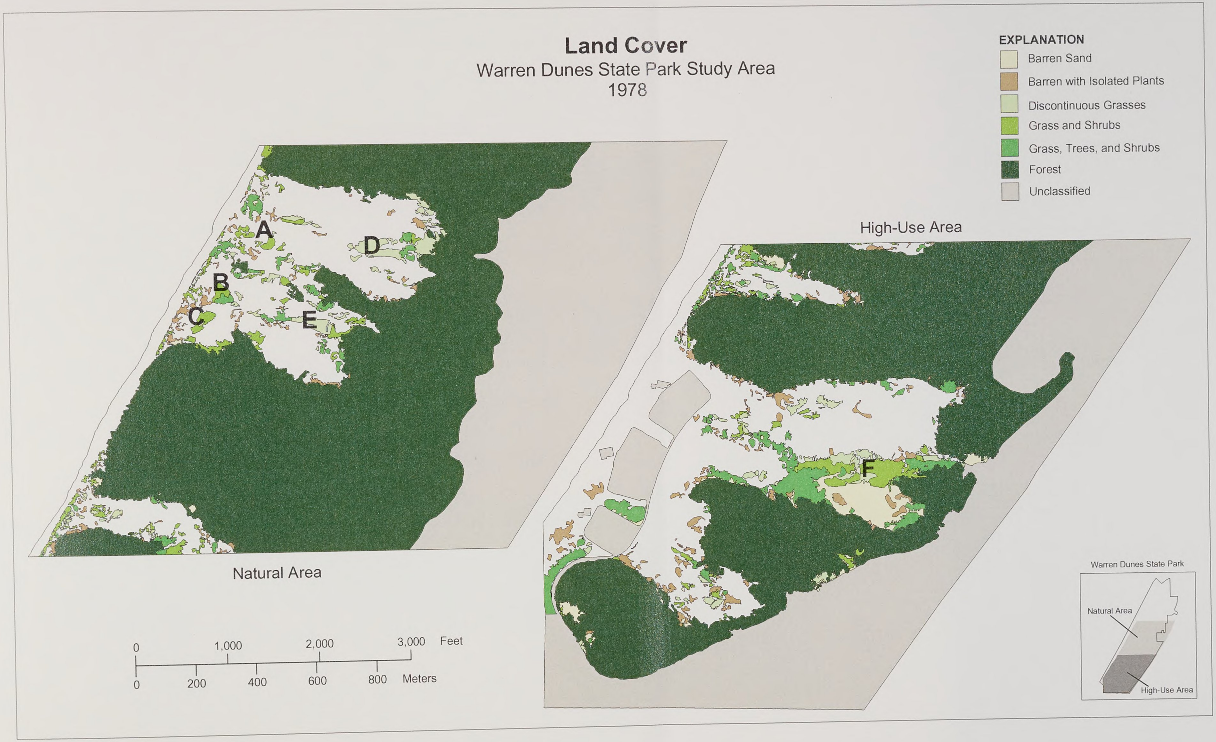
Ikonos or QuickBird imagery could be substituted in place of aerial photography. Regardless of the method of image capture, it is highly recommended that ground targets are set up on the date of image capture and that GPS measurements are taken at these targets to increase the available points in the ground control network. This will likely improve the positional accuracy of the orthoimages.

Additionally, it is recommended that the link between vegetation cover interpreted from remotely sensed imagery and geomorphic processes be tested. Sand traps and erosion pins could be used on the dunes to measure rates of deposition and erosion (Livingston and Warren, 1996; Arens et al. 2002). Remotely sensed imagery could be used simultaneously with these sand transport measures to test the relationship between geomorphic processes and land cover change.

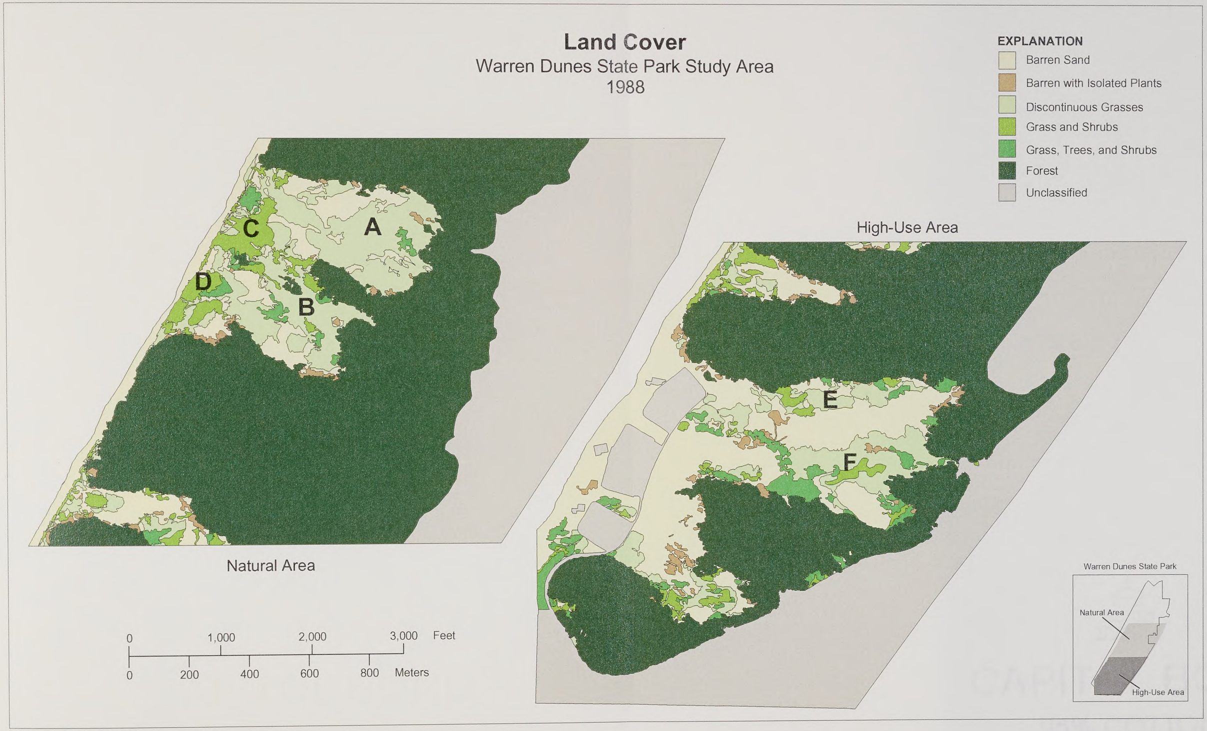
This investigation is a beginning step toward future studies that could examine the dynamics of Lake Michigan dunes on a small time scale using remote sensing techniques. The goal of such studies would be to study present-day phenomena in a manner consistent with the ideas of uniformitarianism. Observing coastal dune behavior in the present might increase our understanding of ancient processes that have formed these dune fields. Additionally, these studies would allow us to predict forward into the future to project how these dunes may change in response to changes in climatic or cultural influences. An extensive body of knowledge regarding Lake Michigan coastal dunes will lead to sound management strategies and policy decisions to conserve and/or preserve these valuable natural and recreational resources.

Appendices

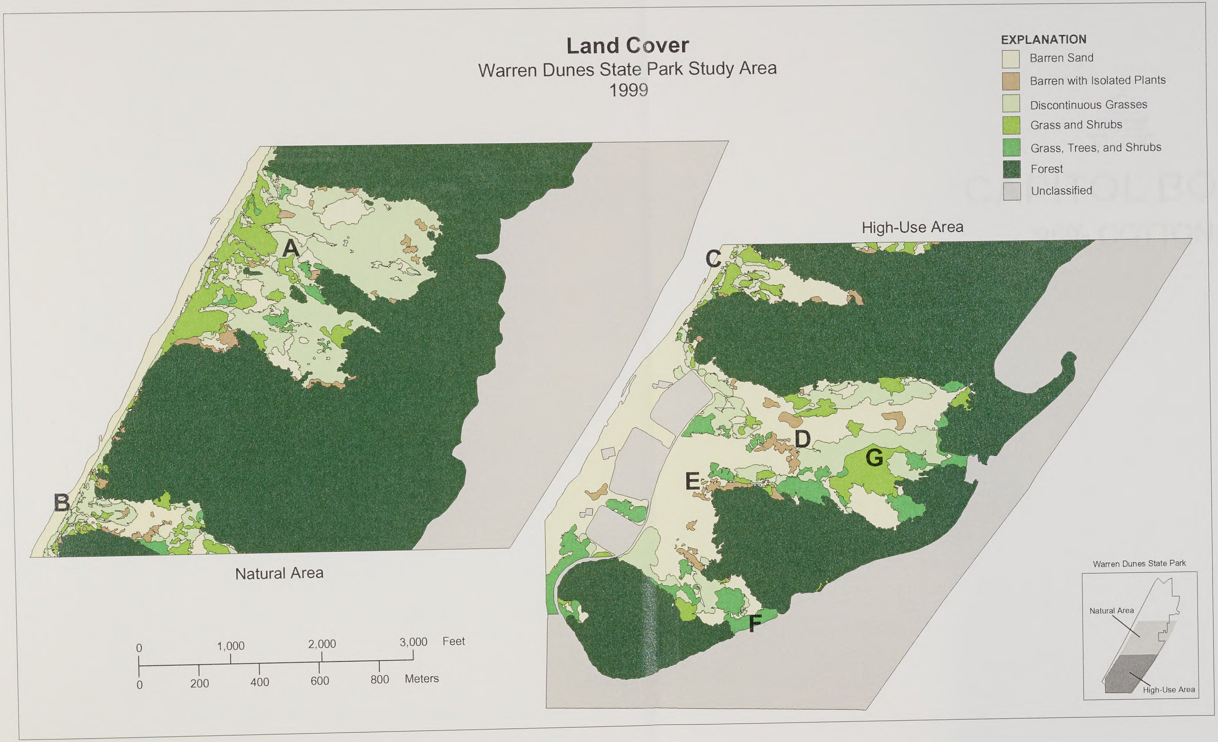
Appendix A. Land cover in WDSP, 1978.



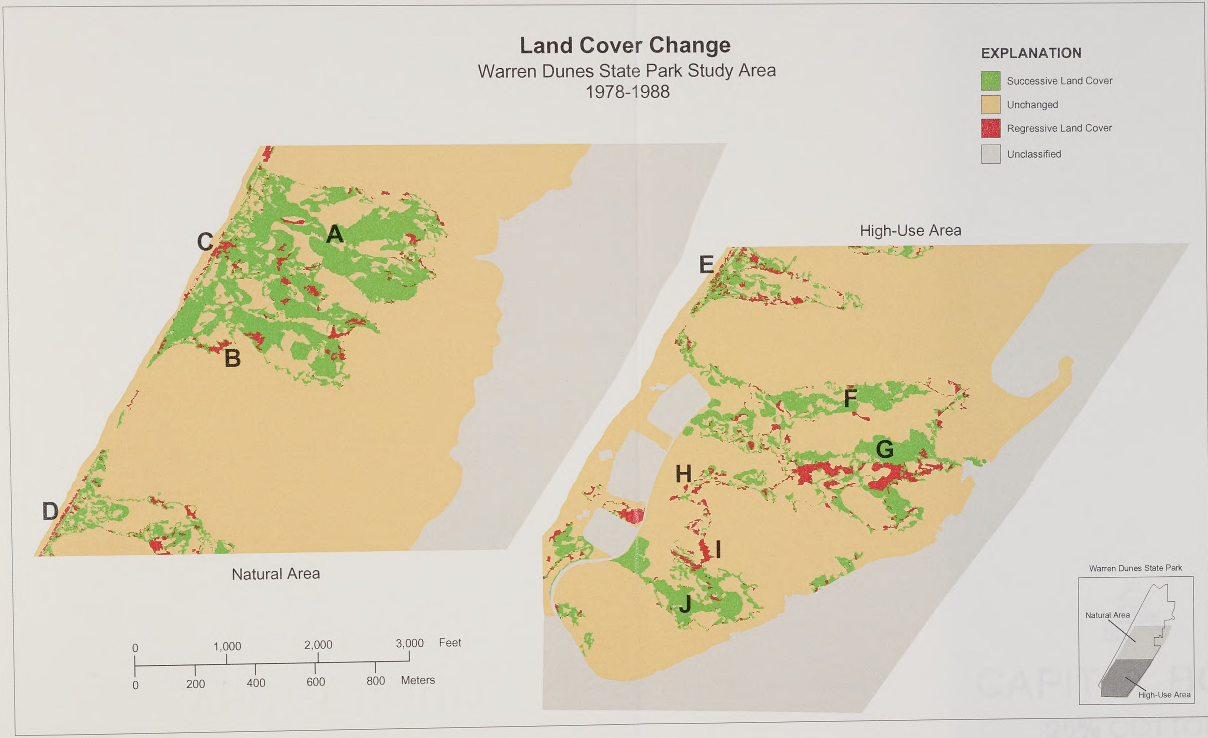
Appendix B. Land cover in WDSP, 1988.



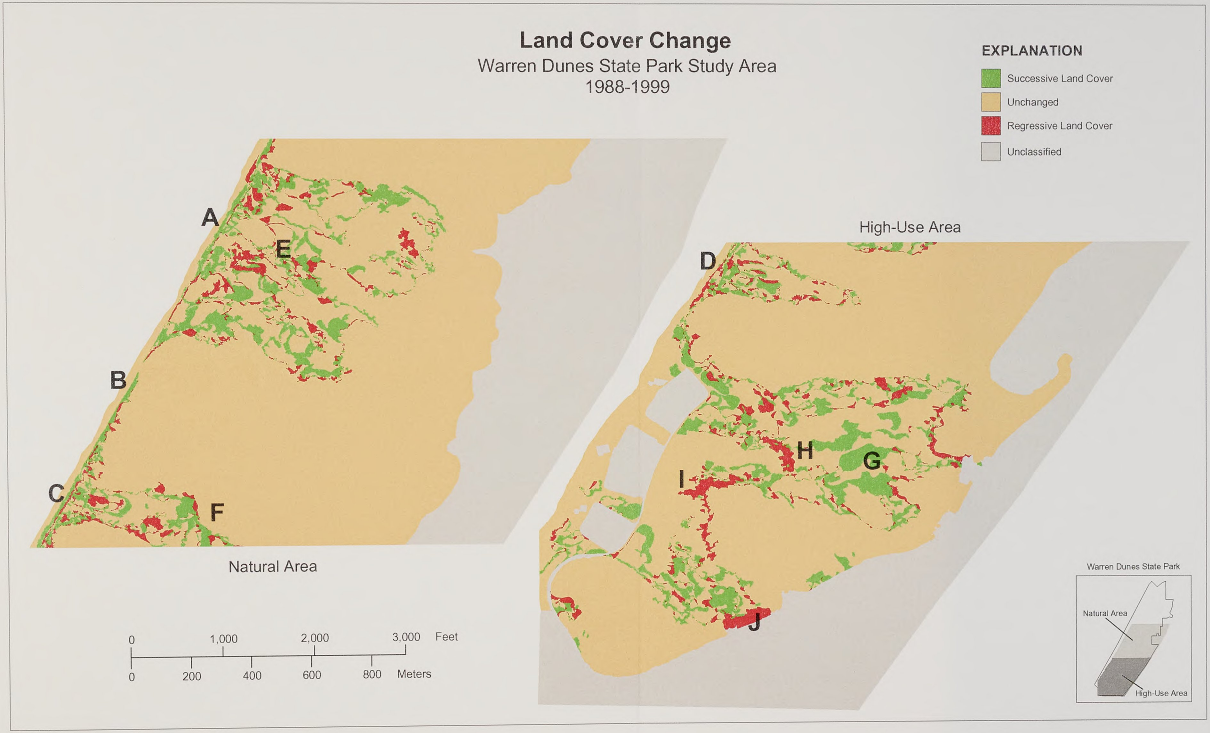
Appendix C. Land cover in WDSP, 1999.



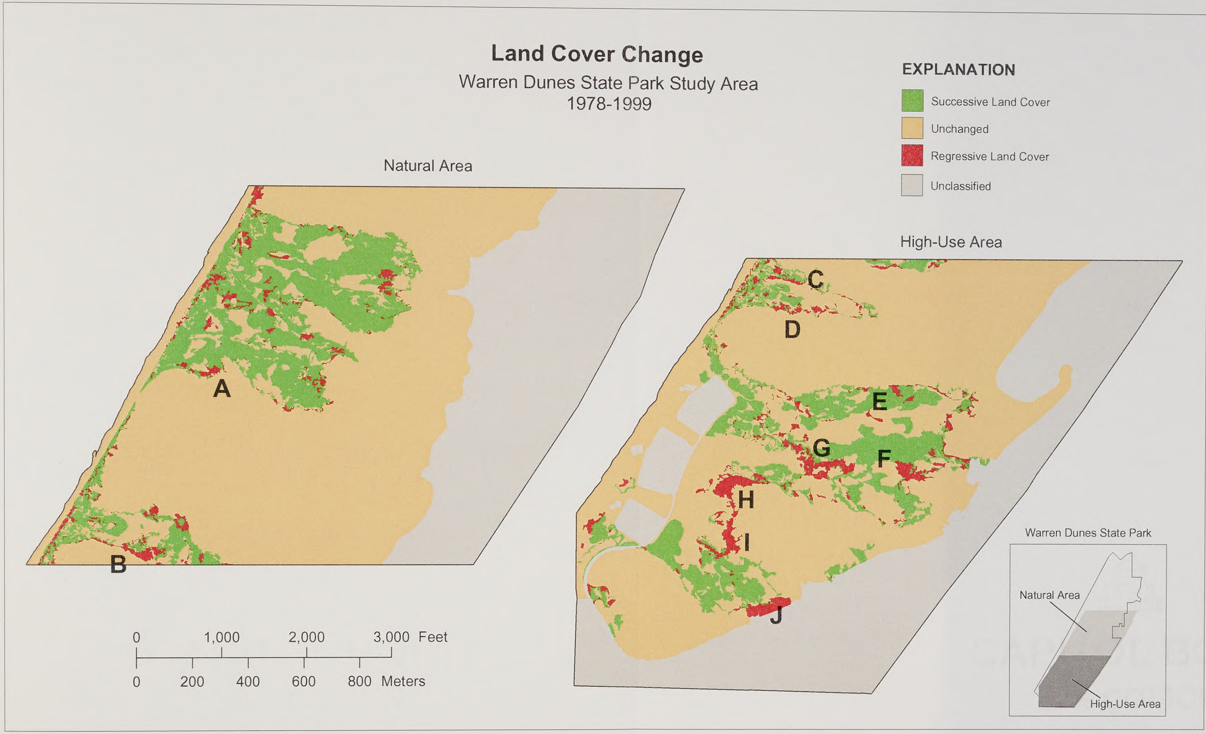
Appendix D. Land cover change in WDSP, 1978-1988.



Appendix E. Land cover change in WDSP, 1988-1999.



Appendix F. Land cover change in the High-Use Area compared to the Natural Area, 1978-1999



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