This is to certify that the

thesis entitled

Airphoto Interpretation of Vegetative Cover Change on the Sleeping Bear Dunes Complex, Leelanau County, Michigan, 1938-1987

presented by

Shirley A. Businski

has been accepted towards fulfillment of the requirements for

M.A. degree in Geography

Major professor

Date 10-23-92

A:

S

Dat

O-76

PLACE IN RETURN BOX to remove this checkout from your record.
TO AVOID FINES return on or before date due.

DATE DUE	DATE DUE	DATE DUE
~~SEP 0 4 1995~~ ~~IL: 0010978~~	JAN 0 7 2001	AUG 0 6 2002
55	JAN 1 9 2001	APR 0 4 2007
JUL 2 8 2005	APR 0 1 2002	
[illegible]		
JAN 2 6 1999		
MAY 1 7 1999 JAN 1 7 2000		

MSU Is An Affirmative Action/Equal Opportunity Institution

c:\circ\datedue.pm3-p.1

AIRPHOTO INTERPRETATION OF VEGETATIVE COVER CHANGE ON THE SLEEPING BEAR DUNES COMPLEX, LEELANAU COUNTY, MICHIGAN, 1938-1987

By

Shirley A. Businski

A THESIS

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

MASTER OF ARTS

Department of Geography

1992

ABSTRACT

AIRPHOTO INTERPRETATION OF VEGETATIVE COVER CHANGE ON THE SLEEPING BEAR DUNES COMPLEX, LEELANAU COUNTY, MICHIGAN, 1938-1987

By

Shirley A. Businski

The purpose of this study was to determine the general trends in vegetative cover on the Sleeping Bear Dunes complex from 1938 to 1987. Vegetative cover on the dunes complex was classified based on interpretation of aerial photographs taken in 1938, 1973, and 1987. The C-MAP geographic information system (GIS) was used to digitize and map the classified areas. The number of polygons and acreage of each vegetative cover type were measured and compared for each year.

The most noticeable trend was the fragmentation of large areas of one vegetative cover type into many smaller areas of the same or a different vegetative cover. The Grass and Shrubs cover type increased in acreage and percentage of total cover, while the Continuous Grass cover type decreased in both of these categories. Overall, there was an increase in the total area of the vegetative cover types and a decrease in acreage of the Unvegetated cover type.

Dedicated to the memory of Michael Businski

and to our children, Erica and Tara

ACKNOWLEDGEMENTS

I express my appreciation to the following individuals without whom this thesis would not have become a reality: Dr. Michael Chubb, chairman of my committee, whose interest in and knowledge of the Sleeping Bear Dunes National Lakeshore helped to develop this research topic. His guidance and support throughout the project was invaluable; Dr. David Lusch, of the Center for Remote Sensing, whose patience and ability to provide technical expertise in understandable terms was greatly appreciated; Dr. Randall Schaetzl who provided encouragement throughout my Masters degree program and whose superior editing skills were most helpful; and Dr. David Campbell who took the time to read this research and provide valuable comments.

The three years I spent in the Masters degree program were brightened and made easier by the staff of the Geography Department. I thank Marilyn Bria, Sharon Ruggles, and Judy Slate for helping me to keep things in perspective and to find the humor in what sometimes became an overwhelming situation.

I thank Mike Beaulac and Dave Forstat for their encouragement and understanding of the demands of finishing a thesis. They made it possible for me to maintain my job and my sense of humor.

I thank Betsy Saunders for her friendship and faith in me and for helping me to stay focused over the last few years. Because of her emotional and moral support, this dream became a reality.

And I thank my daughters, Erica and Tara, who had to grow up fast as the Masters program progressed and took an ever increasing amount of my time and energy. They learned to care for themselves, kept our household functional, and kept me sane. It is a tribute to them that I was able to complete this undertaking.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

The Study Area

The Sleeping Bear Dunes complex is a unique physiographic area of perched sand dunes lying within the Sleeping Bear Dunes National Lakeshore, a unit of the United States national park system. The national lakeshore is located along the northwest coast of Michigan's lower peninsula (Figure 1) and includes over 60,000 acres of land and several inland lakes in Leelanau and Benzie counties, and approximately 10,000 acres of Lake Michigan (NPS, 1974).

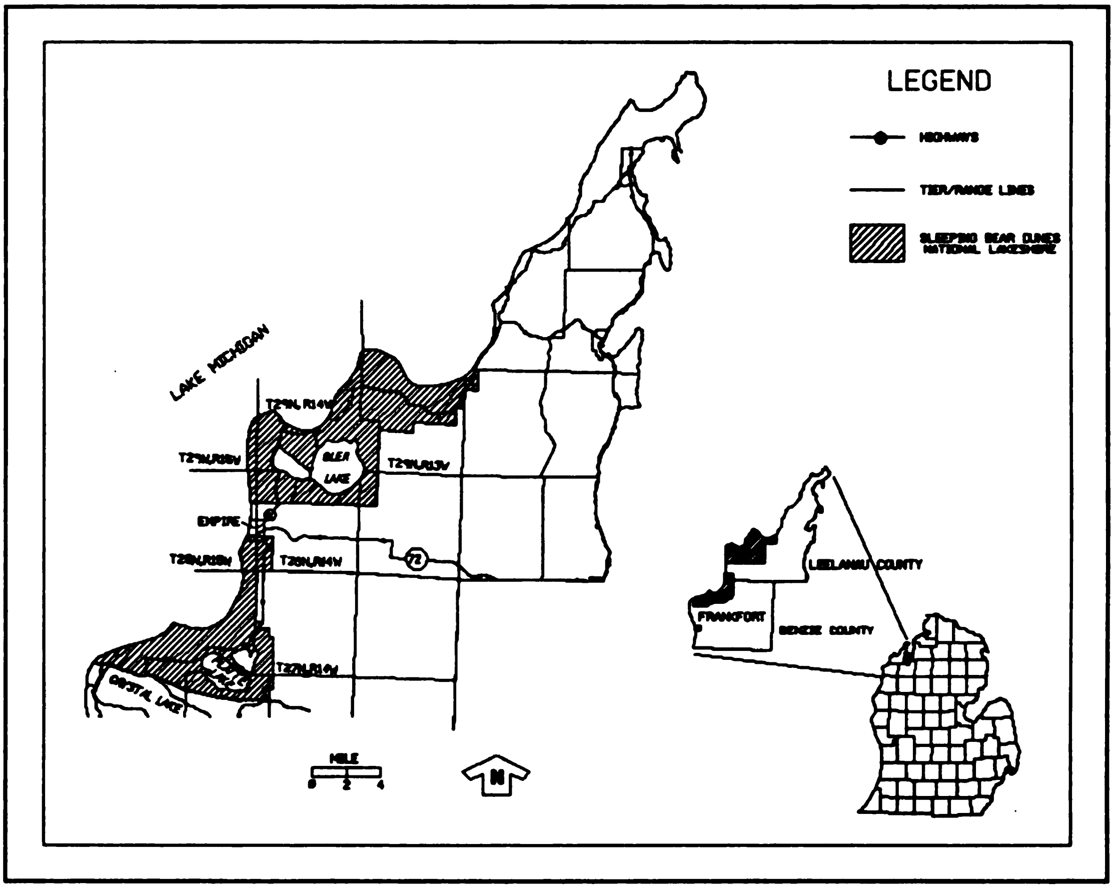


Figure 1 Location Map of Sleeping Bear Dunes National Lakeshore, Mainland Portion

The Sleeping Bear Dunes complex lies mostly within T29N,R14W and R15W and covers approximately 6 square miles, extending 4 miles in a north-south direction, and 1.5 miles in an east-west direction. The southern two- thirds of the complex is a highland rising some 400 feet above Lake Michigan. A steep escarpment separates this highland from the lowland which covers the northern third of the complex. As shown in Figure 2, Lake Michigan forms the western boundary of the dunes complex. The northern boundary is formed by the Manitou Passage and Sleeping Bear Bay sections of Lake Michigan. The eastern and southern boundaries of the dunes complex are formed by morainic hills (Snyder, 1985). The dunes complex is the largest area of Michigan's 250,000 acres of primary coastal dunes that is not covered with hardwood forest.

Brief Natural and Human History

Natural History

The origin of perched dune fields such as the Sleeping Bear Dunes complex is not readily explained by observing the current environment. Large quantities of sand and sizeable dunes occur hundreds of feet above the present Lake Michigan shoreline. Although wind is a powerful mechanism for moving sand, it is not likely that normal wind speeds would move that quantity of sand so far from any obvious current sand source. Clues to the probable origin of this perched dune

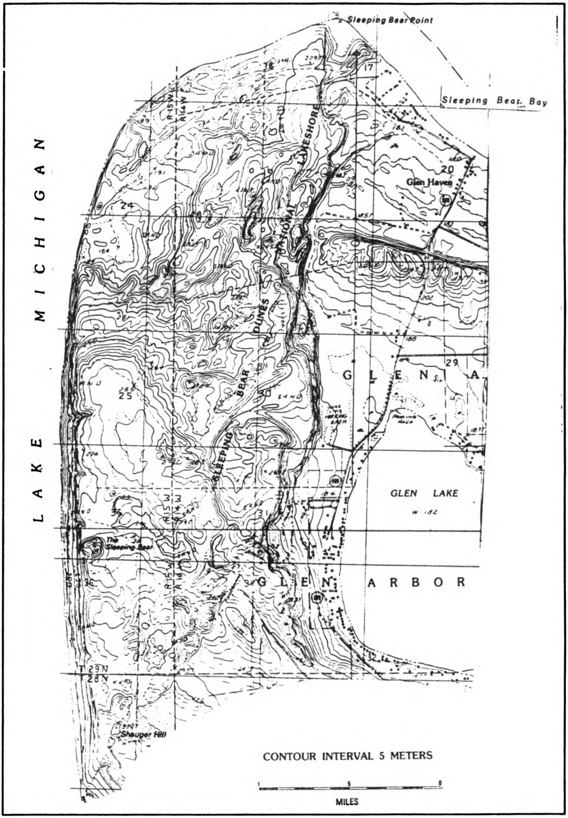


Figure 2 Map of the Sleeping Bear Dunes Complex

field can be found by examining the effects of the Pleistocene glaciation on this area.

The ice of the Wisconsin continental glaciation is believed to have retreated from the Sleeping Bear region approximately 11,000 years ago. The Manistee Moraine was formed during the Port Huron stage of the Wisconsin glaciation. The Port Huron and Valders stage were primarily responsible for the inland topography of the Sleeping Bear region. The shoreline features underwent major changes during both the glacial and post-glacial lake phases.

At the beginning of the Lake Algonquin period (11,500 B.P.; 605′ MSL[1] elevation), "the study area ... consisted of long peninsulas (interlobate moraines) and islands interspersed with deep, narrow bays" (NPS, 1961, p. 10). During this stage, some of the moraines were truncated, and some bays were sealed off with bars and beaches. The water level of Lake Algonquin dropped as the ice continued a steady retreat (Dorr & Eschman, 1970). This stage ended with the lowest of all Great Lakes water levels, known as Lake Chippewa (9,500 B.P.; 230′ MSL elevation) (Dorr & Eschman, 1970). "From this time on, the entire Great Lakes area has been free from the direct influence of glacial ice" and is referred to as "postglacial time" (Dorr & Eschman, 1970, p 175).

---

[1]Mean Sea Level

Lake Nipissing (4,000 B.P.; 605' MSL elevation) was the first postglacial lake, but before it came into existence isostatic rebound[1] of the surface occurred. Lake Nipissing's elevation of 605 feet MSL was the same as that of Lake Algonquin, but the shore features associated with Lake Nipissing are lower in the modern landscape than those of Lake Algonquin because of isostatic uplift of the land surface. The larger dunes along the Lake Michigan shoreline, including the perched dunes of the Sleeping Bear Dunes complex, are believed to be associated with the Lake Nipissing stage.

Lake Algoma (3,500 B.P.; 595' MSL elevation) was the second post-glacial lake stage. It filled the upper Great Lake basins, until about 3,200 B.P. when the St. Clair outlet was lowered (Dorr & Eschman, 1970). At that time, the current lakes Michigan and Huron, with elevations of approximately 580' MSL, came into existence (Dorr & Eschman, 1970).

The lakes themselves have not changed significantly in the last 2500 years, but some beach features associated with former lake stages, which rise high above current lake levels, have changed and continue to change. Evidence of geomorphic activity can be found on the Sleeping Bear Dunes complex.

---

[1]Isostatic rebound refers to the uplifting or rebounding of the earth's surface after the weight of the glacial ice is removed.

> It seems probable that at some stage, a system of high, perched dunes developed along the western face of the Sleeping Bear Moraine, of which the Sleeping Bear Dune is a solitary survivor. As the moraine diminished to the landward [side] these dunes were rejuvenated and blown over the lee or northeast slope of the moraine where they lie today (NPS, 1961, p.18).

As indicated in the above discussion, the present environment on the Sleeping Bear Dunes complex had its origin in the early postglacial period when lake levels were significantly higher. How the area developed and has changed over time is of interest to many researchers.

Human History

The Sleeping Bear Dunes National Lakeshore area has experienced varying levels of human use. The area surrounding the dunes complex was logged for timber by European settlers in the mid to late 1800s (Muhn, 1984). After depletion of the timber supply, agriculture was attempted. Most agriculture failed due to the poor, sandy soils, but fruit production was established along the shoreline due largely to the extended growing season resulting from lake modification of the climate (Muhn, 1984).

The natural beauty of the area soon became known, and it became a resort for the wealthy early in the 20th century. In 1921, lumber baron D. H. Day donated 32 acres of forest just east of the dunes complex to the State of Michigan and this area became Michigan's first state park

(D. H. Day State Park) (Muhn, 1984). During the 1930s, tourist attractions in the area included boat races, flying gliders, and dune rides (Muhn, 1984). In the 1950s and 60s, increased discretionary income, widespread automobile ownership, and improved highways resulted in the area becoming a favored vacation destination for cottagers, campers, and tourists. Resorts, motels, and summer homes were built in and around the Sleeping Bear area, and recreational use of the dunes complex increased.

A number of citizens and community leaders became concerned that the uniqueness and natural beauty of the Sleeping Bear environment were threatened by the increased use and unmanaged development of the area. During the 1960s, proposals were submitted to establish a national lakeshore to protect and preserve the fragile environments found in the area. After much political and public controversy, the United States government established the Sleeping Bear Dunes National Lakeshore in 1970 (Muhn, 1984).

Since the establishment of the national lakeshore, the National Park Service has expanded the amount of public land within the park's boundaries, instituted management plans, provided easier access to some areas, and limited access to others. Its statutory management goals are to permit use and enjoyment of the area while protecting the environments that make the Sleeping Bear Dunes area so unique and special (NPS, 1988).

Present Environment

Physiography

Snyder (1985) classified the Sleeping Bear Dunes complex as "84.5% eolian features, 6.8% lake bluff, 6.2% interlobate moraine, 1.25% lacustrine plains, 0.8% beach, and 0.5% ground moraine" (p. 12). He describes the dunes complex as "being superimposed upon a platform ... which is composed of unconsolidated sediments and has a topographic profile analogous to that of a monoclinal fold" (Snyder, 1985, p.12). The platform has two distinct divisions: a highland and a lowland.

According to Snyder (1985), the Sleeping Bear Highland, a broad, flat summit covering the southern two thirds of the dunes complex, is part of the Manistee Moraine (Wisconsin Stage). He refers to this flat, broad summit as the Sleeping Bear Plateau. This plateau

> ends abruptly where the Sleeping Bear Highland's northern flank descends 100 meters to the Sleeping Bear Lowland. The Sleeping Bear Lowland occupies the northern one-third of the dunes complex and consists of a ground moraine and lacustrine plains (Snyder, 1985, p. 14-15).

The western edge of the Sleeping Bear Highland consists of a high lake bluff, which is receding due to shoreline erosional processes. The west-central edge of the Sleeping Bear Lowland is a wave-cut scarp. North and south of the wave-cut scarp, the Sleeping Bear Lowland gradually merges with the beach (Snyder, 1985). Snyder (1985) contends that the beach along the western edge of the highland and lowland has maintained a relatively constant width over time, but the beach becomes broader along the northern edge of the Lowland.

Climate

Vegetation is influenced by and can reflect both the micro- and macro-climatic conditions of an area. It is not within the scope of this investigation to study this relationship, but a description of the macroclimate of the study area is included to provide the reader with a better understanding of the environment on the dunes complex.

The climate in the study area is humid continental, with a warm summer (Strahler & Strahler, 1984). Climatic conditions of the Sleeping Bear Dune area are moderated by Lake Michigan. Lake effect influences include cooler spring and summer temperatures, milder winters, and increased amounts of snowfall than would normally occur at inland locations. No long-term weather data have been gathered within the park itself; however Strommen (1972) summarized climatic records from nearby Frankfort-Elberta (21 miles south of the study area, on Lake Michigan) to indicate the probable localized climatic conditions in the study area.

Mean monthly temperatures range from 22°F in January and February to 67°F in July and August, resulting in a 45° annual range of temperature. Extremes of temperature are moderated by the lake's influence, with "three quarters of the minimum summer daily temperatures above 61°F, and in winter, readings below 0°F are recorded on average only 4 days per year" (Strommen, 1972, p.1).

Mean monthly precipitation ranges from 1.5" in January to 3.9" in September, with a mean annual precipitation of 30.4". Snowfall usually begins in September (0.2" mean) and continues into May (0.6"mean), with the highest average snowfall occurring in January (30.9"). The average annual snowfall is 97.3" (Strommen, 1972).

Strommen (1972) used wind data from the Muskegon weather station (116 miles south of Sleeping Bear Dunes, on Lake Michigan) to indicate that the "prevailing wind direction [is] from the southwest, averaging 10.8 mph" (p.1) except in the fall when the prevailing direction is northwest and in late winter when the direction is northeasterly. The strongest winds, averaging 12 mph, occur from December to April, and the lowest average wind speeds (8 mph) occur in July and August. This suggests that more sand movement could occur in late winter and early spring than at other times of the year.

Soils

The Soil Conservation Service (SCS) classifies the soils of the Sleeping Bear Dunes complex as predominantly Dune Land (Du), with small strips of Lake Beaches (Lb) and Lake Bluffs (Lk) occurring along the immediate shoreline (Weber, 1973) as shown in Figure 3.

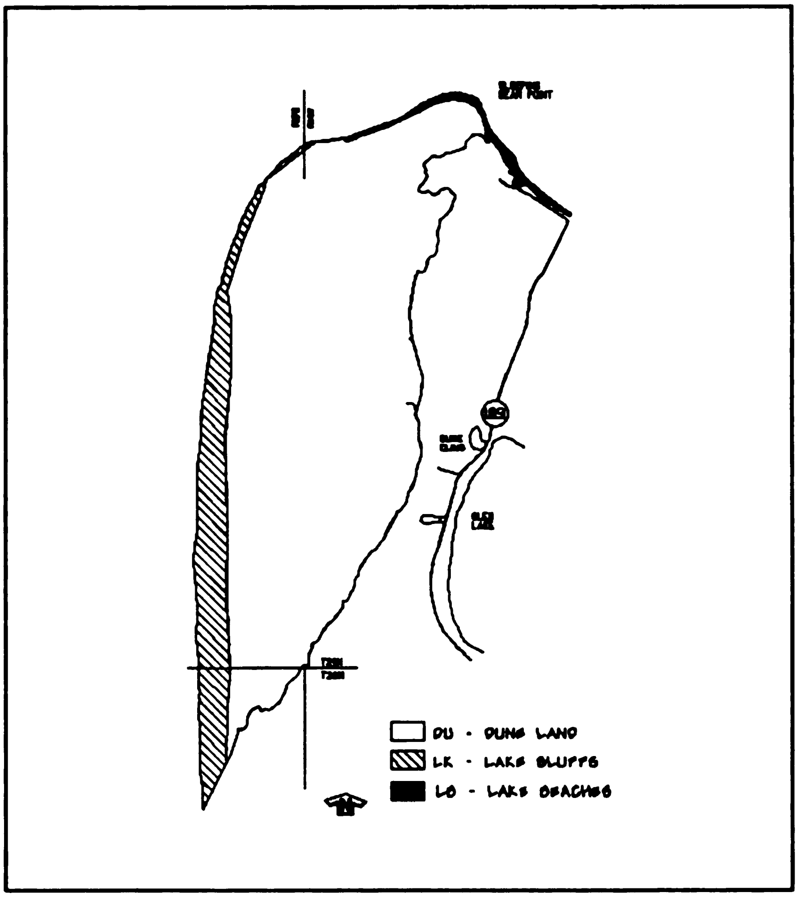


Figure 3 Soil Map of the Sleeping Bear Dunes Complex

The SCS description of dune land (Du) specifies a surface layer of shifting sand with slopes of 6 to 60 percent. Within this mapping unit, "outcrops of loamy sand, sandy loam, finer textured till...and medium textured till" can occur (Weber, 1973, p 13). This land type includes active sand dunes.

Lake beaches (Lb) are defined as occurring below the high water level line with slopes ranging from 0-13 percent (Weber, 1973). Soil material is described as being very variable, ranging from "sand, sand and gravel, and glacial till ... to cobblestones and mucky and silty material" (Weber, 1973, p 24).

Lake bluffs (Lk) are described by SCS as steep escarpments, rising from 200 to 400 feet above Lake Michigan, with slopes of 20 to 30 percent. The soil material is glacial till, which is unstable due to undercutting by waves, wind erosion and lack of stabilizing vegetation (Weber, 1973).

Snyder (1985) states that the two most influential factors permitting the existence of plant life on this dunes complex are topography and surface material. These factors influence an area's "exposure to wind ... and nutrients available for plant growth, and have a substantial effect on the degree of evaporation, amount of windblown sand, and water availability ..." (p. 19).

Time is an important factor in determining plant succession and soil formation. Most soils on the dunes complex are poorly developed having only "A" and "C" horizons. Because conditions on the dune complex are dynamic, long-term soil formation in any given area is difficult to achieve. Changing environmental conditions can make plant life impossible at one site, while simultaneously allowing it to begin elsewhere (Snyder, 1985).

Previous Investigations

Geomorphic Studies

The Sleeping Bear Dunes area was included in the national park system partly because of its "unique ecology and geology" (Muhn, 1984, p. 150). Some topographic changes that have occurred over time on the dunes complex have been documented, but in general, this area has received comparatively few geomorphic inquiries.

The most noticeable geomorphic change on the dunes complex has been the demise of the once magnificent Sleeping Bear Dune. In 1866, Winchell described the "Bear [as] an isolated mound rising an (sic) hundred feet above this desolated plateau and singularly covered with evergreens and other trees" (cited in Sprague & Smith, 1903, p 332). In 1906, the Army Corp of Engineers measured the dune's height at 234 feet above the plateau (Gillis & Bakeman, 1963). Waterman (1926) noted that erosion of the large dune was beginning in the early 1920s. Gates (1950) documented changes in the perched dune from 1928 to 1949, and in 1935 measured the dune's height at 159 feet above the plateau. In 1961, the dune was measured at 132 feet above the plateau (Gillis & Bakeman, 1963). Only about one fifth of this dune now remains.

Snyder (1985) concluded that "the parabolic perched dunes are non-migratory, remaining attached to and growing outward from the original zone of accumulation" (p. 148).

About 88% of the slip-face movement occurs in the winter months from December to May, suggesting that sand movement activity increases in the winter (Snyder, 1985).

Vegetation Studies

Presettlement Vegetation.--Notes of the field crew employed by the U.S. Surveyor General (1839 and 1850) describe the dunes complex as barren sand. Surveyors often mentioned the types of forest along survey lines and species of witness trees when appropriate but generally did not mention herbaceous and shrub vegetation. Areas of herbaceous and shrub vegetation on the dunes complex were not noted by the surveyors. Islieb's map of pre-settlement vegetation of northwestern lower Michigan including the study area (cited in Lovis, Mainfort & Noble, 1976) shows deciduous and pine forest associations dominating the area, but the dunes complex itself is mapped as bare sand.

Botanical Studies.--Thompson (1967) published a guide to the vegetation of the Sleeping Bear area, describing the principal ecological communities and names of the plants commonly found in the area. He describes the environment on the dunes complex as an area where "plants . . . must adjust themselves to strong sunlight, limited moisture, violent wind action, . . . low soil fertility . . . and changing sand levels" (Thompson, 1967, p. 12). He identifies beach grass and sandreed grass as two species that act as sand binders, and once established, make it possible for other herbaceous species to grow.

Hazlett (1986) produced a comprehensive inventory of the flora and fauna of the entire national lakeshore, and mapped the plant communities that he identified. A major objective of his study was to identify endangered species and their locations in the park. He mapped the dunes complex as one type, called "dunal vegetation", which he described as grasses, herbs, and an occasional tree.

Ecological Studies

The environment of the Sleeping Bear Dunes area has been of interest to many researchers. In 1899, Cowles described the ecological relationships occurring in a dune environment based in part on his study of the vegetation in this area. He suggested a relationship between dune shape and the type of vegetation found on a dune. Waterman (1926) studied the Sleeping Bear area and expanded on the ecological concepts of Cowles. Although both researchers described the vegetation of the area in detail, neither produced a vegetation map of the area or analyzed change over time.

Based on the work of Cowles and Waterman, shoreline dune environments can be described in terms of ecological zones.[1] The Wet Beach area has no plant life. The Middle

[1]The species referred to in the following descriptions are typical of these zones in the Sleeping Bear Dunes area.

Beach area is covered with water from high waves during winter storms, but the American searocket grass may occur in this area. The Upper Beach zone has various biennial and perennial plants. Although it may be subject to very severe winds, it is not inundated with water. The Foredune zone, on the windward side of the dune, is characterized by the sand-binding American beachgrass, and on the crest of the dune there may be sandreed grass and American beachgrass. The Trough or Deflated zone behind the foredune is characterized by a variety of plants. In protected areas, dune-building species such as little bluestem, creeping juniper, and bearberry are common. There may be sporadic trees present, such as eastern cottonwood, balsam poplar, black spruce, with jack pine being the most common. Evergreen shrubs such as bearberry, common juniper, and creeping juniper, and deciduous shrubs such as sand cherry, and chokecherry are also common in this zone. Beyond the deflated zone, areas of deciduous, coniferous, and mixed forests may occur as soil and moisture conditions improve (NPS, 1961).

Olson (1958) studied the relationship between dune shape, growth, and stability, and different types of vegetation. He found that marram grass is "pre-eminently adapted to tolerating deposition . . .(but is also) notorious for requiring deposition for vigorous growth" (p. 348). Sandreed grass is generally associated with marram grass and is considered a major dune builder. It is slightly less tolerant of very rapid deposition, but is more persistent on stable or nearly stable dunes (Olson, 1958). The occurrence of little bluestem bunchgrass suggests that deposition has decreased significantly. It is generally found on dunes that have been stabilized for a few years.

Shrubs such as red ozier dogwood, choke cherry and especially sand cherry "become established rapidly on many dune surfaces when deposition stops or decreases to a few centimeters per year" (Olson, 1958, p. 349). Cottonwood and poplar trees

> ...arise from prolific moist-sand beds or vegetative sprouts at water level but . . .may grow while being buried until they are found on the dune crests. Here they serve to remind us of their great potential for height growth . . .sometimes they reveal the former presence of dune depressions in positions that could hardly be guessed from present topography (Olson, 1958, p. 349)

As Olson and other ecological researchers have suggested, a close relationship exists between a dune environment and its vegetation.

Purpose of This Investigation

Vegetation can be an important indicator of both long- and short-term environmental conditions in dune areas. Knowledge of the presence, amount, type, or absence of vegetation, and where and how these characteristics have changed over time can provide important information about the condition of the dune environment. Kuchler (1953) notes that plants are the most comprehensive indicators of the nature of the environment in a given area.

Fairly extensive ecological and botanical investigations have been conducted in the Sleeping Bear Dunes National Lakeshore. However, research related specifically to the vegetation of the dunes complex is extremely limited. Little, if any information exists documenting if and how the vegetative cover on the dunes complex has changed over time.

The current study was designed to gather information regarding the change in vegetative cover on the Sleeping Bear Dunes complex based on analysis of historic aerial photography. The period covered is from 1938 to 1987. The objectives of this study are to:

- Describe the general trends in vegetative cover on the dunes complex during this period.
- Document areas and types of change in the vegetative cover on the dunes complex.

To achieve these objectives, the following tasks were undertaken:

- Classification of the vegetative cover of the Sleeping Bear Dunes complex based on interpretation of medium-scale aerial photography taken in 1938, 1973, and 1987.
- Production of a vegetative cover map of the Sleeping Bear Dunes complex for each period.

A description of the methods used to accomplish the above tasks and achieve the objectives of this research is included in Chapter II. In particular, the choice of aerial photography, the development of the vegetative cover classification system, and the use of a geographic information system (GIS) for analysis and mapping are discussed.

The results of these investigations are presented in Chapter III along with a discussion of the findings. Vegetative cover maps and data tables are used to illustrate the change in vegetative cover on the dunes complex. Chapter IV summarizes the results of this work and includes recommendations for future research concerning the Sleeping Bear Dunes complex.

CHAPTER 2

METHODS

Introduction

Data for this study were gathered from the interpretation of historic and recent aerial photographs. Analysis and mapping of the data were accomplished using the C-MAP geographic information system (Enslin, 1992). This chapter begins with a review of the use of aerial imagery and geographic information systems (GIS) for temporal analysis followed by a detailed discussion of the imagery and methods used in this investigation.

Use of Aerial Imagery

Remote sensing, considered to be an economical and efficient method to inventory and monitor the environment, has become an established procedure in geographic research. Remotely sensed images can range from black and white panchromatic photographs to digital satellite imagery. Although computer analysis of satellite data is increasing rapidly "aerial photographs still provide the highest resolution and capture the spatial and textural essence of the scene with greater fidelity than any other procedure" (Tueller, 1989, p. 443).

Early aerial photographs of an area are a great historical resource, providing a concrete record of the past and, when compared with more recent photographs, give an indication of changes that have occurred in an environment. The following excerpts from the Manual of Remote Sensing describe the utility of aerial photographs in the rangeland environment:

> [Aerial] photos show major changes in plant communities and physical attributes that are indicators of long term changes in range condition and past management practices. The value of older photographs is not in the direct determination of ecological range condition, but rather the identification of plant communities in which there has been substantial change over time (ASP, 1983, p. 2357).

However, quality and comparability of aerial imagery must be considered before conducting a temporal change analysis based on interpretation of the imagery. As the manual suggests:

> ...medium scale aerial photographs show only the more conspicuous changes, [but] they contain clues to subtle changes in ...condition... Whereas current photographs of similar type, scale and season as the older photos are desirable for the comparison of change, this is not a prerequisite. Other film types and scales may be more desirable not only to observe where changes have occurred, but for purposes of evaluating the change in greater detail...(ASP, 1983, p. 2358).

MacConnell (1973) designed a long-range research project to document and monitor changes in the land use and land cover of Massachusetts and Rhode Island. The initial phase of the project involved analysis of medium-scale (1:20,000) aerial photographs from 1951 and 1971 to provide an historical perspective of the land use and land cover changes. Once this baseline information was gathered, the second phase of the project involved the use of satellite imagery and computer analysis to monitor changes and provide information for resource managers in the future.

MacConnell's objectives included testing photogrammetric techniques for identifying and classifying land use and land cover categories, determining change in vegetation and land use between 1951 and 1971, and providing vegetative cover and land use maps of the entire state for use by resource managers and decision makers. The imagery used in the photographic analysis for both years was 1:20,000 scale, black and white panchromatic taken during the same season. The 1951 imagery was of lower quality than the 1971 photographs because of the advancements in photographic materials and equipment that occurred between 1951 and 1971.

Kelsch and Hendricks (1982) used aerial imagery to conduct a temporal analysis of a wetland environment along the Texas Gulf Coast. They used medium scale photography (1:20,000 and 1:24,000) taken on five dates during a 24 year period. An objective of their research was to estimate the accuracy of an ecological assessment based on temporal aerial interpretation. They compared the interpretation results of two experienced interpreters and found little significant difference between the two interpretations. They concluded that:

> ...the method...of aerial photographic analysis of sequential photography provides an economical and accurate means of wetland assessment even in the

> absence of field verification...(and that) results accurate enough to detect trends can easily be interpreted from a single photointerpretation (p.230).

Several researchers have used aerial photography to gather information about vegetation in sand dune environments. Hazlett (1986) began his botanical investigation of the Sleeping Bear National Lakeshore by mapping the major vegetation communities of the area based on interpretation of medium-scale black and white panchromatic and color infrared (CIR) aerial imagery.[1] Daniels (1976) used both large scale (1:12,000) photographs and small scale (1:200,000) satellite imagery to develop a resource classification and inventory of the Assateague Island National Seashore located along the Atlantic coasts of Maryland and Virginia.

The information gathered from a temporal analysis of aerial imagery can be seen as a first step in the process of environmental monitoring and management. The trends of change indicated from such an analysis can assist decision makers in the allocation of resources for environmental management and protection. However, as the Manual of Remotes Sensing notes:

> ...photo interpretation does not always provide conclusive explanations for change, but areas on the ground that warrant closer examination can be identified. Through this process, it is possible to more effectively utilize field crews for determining the causes of the changes (ASP, 1983 p. 2358).

---

[1]Hazlett mapped the entire dunes complex as a single unit of dunal vegetation.

The interpretation of historic and recent aerial photographs to discern the change in vegetative cover on the Sleeping Bear Dunes complex is a first step in gathering important environmental information about the area.

Use of GIS Analysis and Mapping

Geographic information systems (GISs) are computer-based systems for the analysis and mapping of spatial data. Johnson (1990) stated that "the power and utility of the GIS has ... gained wide-spread recognition in the fields of urban and regional planning, natural resource planning and management, and landscape architecture" (p. 32). Any data that can be located in space can be entered into a GIS, updated more easily, and combined with other spatial data for further analysis. The production of maps based on this analysis is relatively quick and inexpensive compared to manual cartographic methods.

According to MacEachren (1987) "more than ever before, we have the ability to analyze complex environmental problems that change through time" (p. 106). Some examples include Johnston and Naiman's (1990) analysis of long term landscape alteration by beaver, Turner's (1990) study of the change in landscape patterns, an examination of desertification in Africa by Dangermond (cited in MacEachren, 1987), and an analysis of the environmental effects of oil production in the tundra by Walker et al (cited in MacEachren, 1987).

The system used in this research project was C-Map, a GIS software program developed by the Center for Remote Sensing at Michigan State University (Enslin, 1992). It is a vector based, microcomputer program that can be used to digitize, analyze, update, and map data.

Interpretation Procedures

Choice of Imagery

Table 1 contains an inventory of the aerial imagery of the study area. Although this list may not be comprehensive, it provided realistic choices for this research. Within the context of the objectives of the study, the choice of imagery was influenced by several factors including availability, quality, scale, film type, and date of photography. The earliest (1938) and most recent (1987) imagery proved to be acceptable choices providing "beginning" and "ending" data for the temporal analysis of change. To obtain a better impression of the change process, a third, intermediate set of imagery was required.

There was not a clear choice of imagery to provide data for the middle of the period between 1938 and 1987. Taking into consideration the objectives of the study and the limitations of each set of imagery, I chose the 1973 black and white panchromatic imagery. The main limitation imposed on my study by this choice was the limited amount of

TABLE 1

Inventory of Aerial Imagery of the Study Area

DATE[1]	FILM TYPE[2]	SCALE	AGENCY[3] ROLL:FLIGHT #	COMMENTS
7-17-38	**BWP**	**1:20,000**	USDA/AAA BEA:3,3R	Earliest available; fair quality;mid-summer vegetation.
8-13-52	BWIR	1:15,840	USDA/PMA BEA:5K	Poor tonal range-high reflectance from sand.
10-12-63	BWP	1:20,000	USDA/ASCS BEA:2DD	Fall vegetation; not all frames available.
7-16-73	**BWP**	**1:40,000**	USDA/ASCS 26089:173	Small scale; good quality; mid-summer vegetation.
6-3-78	CIR	1:15,840	MDNR 13:31	Poor tonal range-high reflectance from sand.
5-7-81	CIR	1:60,000	SCS 448616:HAP81F	Small scale of photos limits interpretation.
6-3-87	**BWIR**	**1:15,840**	MDNR 313:16,17	Excellent tonal range;early summer vegetation.

[1]Imagery used in this study is shown in bold

[2]BWP=Black and White Panchromatic; BWIR=Black and White Infrared; CIR=Color Infrared

[3]See Appendix A for Agency Information

information that could be interpreted at the smaller (1:40,000) scale.

The 1938 imagery was produced in mid-July using standard black and white panchromatic (BWP) film at a scale of 1:20,000. Although the general quality of the film used appears to be with less contrast between gray tones than on later photography, this imagery provided historic information that was unavailable elsewhere.

The 1973 imagery was photographed in early July using standard black and white panchromatic (BWP) film at a scale of 1:40,000. The quality is somewhat improved over the 1938 photography, but the small scale limited interpretation.

The 1987 imagery was photographed in early June using black and white infrared (BWIR) film at a scale of 1:15,840 (4"=1 mile). This imagery was the highest quality of the three sets, providing the best tonal range and resolution.

Classification System

The development of a classification system for the mapping of the Sleeping Bear Dunes complex vegetative cover was based on an assessment of the photographic resolution provided by the selected imagery, the type and amount of vegetation occurring on the study area, and the classification systems used in similar research. Relatively few systems which classified rangeland or dune vegetation for mapping from aerial photographs were discovered.

Mueller-Dombois and Ellenberg (1974) developed a key for:

> ...mapping structural vegetation types in Southeast Ceylon (Sri Lanka) on aerial photograph mosaics at the scale of 1:31,680 ... that is also applicable to any larger scale and to scales reduced to about 50% (p. 489).

Their key divides vegetation into four major classes: Forest Cover Types, Scrub Cover Types, Herbaceous Cover Types, and Other Areas, and was used to map vegetative types that were at least five (5) acres in area. The Herbaceous Cover Types most closely resembled the dune vegetation of the Sleeping Bear Dunes complex, but a classification system better suited to the dunes vegetative cover was needed.

Jacobberger and Hooper (1991) used Landsat[1] imagery to analyze the geomorphology and reflectance patterns of vegetation on sand dunes in Botswana. Their classification system took into account the close relationships between geomorphology and vegetation in a dune environment. Because a geomorphic analysis of the Sleeping Bear Dunes complex was not part of my research, a classification system that did not include geomorphic variables was needed.

Martin (1959) used a very detailed classification system in mapping the vegetation units of Island Beach State Park, New Jersey. His objective was to provide a permanent record of the vegetation of the park. His system used

---

[1]Landsat is the satellite global resource monitoring system operated by the Earth Observation Satellite Company (EOSAT)

specific species to classify sub-units of the major classification units.

Daniels (1976) provided a review of several classification systems used to map barrier island vegetation. She designed a biophysical classification system for use with 1:200,000 scale Landsat imagery and 1:12,000 color infrared (CIR) imagery to inventory the resources of Assateague Island National Seashore. Her objective was to provide land use capability information for management decisions. Daniels' classification system had five community habitat types which were subdivided into nine individual plant communities.

Based on an examination of the above classification systems in conjunction with a preliminary analysis of the three sets of imagery, I developed the eight class system of vegetative cover shown in Table 2. In order to compare the change in vegetative cover over time, I used the same classification system for all three periods. However, the small scale of the 1973 imagery (1:40,000) limited my ability to consistently classify the vegetative cover into eight classes. For the 1973 imagery, the eight cover classes were collapsed into the six classes shown in Table 3. The 1938 and 1987 imagery were interpreted using the eight class system shown in Table 2. A second interpretation was completed of the 1938, 1973, and 1987 imagery using the six class system shown in Table 3.

A continuum of vegetation biomass is suggested in this

TABLE 2

Vegetative Cover Classification System - Eight Classes

(Minimum mapping area - 2.5 acres)

CLASS	NAME AND DESCRIPTION
1	**Unvegetated** Bare sand or gravel with few isolated or no plants
2	**Barren with Isolated Plants** Bare sand or gravel with isolated shrubs, trees, or clumps of grass
3	**Discontinuous Grass** Dunegrasses predominate but do not constitute a continuous cover; Isolated shrubs or trees may be present
4	**Continuous Grass** Continuous grass cover - isolated shrubs or trees may be present
5	**Grass and Partial Shrubs** Grass cover with clusters of shrubs or scattered shrubs covering approximately 25-50% of the area
6	**Grass and Dense Shrubs** Grass cover with clumps of shrubs or scattered shrubs covering more than 50% of the area
7	**Grass, Shrubs, and Trees** Grass and shrub cover with clumps of trees or scattered trees
8	**Forest** Closed canopy deciduous, coniferous, or mixed forest

TABLE 3

Vegetative Cover Classification System - Six Classes

(Minimum mapping area - 2.5 acres)

CLASS	NAME AND DESCRIPTION
1	**Unvegetated** Bare sand or gravel with a few isolated or no plants or with isolated shrubs, trees, or clumps of grass (Classes 1 and 2 in Table 2)
2	**Discontinuous Grass** Dunegrasses predominate but do not constitute a continuous cover. Isolated shrubs or trees may be present (Class 3 in Table 2)
3	**Continuous Grass** Continuous grass cover - isolated shrubs or trees may be present (Class 4 in Table 2)
4	**Grass and Shrubs** Grass cover with clusters of shrubs or scattered shrubs covering more than approximately 25% of an area (Classes 5 and 6 in Table 2)
5	**Grass, Shrubs, and Trees** Grass and shrub cover with clumps of trees or scattered trees (Class 7 in Table 2)
6	**Forest** Closed canopy deciduous, coniferous, or mixed forest (Class 8 in Table 2)

classification system, with increasing biomass expectedalong a gradient from an unvegetated area to a closed-canopy forest. Due to the widely varying geomorphology on the dunes complex, the vegetation communities occurring there exhibit great spatial variability. For example, it is possible to find areas of low biomass (bare sand or discontinuous grass) and areas of high biomass (forest) very close to each other. Ground photographs illustrating the eight classes of vegetative cover are shown in Figures 4-11.

Figure 4 illustrates an Unvegetated (Class 1) area; the foreground is bare gravel, the right center is bare sand. An area of Discontinuous Grass (Class 3) is shown in the background.

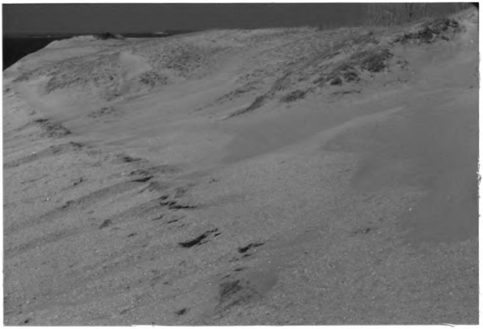


Figure 4 Ground Photograph of Unvegetated (Class 1)

In the foreground of Figure 5, the area with a few scattered trees growing on the side of the dune is an example of the Barren with Isolated Plants (Class 2) cover type.

Figure 5 Ground Photograph of Barren with Isolated Plants (Class 2)

Figure 6 illustrates the Discontinuous Grass cover type (Class 3) in the foreground. In the center of the photograph is an Unvegetated (Class 1) area, and in the background Continuous Grass (Class 4) covers the side of the dune. An area of Continuous Grass cover is also shown in the left foreground and center of Figure 7.

Figure 6 Ground Photograph of Discontinuous Grass (Class 3)

Figure 7 Ground Photograph of Continuous Grass (Class 4)

Figure 8 includes an area of Grass and Partial Shrubs (Class 5) in the center of the photograph. The foreground illustrates Continuous Grass (Class 4) cover type.

Figure 8 Ground Photograph of Grass and Partial Shrubs (Class 5)

An area of Grass and Dense Shrubs (Class 6) is illustrated in the center and background of the photograph in Figure 9. The foreground is an area of Discontinuous Grass (Class 3).

Figure 10 illustrates the Grass, Shrubs and Trees cover type (Class 7) in the foreground. Figure 11 shows a closed canopy Forest (Class 8). The photograph is of a deciduous forest (after the leaves have fallen), but there are also coniferous and mixed forests in the study area.

Figure 9 Ground Photograph of Grass and Dense Shrubs (Class 6)

Figure 10 Ground Photograph of Grass, Shrubs and Trees (Class 7)

Figure 11 Ground Photograph of Forest (Class 8)

As illustrated in the above photographs, the vegetative cover of the Sleeping Bear Dunes complex is varied and can change either gradually or abruptly from one cover type to another across the complex.

The level of detail of mapping was controlled by the scale of the imagery. Although the 1938 and 1987 imagery could have been mapped in greater detail, I used a minimum mapping unit of 2.5 acres based on the 1:40,000 scale of the 1973 imagery. It was not feasible to classify the vegetation by species using the available imagery. However, a list of species commonly found on the dunes complex based on the investigations of Thompson (1967) and Hazlett (1986) is provided in Table 4.

TABLE 4

Species Found on the Sleeping Bear Dunes Complex

GRASSES	COMMON NAME
Ammophilia breviligulata	beach grass
Andropogon scoparius	little bluestem
Calamovilfa longifolia	sandreed grass
Elymus canadensis	Canada wild rye
Arabis lyrata	sand cress
Artemisia caudata	dune wormwood
Asclepias syriaca	common milkweed
Cakile edentula	sea rocket
Lathyrus japonicus	beach pea
Lilium philadelphicum	Philadelphia lily
Lithospermum caroliniense	hoary puccoon
Smilacina stellata	starry solomon's seal
Zigadenus glaucus	dune lily
TREES AND SHRUBS	
Populus deltoides	cottonwood
Populus balsamfera	balsam poplar
Pinus banksiana	jack pine
Prunus pumilia	sand cherry
Juniperus horizontalis	trailing juniper
Juniperus communis	common juniper
Cornus stolonifera	red osier dogwood
Arctostaphylos uva-ursi	bearberry

Source: Developed from Thompson (1967) and Hazlett (1986)

Interpretation Factors

Avery and Berlin (1985) describe the aerial photograph interpreter's job as one of exercising "mental acuity as well as visual perception and consciously or unconsciously evaluating several factors in identifying features on vertical photographs" (p. 27). The factors most commonly referred to include shape, size, tone, texture, pattern, shadow, stereoscopic viewing, and topographic location.

Shape and pattern were not particularly useful in distinguishing between classes of vegetative cover in this study. Size and shadow were important factors in classifying cover types that included either shrubs or shrubs and trees. Tone and texture, in conjunction with stereoscopic viewing, were the most useful factors in analyzing and classifying vegetative cover on the Sleeping Bear Dunes complex. As expected, there was also a relationship between topographic location and vegetative cover type. For example, areas of forest or dense shrub tended to occur on the eastern side of dune formations; likewise, bare sand areas tended to occur on the western side of dunes and in blowouts.

Film type and imagery quality were also influential in determining the amount and type of information that could be obtained from photo interpretation. Both the 1938 and the 1973 imagery were photographed using standard black and white panchromatic (BWP) film. According to Avery and Berlin (1985), "images on panchromatic photographs are rendered in varying shades of gray, with each tone comparable to the density of an object's color as seen by the human eye" (p.9). A major disadvantage of BWP film, is its "lack of sensitivity to green light making separation of vegetative types (e.g. tree species) difficult" (Avery & Berlin, 1985, p. 9). Because the objectives of this study required only the mapping of vegetative cover types and not species identification, black and white panchromatic film was acceptable.

The 1987 imagery was photographed using black and white infrared (BWIR) film. According to Avery and Berlin, "the gray tones on an infrared photograph result from the degree of near-infrared reflection of objects" (1985, p.10). "Plant reflectance (in the near infrared range) results primarily from the internal structure of plant leaves" (Lillesand and Kiefer, 1979, p. 17). Because leaf structures vary greatly between plant species, this film type is especially useful in delineating species. Although some species delineation would have been possible on the 1987 imagery, none was attempted, in keeping with the objectives of this study. However, the 1987 imagery provided much greater tonal differentiation and, because of the 1:15,840 scale, much more detail than the earlier imagery.

One generally expects areas of high biomass on black and white panchromatic film to be darker in tone than areas of low biomass. Some areas of vegetative cover on the dunes complex did not necessarily meet this expectation. The situation was most noticeable on the 1938 imagery in the Grass and Shrubs categories (Classes 5 and 6). Areas of Grass and Shrubs which had a discontinuous grass cover were significantly lighter in tone than some areas of Continuous Grass (Class 4).

On the 1987 BWIR photos, areas identified as Discontinuous Grass (Class 3) and Continuous Grass (Class 4) varied considerably in tone within each class. Because these photographs were taken in early June, some of the vegetation was just beginning to grow. If I could detect any evidence of plant growth, I classified the area as Discontinuous Grass (Class 3) rather than Bare Sand (Class 1). Other areas had more noticeable grass cover, (a darker tone) but it was evident that the cover was not continuous. These areas were also classified as Discontinuous Grass (Class 3). Some areas identified as Continuous Grass (Class 4) were very dark on the photos, and some were much lighter in tone, although all appeared to have continuous cover. This was most noticeable on the lowland at the northern end of the dunes complex where a fairly large area of lichens and heath vegetation occur. The herbaceous species growing there had a darker tone on the imagery than dune grasses.

Equipment

Stereoscopic viewing was accomplished using a Delft Scanner Stereoscope with 2x and 4x magnification. Areas that required greater magnification were viewed using a Bausch and Lomb Zoom Transfer Scope or a 10x hand magnifier. This increased magnification was achieved at the expense of stereoscopic viewing.

Upon classifying an area, its boundaries were drawn on a wet media acetate overlay using a 4x0 technical pen (.18 mm) and black ink for film. Each polygon was labeled using the number code indicated in the classification system (see Tables 2 and 3).

Analysis and Mapping Procedures

Digitization

Each polygon drawn and labeled on the aerial photograph overlays was digitized using the C-MAP software program. Variation in scale and distortion problems associated with aerial photographs were corrected to some degree by the use of a GIS system. The stated "nominal" scale of aerial photography is only an approximation since scale varies across an image due to elevation differences in the area being photographed. Distortion due to radial displacement is also a problem with aerial images, and increases with distance from the center of the image.

The polygons on each photograph overlay were digitized at the scale and accuracy of that photograph's set up. Appendix B contains information regarding the accuracy and scale approximations for each photograph set-up.

1938 Set-Up.--The Glen Haven 7.5 minute USGS quadrangle was set up on the digitizer with an average error of 4 feet. Coordinates of four control points were obtained and used to set up the most northern image of the dunes complex (image number 3-27). This photo set-up had an average error of 28 feet, and an average scale of 1:20,985. Coordinates of four control points on image 3-27 were used to setup image 3-3. Image 3-3 had an average error of 20 feet and an average scale of 1:21,251. Coordinates of four control points on image 3-3 were used to set up image 3-4, and coordinates of four control points on image 3-4 were used to set up image 3-5.

1973 Photo Set Up.--The Glen Haven USGS 7.5 minute quadrangle was set up with an average error of 7 feet. Coordinates of four control points from the map were used to set up image 173-79. This photo had an average error of 22 feet and an average scale of 1:41,371. Coordinates of control points on image 173-79 were used to set up image 173-78. Image 173-78 had an average error of 20 feet and an average scale of 1:41,095.

1987 Photo Set Up.--The setup of this series of images was more complex than 1938 and 1973. Because of the large scale, and location of the flight lines, images along the coast of the complex were mostly water with only narrow areas of land. It was necessary to set up the photos just east of the coastal images in order to find control points. Table 12 in Appendix B lists the photos that were digitized and those that were used only to obtain control points for other imagery set ups.

The resulting data file containing location coordinates for each digitized point was, in a sense, "scaleless". Maps can be produced at whatever scale is chosen, but the original data were entered as accurately as possible. After the polygons were digitized and labeled, a check plot was produced and checked against the original interpretation for size, shape, and labeling accuracy. Any necessary changes were completed.

The data file was then "cleaned" (line file checked for topological consistency) and "built" (creation of a topological polygon file). A topological polygon file contains the spatial location of each polygon and information (in this case, vegetative cover class and acreage) associated with that polygon. Once a topologically correct polygon file was created, analysis of the data was conducted.

Measurement and Comparison Procedures

As discussed above, two interpretations of the imagery were completed, one using the eight classes of vegetative cover and one using the six classes of vegetative cover. Two separate comparisons were made. The first comparison was between 1938 and 1987 based on eight classes of vegetative cover. The second comparison was between 1938, 1973 and 1987 based on six classes of vegetative cover.

To analyze the trends of any changes in vegetative cover, the following values were calculated for each period:

- Number of polygons for each class
- Total acreage for each class
- Average-, minimum- and maximum-sized polygon for each class
- Total acreage of vegetation

By comparing the above values for each period, it was possible to discern trends of changes in vegetative cover on the dunes complex.

Presentation of Findings

The results of this analysis are presented both in data tables and as a series of thematic maps. The values calculated to discern trends of change as discussed above are presented in Tables 5 through 10 in Chapter III. A thematic map for each period of the photo-interpreted vegetative cover on the dunes complex is included in Chapter III. A thematic map of the 1987 photo-interpreted vegetative cover at a scale of 1:15,840 (Figure 32) is included in a pocket inside the back cover.

In addition to the thematic maps for each period, a map for each vegetative cover class in each period was produced in C-MAP at a greatly reduced scale. These maps are used in Chapter III to illustrate the type and location of changes for each class.

Limitations of this Investigation

This study has several limitations. First, differences in the quality and scales of the photographs being compared influenced interpretation. Ideally, each period should be flown during the same season, at the same scale, and with the same type of film and quality of developing and print reproduction. When using historic photography, one is limited to the film types, scales and developing quality that are available. Although the situation is less than ideal, the information available from the historic photographs is valuable, despite its limitations. In particular, the small scale and poor tonal range of the 1973 imagery may account for some of the larger variations indicated for some of the vegetative cover classes. It was quite difficult to distinguish between shrubs and trees and between Discontinuous Grass and bare sand on this imagery.

Another factor that may have affected the interpretation and mapping was the variability of the bare sand environments. Many of the interpretation decisions were based on tone. It is not uncommon to have significant variability in the tone of bare sand because of differences in moisture content. Also areas that have recently experienced slumping appeared darker in tone than other Unvegetated areas.

A second limitation is the fact that coastal dune environments are often geomorphically active, but the speed and direction of change is unknown. Geomorphic changes can affect the stability and amount of vegetative cover in dune environments. A documentation of geomorphic change was not attempted and, therefore, its influence on the vegetative cover is unknown.

A third limitation was the lack of a fully functioning geographic information system. The overlay analysis capabilities of C-MAP were not fully developed when this research was being conducted, so it was not possible to analyze the change in each polygon of vegetative cover over this time period. Instead, analysis was based on a comparison of the number of polygons and acreage of each vegetative cover class.

A fourth limitation is the inability to address the question of the cause(s) of change in the vegetative cover on the dunes complex. Factors to be considered when addressing the question of cause include, but are not limited to, the degree and amount of naturally occurring geomorphic and vegetative change, the extent and type of human use and its affect, and weather and climate variability. None of these factors could be controlled for or addressed in this study. Also, the inability to do an overlay analysis limits the understanding of the type and location of specific vegetative cover changes.

A final limitation is the expertise of the photo-interpreter. Photo-interpretation is a skill that, like any skill, can improve with practice. I had studied and practiced photo-interpretation extensively before undertaking this project, however I do not consider myself to be an expert interpreter of vegetative cover. My photo interpretation work was reviewed by two faculty members who are considered expert in their fields, and their comments and suggestions were incorporated in the analysis.

CHAPTER 3

RESULTS AND DISCUSSION

Introduction

This chapter begins with a comparison between the 1938 and 1987 vegetative cover on the Sleeping Bear Dunes complex as interpreted from the aerial imagery. The discussion is based on eight classes of vegetative cover. A thematic map of the vegetative cover for each year is presented. Maps comparing each vegetative class for each period are also included.

A comparison is made between the 1938, 1973 and 1987 data based on six classes of vegetative cover. A thematic map of the photo-interpreted vegetative cover for each period is presented. Maps comparing each vegetative class for each period are included in the discussion. Tables are used to present some of the data for the above discussions. The chapter concludes with a brief discussion of environmental factors that could have influenced the results of this study.

Explanation of Comparison

The following discussion focuses on the change in the number, size, and location of areas of each vegetative cover class between periods. An overlay analysis of the three periods was not performed, nor was any statistical analysis done to compare the precise spatial distributions of vegetative cover for each period. Therefore the changes discussed describe the general trends for each vegetative cover class over the three periods, as opposed to describing how specific areas have changed over the period.

Comparison Between 1938 and 1987 (Eight Classes)

General Discussion

Maps of the photo-interpreted vegetative cover on the Sleeping Bear Dunes complex for 1938 and 1987 are shown in Figures 12 and 13, respectively. The vegetative cover was mapped using the eight class system (see Table 2).

On the map for 1938 (Figure 12), the interior of the dunes complex was mapped as a very large, fairly contiguous area of Continuous Grass (Class 4). Large areas of Discontinuous Grass (Class 3) surrounded the large area of Continuous Grass. The western and northern edges of the dunes complex were bordered by Unvegetated (Class 1) bluffs and beaches. A few, relatively small areas of Unvegetated (Class 1) land occurred along the eastern edge of the dunes complex. Areas of Grass and Partial Shrub (Class 5) were scattered throughout the interior of the dunes complex. Areas of the higher biomass cover types (Grass and Dense Shrubs, Grass, Shrubs and Trees, and Forest) were very limited in extent and located mostly on the southern end and on the east central edge of the dunes complex.

The vegetative cover map for 1987 (Figure 13) has quite a different appearance than the map for 1938 (Figure 12).

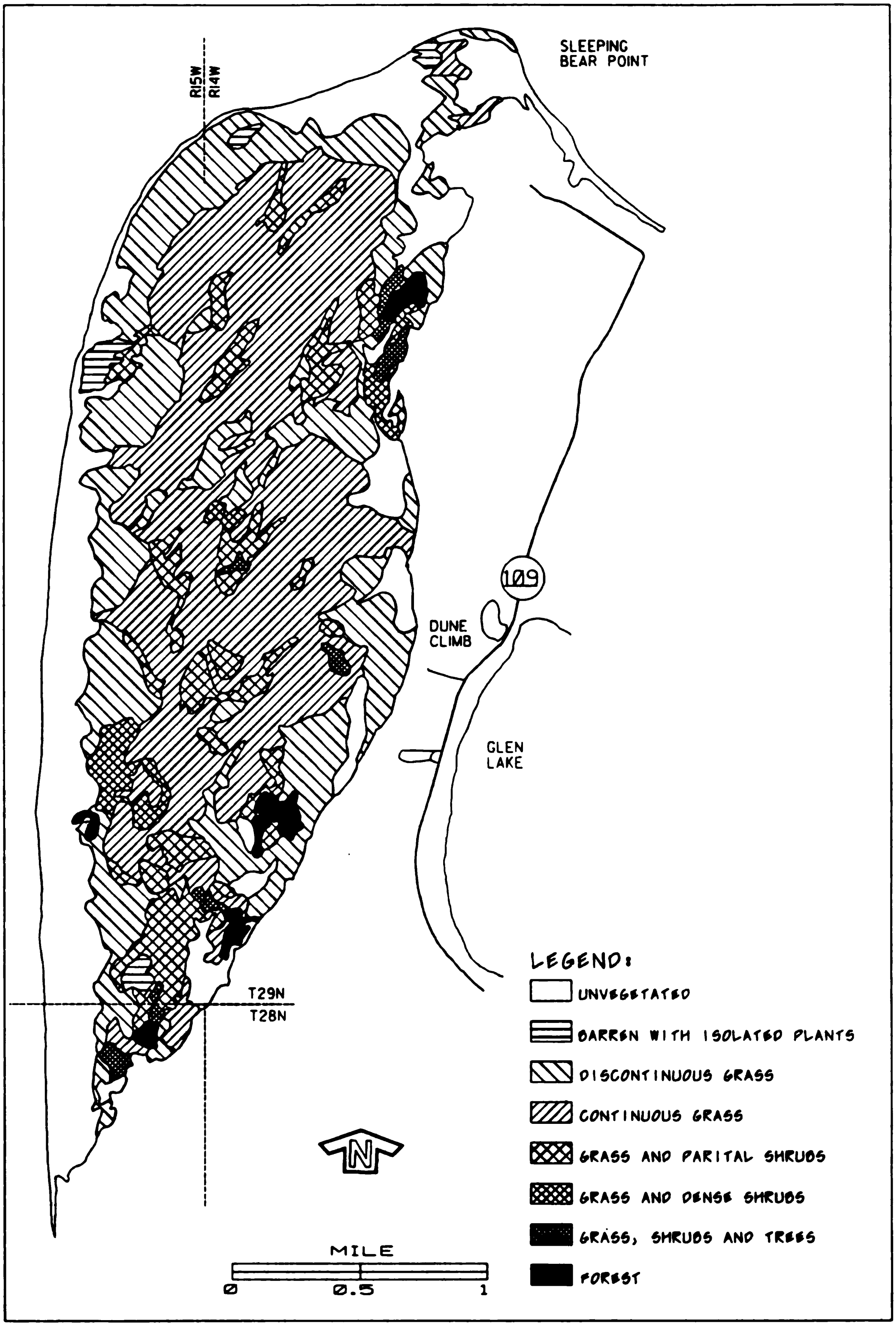


Figure 12 Vegetative Cover Map for 1938 (8 Classes)

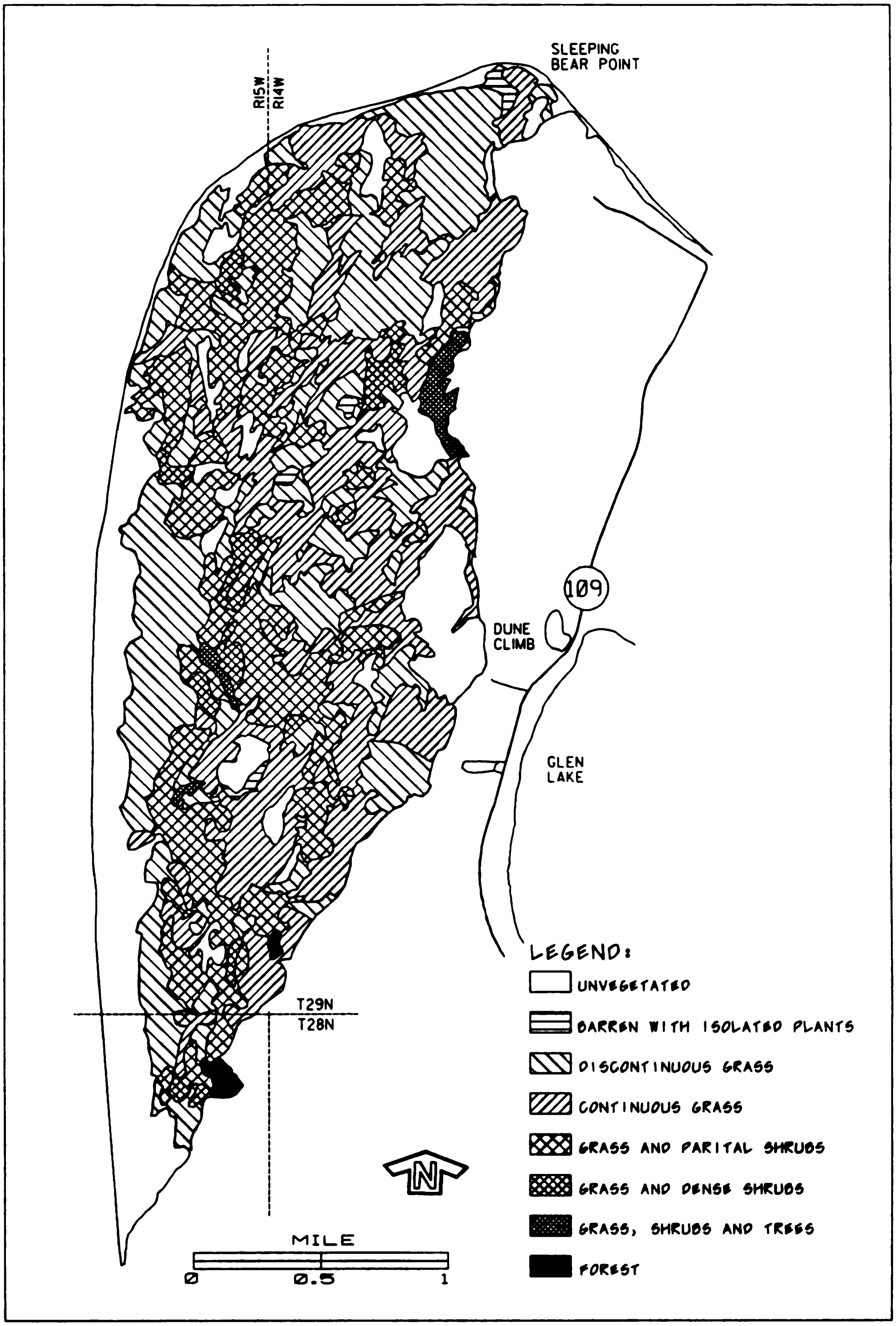


Figure 13 Vegetative Cover Map for 1987 (8 Classes)

One very noticeable difference is the lack of any large, contiguous areas of a single vegetative cover type. The interior of the dunes complex was fragmented into many small areas of varying cover types. There was a noticeable increase from 1938 in the area classified as Grass and Partial Shrubs (Class 5) and an apparent decrease in the area covered with Continuous Grass (Class 4). Unvegetated (Class 1) area still covered the western and northern edges of the dunes complex, but the area at the northern end was much smaller than in 1938.

The total number of polygons and total acreage mapped for each class for 1938 and 1987 are shown in Table 5. The total acreage mapped was 43 acres (1.6%) less in 1938 than in 1987. This slight difference in total area could have originated during the digitization process, or it could indicate an actual change in the size of the dunes complex. A margin of error of less than two percent during digitization is within acceptable standards, and is the most likely explanation for the difference in total area.

As was indicated by Figures 12 and 13, many more (57%) polygons were mapped in 1987 than in 1938. A possible explanation of the increase in the number of polygons between 1938 and 1987 is that fragmentation of larger polygons occurred.

In order to better understand these changes, each vegetative cover class is discussed separately below and

TABLE 5

Total Number of Polygons and Total Acreage For Each Class: 1938 and 1987

	Total Number of Polygons		Total Acreage	
CLASS	1938	1987	1938	1987
1 Unvegetated	10	20	599	561
2 Barren with Isolated Plants	4	4	29	16
3 Discontinuous Grass	21	43	691	768
4 Continuous Grass	8	21	973	690
5 Grass and Partial Shrubs	23	24	233	551
6 Grass and Dense Shrub	4	10	58	71
7 Grass, Shrubs And Trees	7	3	34	32
8 Forest	5	2	41	12
TOTAL	**82**	**129**	**2,658**	**2,701**

maps comparing each vegetative cover class for each period are included.

Unvegetated (Class 1)

The total area classified as Unvegetated decreased by 38 acres (6.3%) from 1938 to 1987, indicating a net increase in vegetative cover for the dunes complex over that period. The number of polygons doubled, from 10 to 20 (Table 5). The area of the average and largest polygon of this cover type decreased during this period (Table 6). Figure 14 depicts the locations of Unvegetated areas in 1938 and 1987; a trend toward more and smaller areas in 1987 compared with 1938 is obvious. In 1938, the second largest polygon delineated on the dunes complex (444 acres) was classified as Unvegetated. The largest polygon classified in 1938 (926 acres) had Continuous Grass cover. By 1987 this situation was reversed. A 355 acre Unvegetated area was the largest polygon, followed by a 185 acre area of Continuous Grass.

Locations of increased Unvegetated land included:

- A number of small areas on the interior of the dunes complex in 1987;
- The Unvegetated area in the vicinity of the dune climb on the west-central edge of the dunes complex expanded. Unvegetated land appeared to occupy a substantial area that was Discontinuous Grass (Class 3) in 1938.

TABLE 6

Acreage of Average, Minimum, and Maximum Polygons for Each Class: 1938 and 1987

	1938			1987		
CLASS	**AVERAGE**	**MINIMUM**	**MAXIMUM**	**AVERAGE**	**MINIMUM**	**MAXIMUM**
1 Unvegetated	60	4	444	28	3	355
2 Barren with Isolated Plants	7	4	13	4	3	7
3 Discontinuous Grass	33	3	168	18	3	157
4 Continuous Grass	122	3	926	33	3	185
5 Grass and Partial Shrubs	10	3	51	23	3	127
6 Grass and Dense Shrubs	14	4	37	7	3	18
7 Grass, Shrubs, and Trees	5	3	7	11	3	23
8 Forest	8	3	16	6	3	9

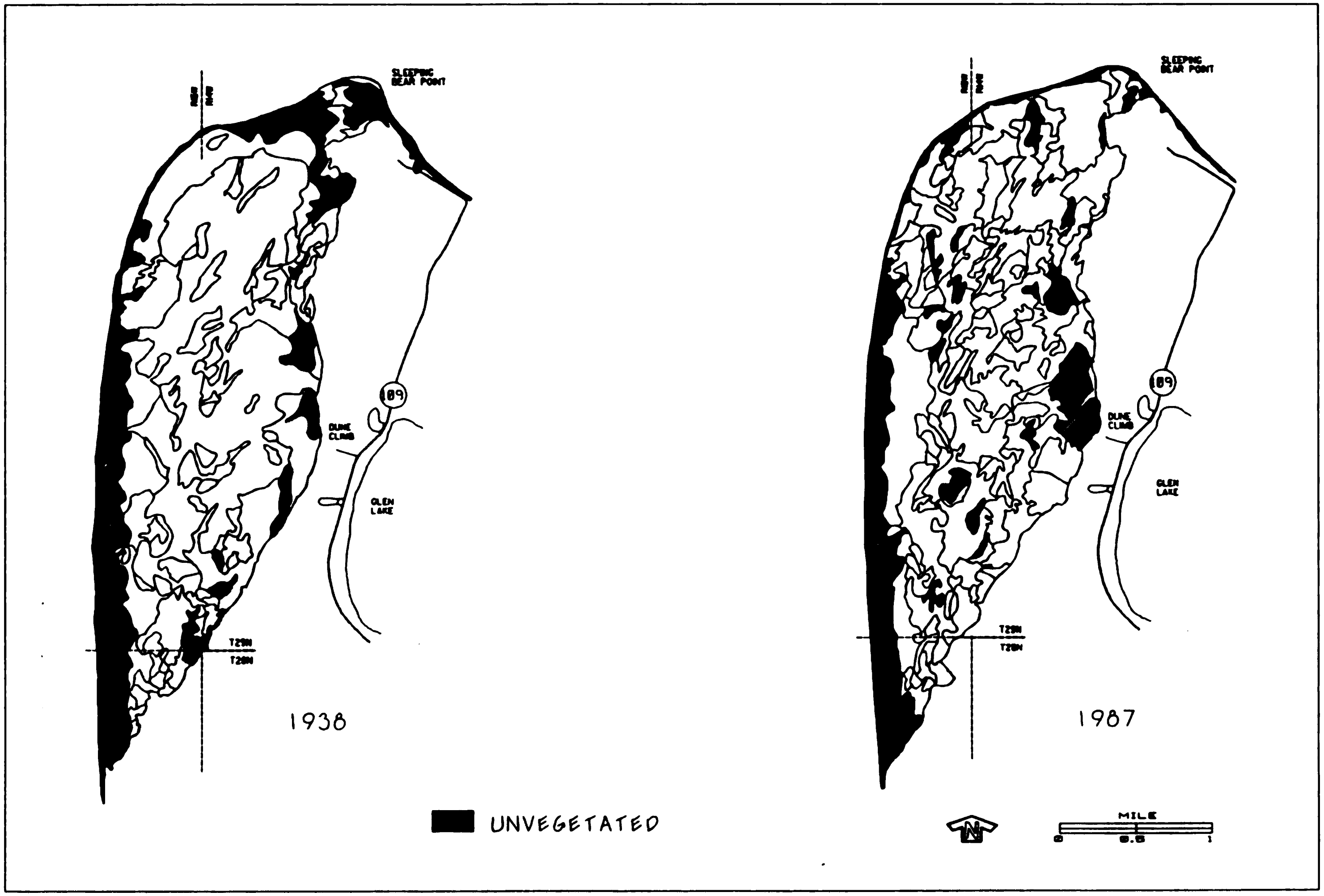


Figure 14 Map Comparing Unvegetated (Class 1): 1938 and 1987

Locations of decreased Unvegetated land included the following:

- At the northern end of the dunes complex, a fairly large area that was Unvegetated in 1938 was classified as Discontinuous Grass (Class 3) in 1987.
- The beach area along the northeastern edge of the dunes complex was much narrower in 1987 than it was in 1938.
- The Unvegetated area extending along the western edge of the dunes complex including the bluffs, was somewhat narrower in 1987 than it was in 1938.

In summary, a decrease in the total area classified as Unvegetated (Class 1) occurred from 1938 to 1987, but more and smaller Unvegetated areas developed over this period.

Barren with Isolated Plants (Class 2)

The area delineated as Barren with Isolated Plants decreased by 13 acres (45%) but the number of polygons did not change (Table 5). The area of the average- and maximum-sized polygon for this class decreased (Table 6).

An examination of the maps contained in Figure 15 shows a change in the location of areas classified as Barren with Isolated Plants, except for an area of this cover type that appeared on Sleeping Bear Point in both periods.

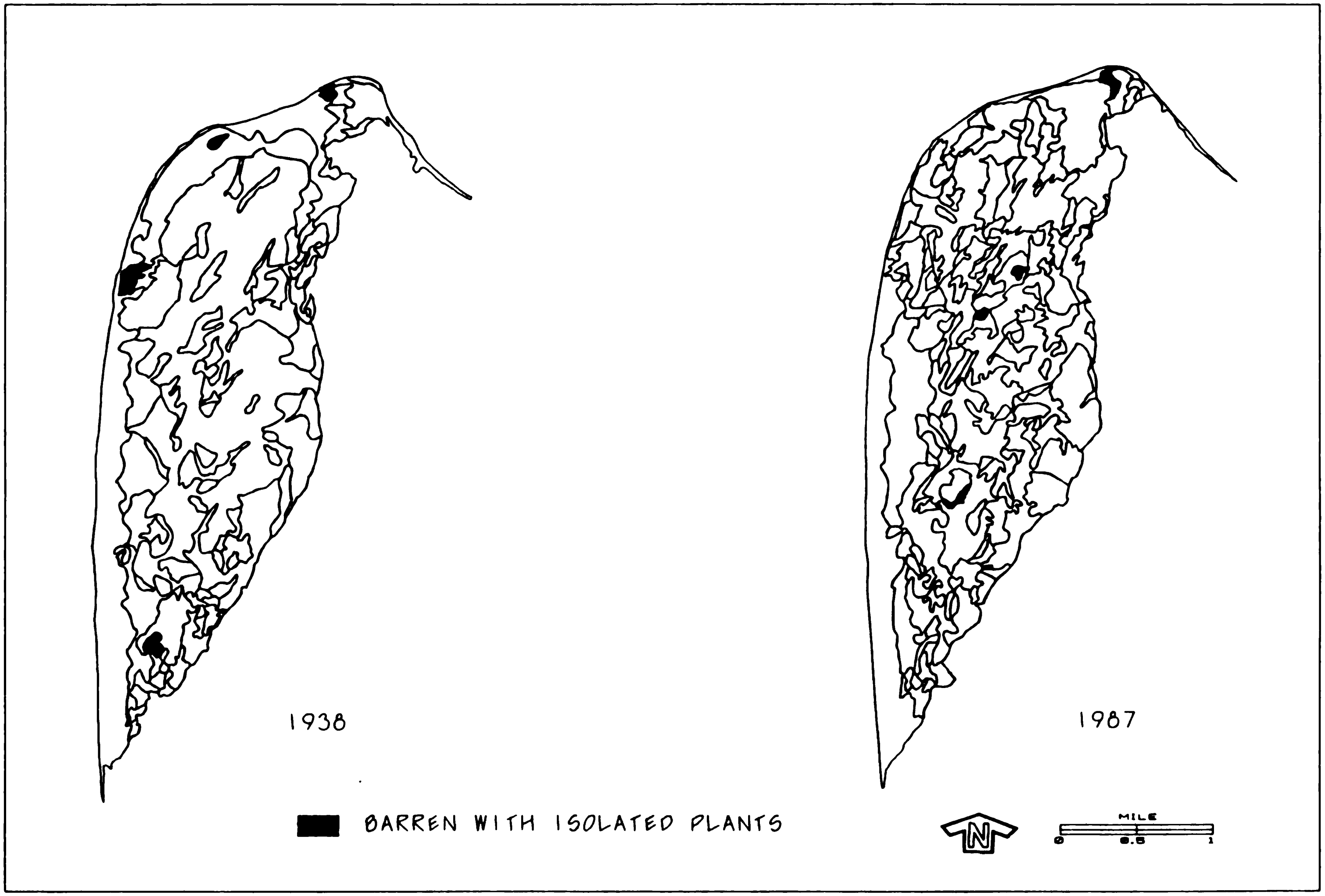


Figure 15 Map Comparing Barren with Isolated Plants (Class 2): 1938 and 1987

Discontinuous Grass (Class 3)

Between 1938 and 1987, the area delineated as Discontinuous Grass increased by 77 acres (11%) and the number of polygons increased 105%, from 21 to 43 (Table 5). The average and largest area of this cover type decreased. These values suggest an increase in area of this cover type accompanied by fragmentation of the larger polygons.

An examination of Figure 16 supports this conclusion. In 1938, several large areas of Discontinuous Grass extended along the western boundary of the dunes complex, just inland from the Unvegetated bluffs and beaches. Large areas were also mapped on the eastern edge of the southern and central dunes complex. On the 1987 map, areas of Discontinuous Grass were smaller and more dispersed across the dunes complex compared to 1938.

It appears that in some places fragmentation of large areas of Discontinuous Grass occurred, but there are also places where smaller areas of this cover type expanded during this period. The following list describes areas where fragmentation occurred:

- The large area of Discontinuous Grass along the northwest edge of the dunes complex in 1938 was fragmented into smaller areas of Discontinuous Grass, and areas of Continuous Grass (Class 4), Grass and Partial Shrubs (Class 5) and Unvegetated (Class 1) by 1987.

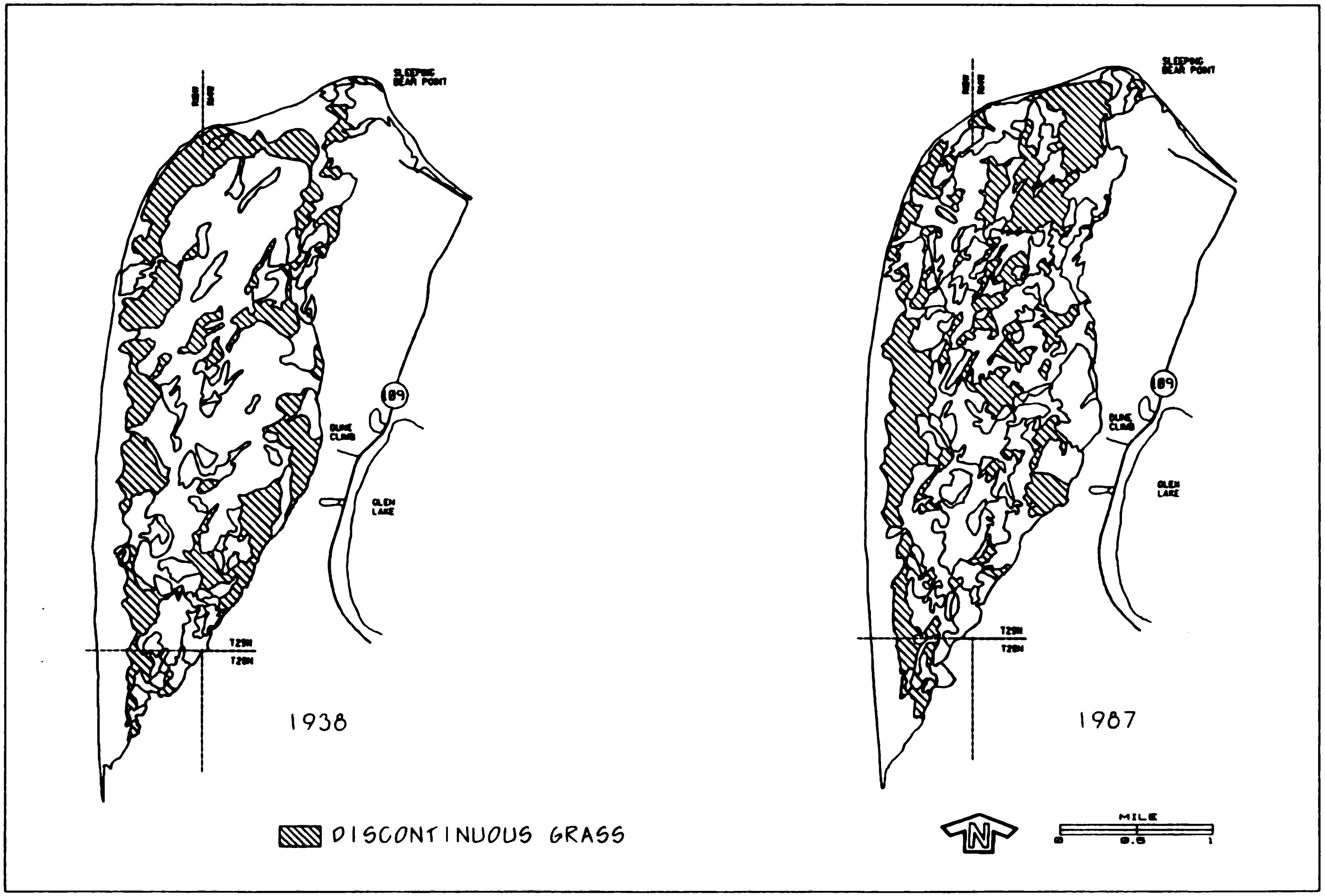


Figure 16 Map Comparing Discontinuous Grass (Class 3): 1938 and 1987

- In 1938, a few medium-sized areas of Discontinuous Grass were located on the central interior of the dunes complex. By 1987, the central interior had numerous smaller areas of Discontinuous Grass.
- The large area of Discontinuous Grass along the central eastern edge of the dunes complex (the dune climb area) in 1938 was considerably smaller in 1987 and the surrounding area was Unvegetated.
- The large area of Discontinuous Grass located just south of the dune climb area in 1938 had decreased in size by 1987 and was basically surrounded by Continuous Grass (Class 4).

As suggested in the above list, some large areas of Discontinuous Grass in 1938 were broken up into smaller areas of the same and other cover types by 1987. Some of the "new" areas in 1987 had higher biomass cover types, while others had less vegetative cover.

The following list describes areas where small polygons in 1938 appeared to expand into larger areas by 1987:

- In 1938, several disconnected, fairly large polygons of Discontinuous Grass extended along the western edge of the dunes complex. By 1987, there was one large area along the west central edge of the dunes complex, and it appears that the disconnected areas in 1938 had become "connected" by 1987.
- At the northern edge of the dunes complex, there was a large area of Discontinuous Grass in 1987 that was

mostly Unvegetated in 1938. Although a few small areas of Discontinuous Grass were there in 1938, it appears that this cover type expanded in this area. In summary, Discontinuous Grass cover increased both in acreage and in the number of polygons on the dunes complex between 1938 and 1987. Both fragmentation of large areas and expansion of small areas of Discontinuous Grass occurred during this period.

Continuous Grass (Class 4)

Between 1938 and 1987, the area interpreted as Continuous Grass decreased by 283 acres (29.5%) but the number of polygons increased from 8 to 21 (Table 5). The size of the average and maximum area decreased from 1938 to 1987 for this cover type. These values suggest possible fragmentation of larger areas of Continuous Grass over this period.

This trend is evident in Figure 17. In 1938, the largest area mapped was the 926 acres of Continuous Grass that occupied most of the interior of the dunes complex. In 1987, the largest area of Continuous Grass was also on the central interior of the dunes complex but obviously covering a much smaller area (182 acres).

The maps in Figure 17 show an expansion of a small area of Continuous Grass on the northern dunes complex in 1938 into a larger area by 1987. Two new areas of Continuous Grass appeared in 1987. They were located just south of

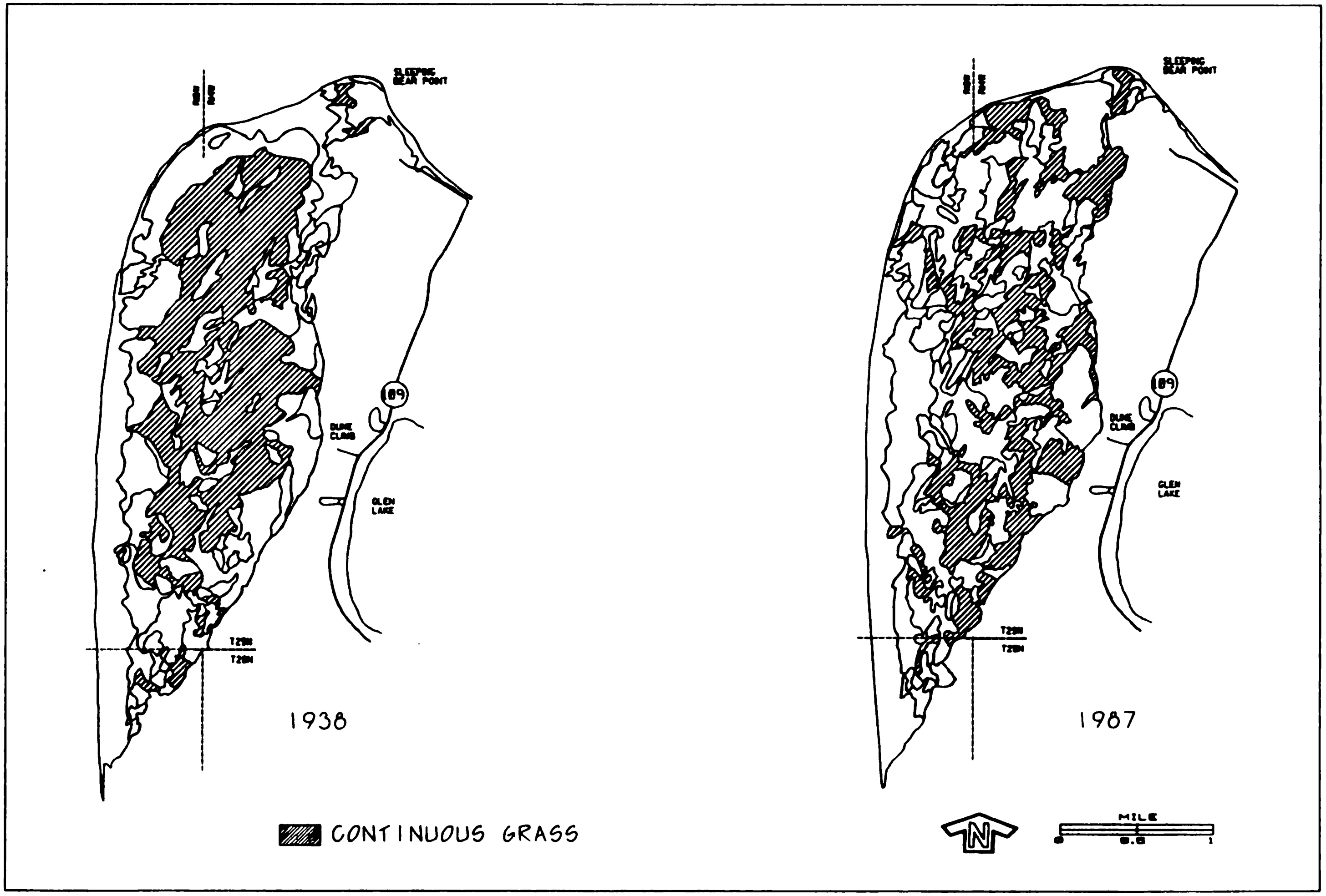


Figure 17 Map Comparing Continuous Grass (Class 4): 1938 and 1987

Sleeping Bear Point, one on the eastern edge of the dunes complex, the other inland from the northwestern lake shore.

In summary, the total area of Discontinuous Grass decreased from 1938 to 1987, the result of fragmentation of what was a very large area in 1938. However, new areas of Continuous Grass cover were identified on the northern portion of the dunes complex.

Grass and Partial Shrubs (Class 5)

Between 1938 and 1987, the amount of acreage classified as Grass and Partial Shrubs increased by 318 acres (136%), but the number of polygons was almost unchanged (Table 5). The size of the average and maximum area of this cover type increased. These values suggest that expansion of smaller areas of this cover type may have occurred.

An examination of Figure 18 indicates that in 1938 the largest area of Grass and Partial Shrubs occurred in the southern part of the dunes complex, with scattered areas on the central dunes complex. In 1987, there were many more and larger areas of this cover type, with apparent expansion of the areas that existed on the southern and central parts of the dunes complex in 1938. Significant areas of Grass and Partial Shrubs existed inland along the northwest edge of the dunes complex in 1987; this area was classified as mostly Discontinuous or Continuous Grass (Classes 3 or 4) in 1938.

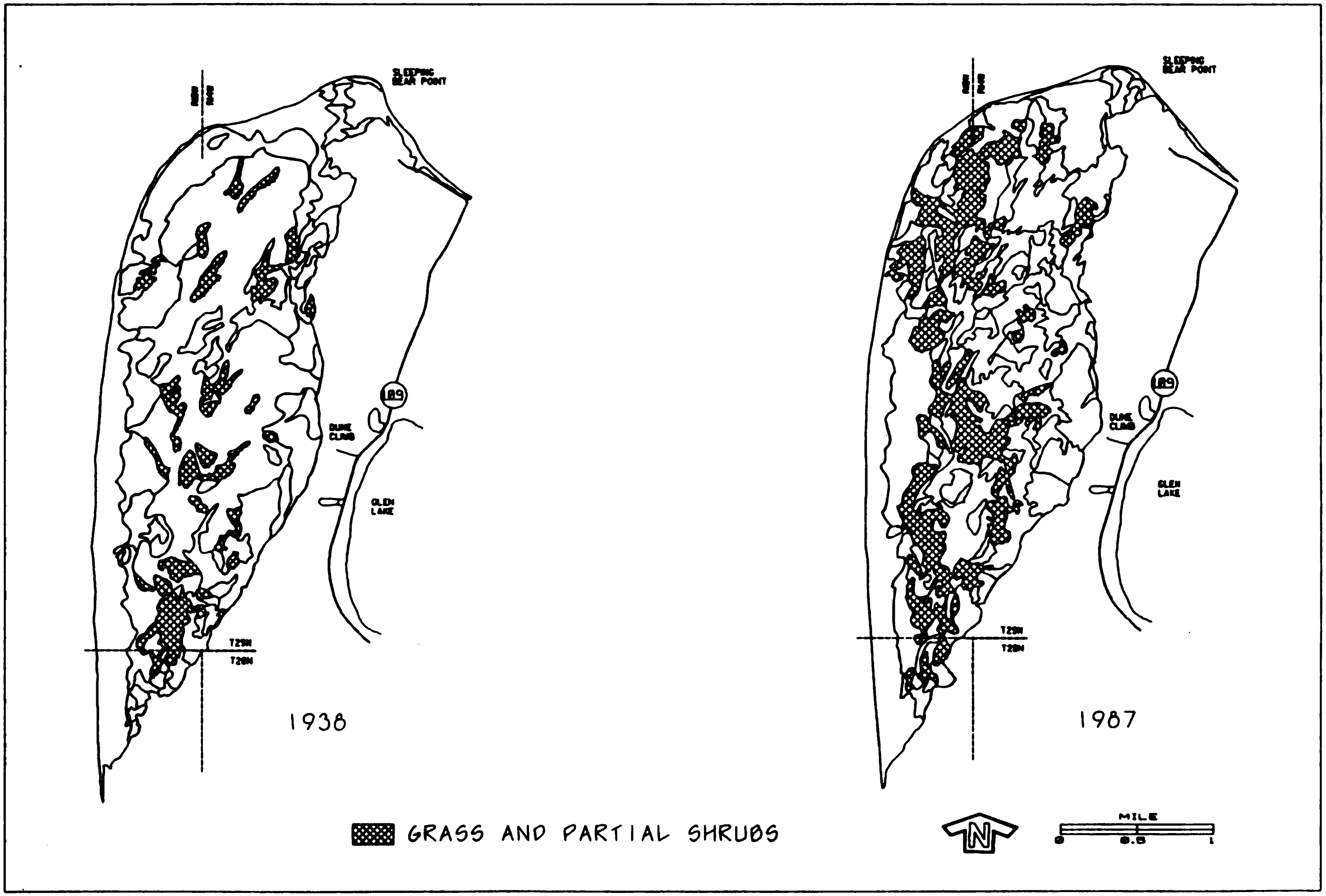


Figure 18 Map Comparing Grass and Partial Shrubs (Class 5): 1938 and 1987

In summary, the amount of area identified as Grass and Partial Shrubs increased significantly between 1938 and 1987. The increase appears to have occurred by expansion of areas having this cover type in 1938, and by invasion of shrubs into areas that were classified as Discontinuous or Continuous Grass in 1938.

Grass and Dense Shrubs (Class 6)

Between 1938 and 1987 the area classified as Grass and Dense Shrubs increased by 13 acres (22%) and the number of polygons increased from 4 to 10. The size of the average, minimum, and maximum areas of this cover type all decreased from 1938 to 1987. These values suggest that a fragmentation of areas with this cover type may have occurred, accompanied by an increase in total acreage.

Figure 19 indicates a change in the location of areas with this cover type, as opposed to fragmentation or expansion of areas existing in 1938. The large area on the southwestern edge of the dunes complex in 1938 was absent in 1987. Several small areas of Grass and Dense Shrubs were scattered across the dunes complex in 1987, but they appeared to be locationally unrelated to the areas of this cover type in 1938.

In summary, the location of areas of Grass and Dense Shrubs changed from 1938 to 1987, and there was a slight increase in acreage of this cover type. Areas with dense

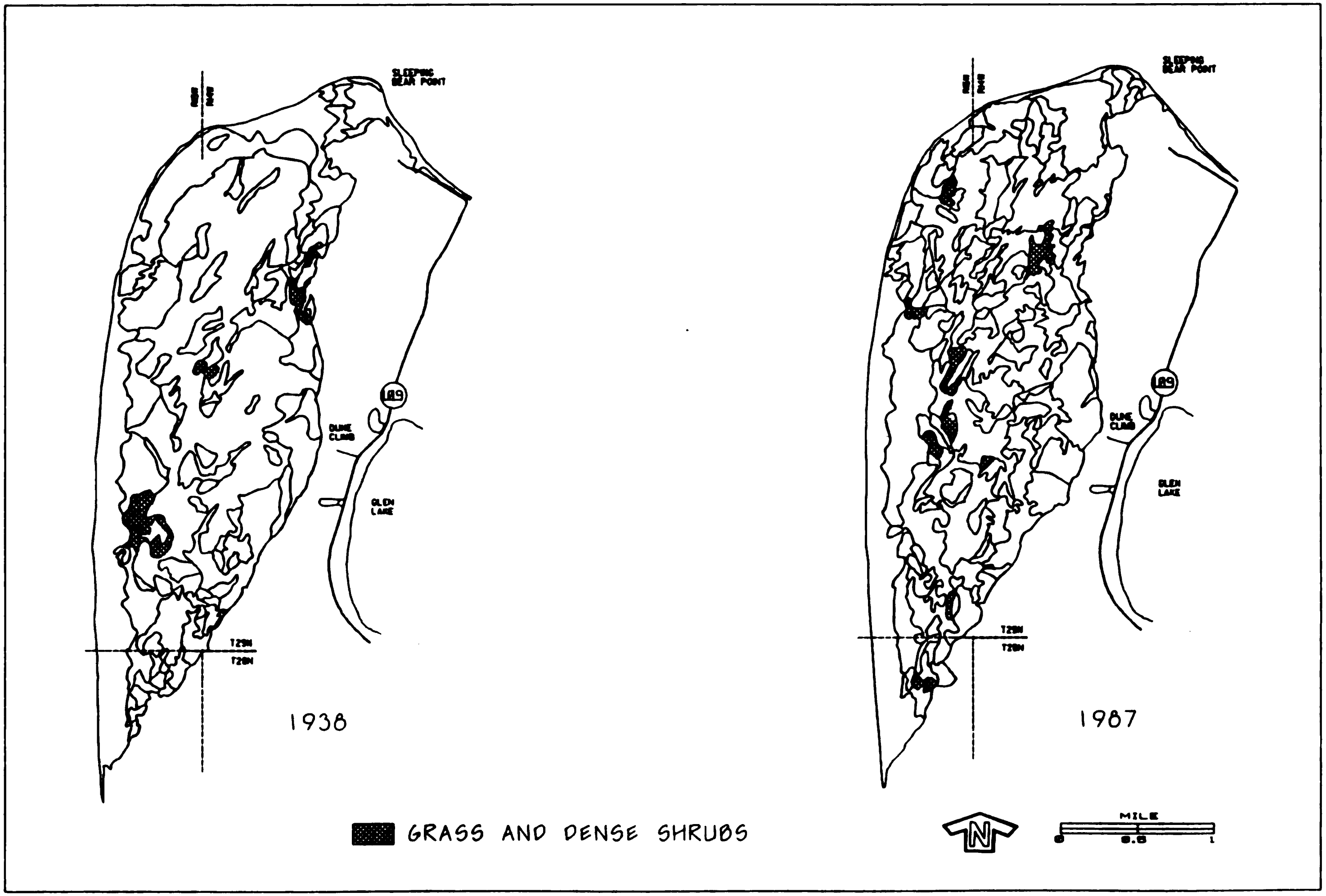


Figure 19 Map Comparing Grass and Dense Shrubs (Class 6): 1938 and 1987

shrub cover may indicate a stabilized area with little sand movement.

Grass, Shrubs and Trees (Class 7)

Between 1938 and 1987, the area classified as Grass, Shrubs and Trees decreased by 2 acres (6%) and the number of polygons decreased from 7 to 3. The size of the average and maximum areas of this cover type increased from 1938 to 1987. Although this cover type is not prevalent on the dunes complex, these values suggest larger areas existed in 1987 than in 1938.

Examination of Figure 20 indicates a fairly large area of Grass, Shrubs and Trees along the eastern edge of the central dunes complex in 1987. Part of this area was mapped as Forest (Class 8) in 1938, indicating a net loss of some trees during this period. The most common tree species on the dunes complex is cottonwood. The loss of trees in this area could be the result of older cottonwood trees dying and being replaced by shrubs. The loss of trees could also be a result of increased sand movement in the area.

Several small areas of this cover type occurring on the southern dunes complex in 1938 were mapped as Grass and Partial Shrubs (Class 5) or Grass and Dense Shrubs (Class 6) in 1987 again indicating a net loss of some trees.

In summary, this class of vegetative cover accounted for very little of the total cover on the dunes complex. There was a loss of some trees in some area on the dunes

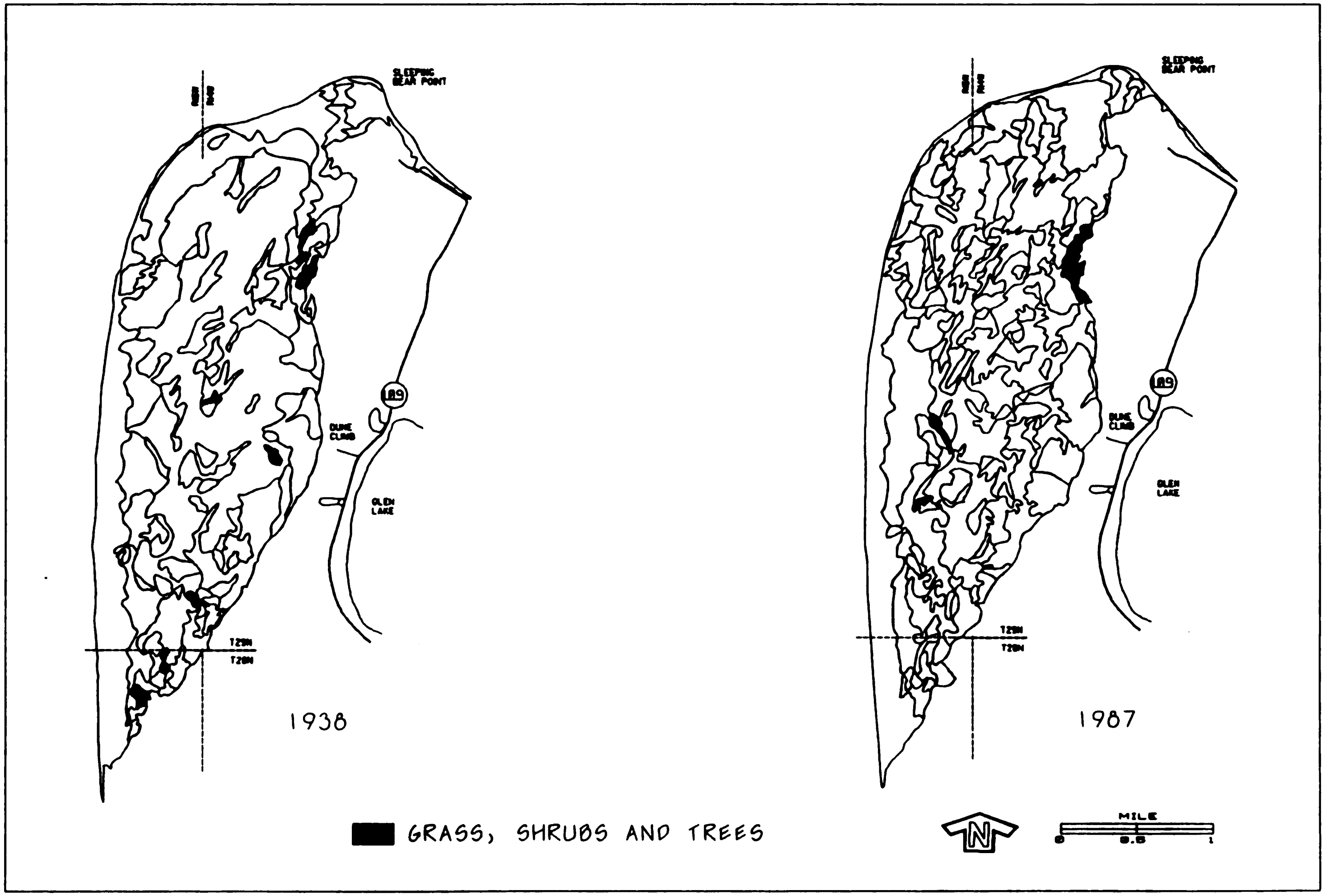


Figure 20 Map Comparing Grass, Shrubs and Trees (Class 7): 1938 and 1987

complex and other areas had an increase in trees, but the total acreage changed only slightly during this period.

Forest (Class 8)

Between 1938 and 1987, the area mapped as Forest decreased by 29 acres (71%), and the number of polygons decreased from 5 to 2 (Table 5). The acreage of the average and maximum polygons also declined (Table 6). These values suggest an overall loss of Forest cover, with only 2 small areas remaining in 1987.

Examination of the Figure 21 maps indicate that these two remaining areas were located on the southern part of the dunes complex. One appeared to be a small remnant of a larger area in 1938, the other was located just east of a what was a small area of forest in 1938.

The areas mapped as Forest in 1938 that were not identified as Forest on the 1987 map were included in areas of Discontinuous Grass (Class 3) and Grass and Partial Shrubs (Class 5) on the 1987 map (Figure 13). As discussed in the previous section, loss of some trees appears to have occurred on the dunes complex during this period, but the forest cover type accounted for a very small percentage of the total cover in both periods.

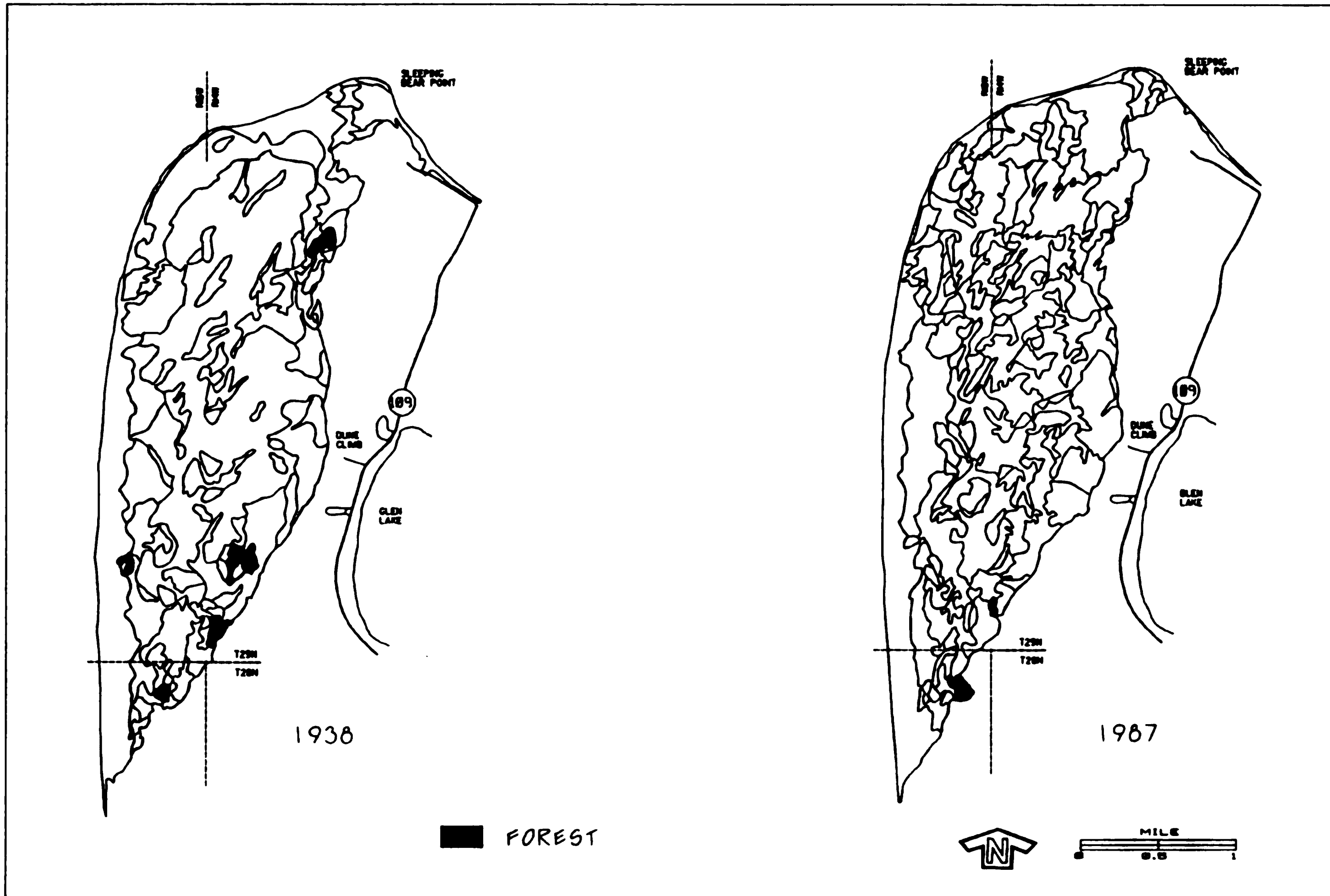


Figure 21 Map Comapring Forest (Class 8): 1938 and 1987

Comparison Between 1938, 1973 and 1987 (Six Classes)

General Discussion

Due to the small scale (1:40,000) of the 1973 imagery, I used the six-class version of the vegetative cover classification system to interpret this imagery. To compare among the three periods, it was necessary to collapse the eight-class interpretation of the 1938 and 1987 imagery into a six-class interpretation. This was accomplished by replacing the vegetative cover class number of each polygon with the new vegetative cover class number, based on six categories. Shared boundaries between polygons having the same label were removed.

The purpose of including a third period in this temporal analysis was to give a sense of the process of change. By looking at just "beginning" and "ending" data, it could be mistakenly inferred that the process has been consistent and the possible changes indicated have been occurring throughout the whole period. This error can be reduced by incorporating data from an intermediate point in time.

The changes that have occurred between 1938 and 1987 (previous section) will be basically the same, whether one classifies the cover into six or eight categories. The point of the following discussion is to gain an understanding of the changes that occurred between 1938 and 1973, and between 1973 and 1987. Maps of the photo-interpreted vegetative cover on the Sleeping Bear Dunes complex for 1938, 1973, and 1987 are contained in Figures 22, 23, and 24, respectively.

The map for 1938 (Figure 22) of six vegetative classes is very similar to the eight-class map (Figure 12) and was described in the previous section. Obvious changes from 1938 (Figure 22) to 1973 (Figure 23) included:

- an increase in the amount of area classified as Grass and Shrubs (Class 4);
- fragmentation by 1973 of the large area mapped as Continuous Grass on the interior of the dunes complex in 1938;
- an increase in areas of Unvegetated land on the eastern part of the dunes complex; and
- narrowing of the Unvegetated area along the Lake Michigan shoreline.

These observations suggest that processes resulting in vegetative cover change were fairly active during this period.

A comparison of the 1973 map (Figure 23) with the 1987 map (Figure 24) indicates the following changes:

- continued fragmentation of larger areas of vegetative cover;
- a decrease in the areas of Unvegetated land on the eastern edge of the dunes complex; and
- widening of the Unvegetated areas of bluffs and beaches along the Lake Michigan shoreline.

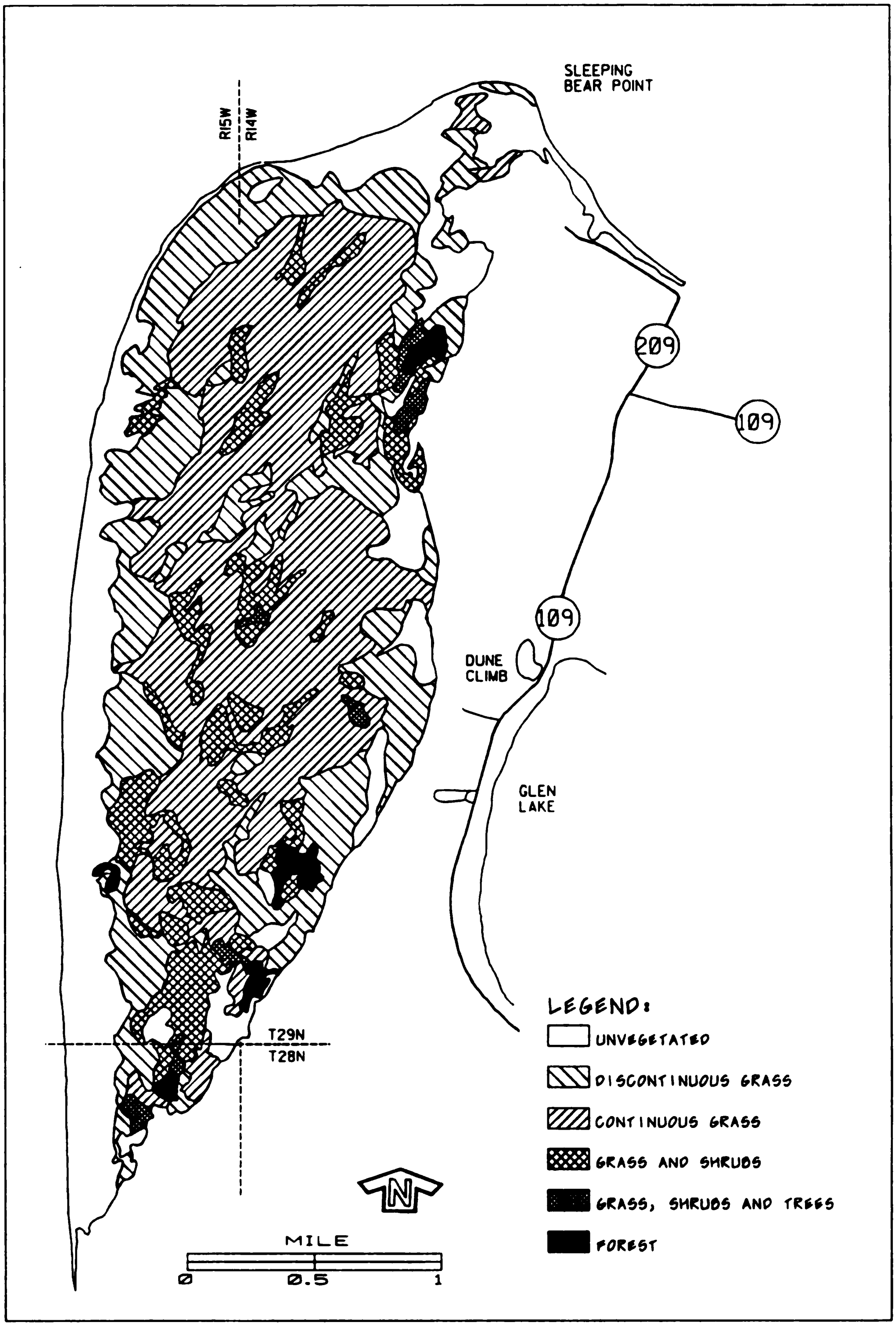


Figure 22 Vegetative Cover Map for 1938 (6 Classes)

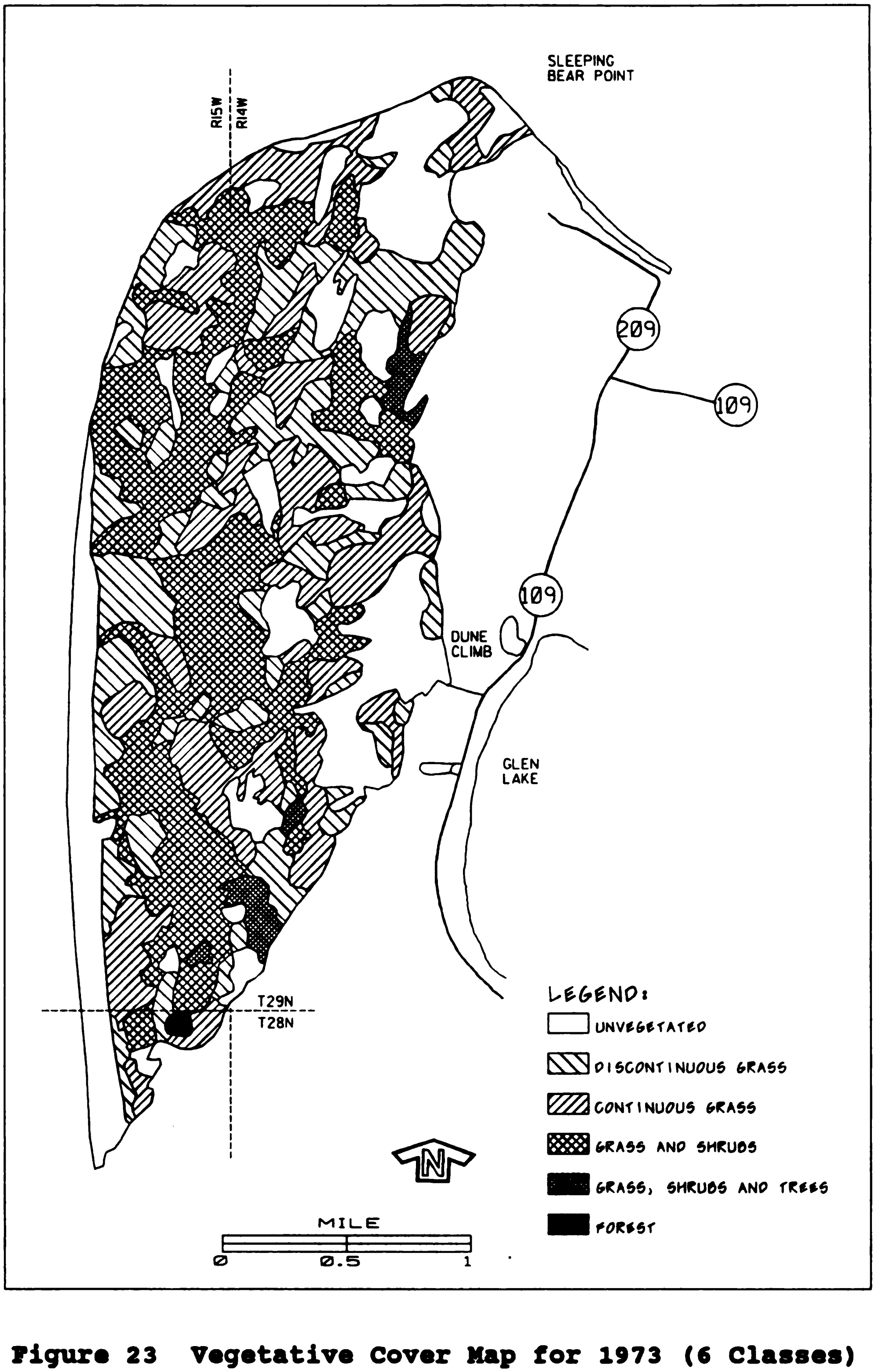


Figure 23 Vegetative Cover Map for 1973 (6 Classes)

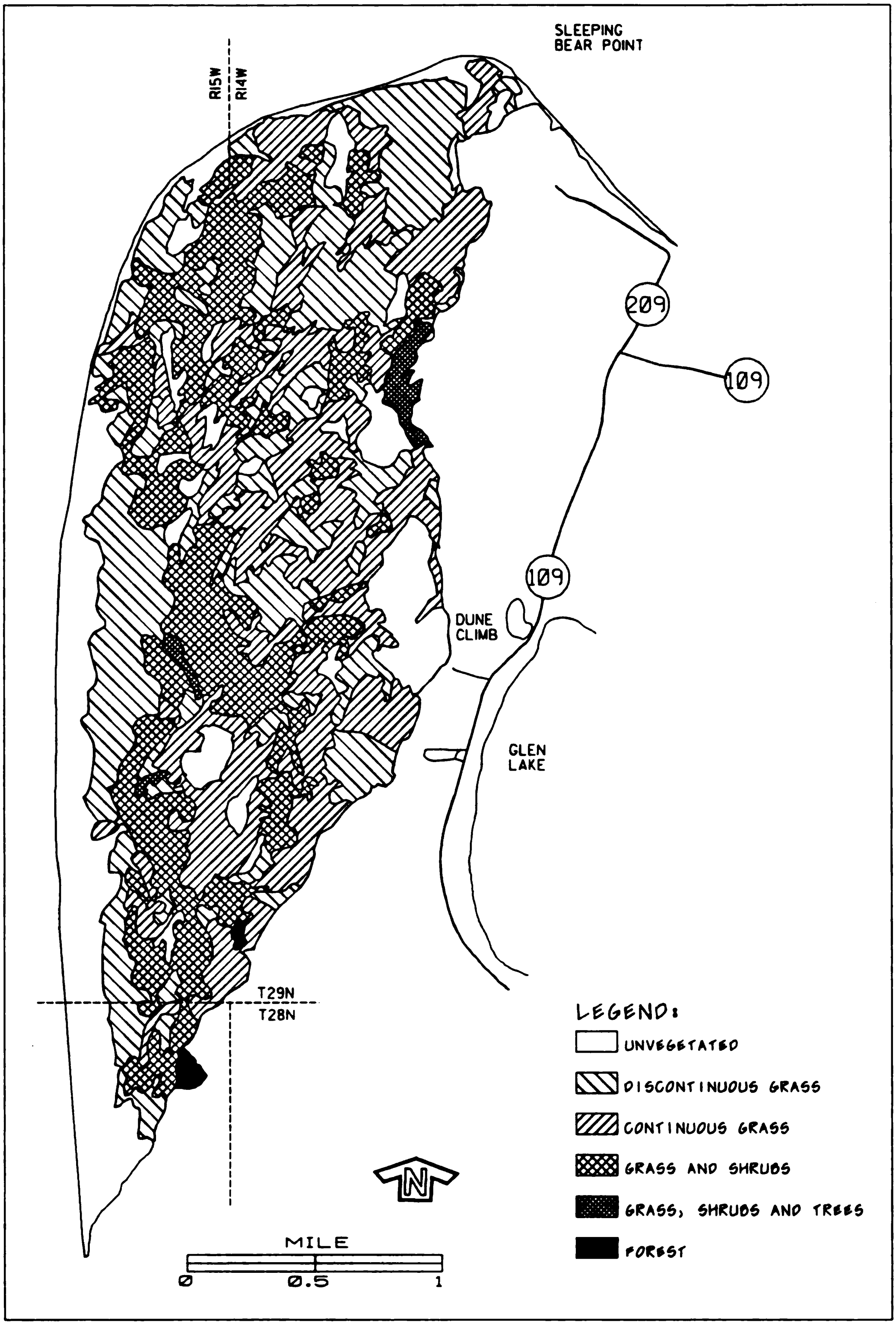


Figure 24 Vegetative Cover Map for 1987 (6 Classes)

These observations indicate that some changes that occurred from 1938 to 1987 continued throughout the period, while other changes were not continuous.

The total number of polygons and total acreage mapped for 1938 and 1987 are contained in Table 7. The total acreage mapped for 1973 was 56 acres (2.1%) less than the total mapped for 1938 and 101 acres (3.8%) less than that for 1987. As discussed in the previous section, these relatively slight differences in total area could have originated during the digitization process, or they may indicate an actual change in the size of the dunes complex. Although the margin of error introduced during digitization is a possible explanation for the difference in total area, other explanations are possible. In 1971 a landslide occurred on Sleeping Bear Point and approximately 20 acres fell into Lake Michigan. This event could account for some of the loss in acreage mapped between 1938 and 1973. Also, Lake Michigan water levels were quite high during the 1970s and early 1980s. Bluff erosion, which often accompanies high lake levels (Buckler and Winters, 1983), may have resulted in a loss of beach and bluff areas from 1973 to 1987.

The increase in the number of polygons from 1938 to 1987 appears to have been a process that took place throughout the period based on the 1973 data (Table 7). Although the increase was continuous, the rate of increase was higher from 1973 to 1987 (18 more polygons

TABLE 7

Total Number of Polygons and Total Acreage For Each Class: 1938, 1973 and 1987

	Total Number of Polygons			Total Acreage		
CLASS	**1938**	**1973**	**1987**	**1938**	**1973**	**1987**
1 Unvegetated	11	26	22	630	661	573
2 Discontinuous Grass	20	37	44	688	544	771
3 Continuous Grass	8	20	22	971	577	688
4 Grass and Shrubs	26	9	22	293	764	629
5 Grass, Shrubs, and Trees	7	4	3	34	50	32
6 Forest	5	1	2	41	5	9
TOTAL	**77**	**97**	**115**	**2,657**	**2,601**	**2,702**

in 14 years) than from 1938 to 1973 (20 polygons in 35 years).

The following discussion compares the changes for each of the six vegetative classes for each period: 1938 to 1973, 1973 to 1987, and 1938 to 1987.

Unvegetated (Class 1)

1938 to 1973.--The number of polygons of Unvegetated land increased by 136% and the acreage increased by 5% (31 acres) during this period (Table 7). The acreage of both the average and largest polygon for this class decreased (Table 8). These values indicate a small increase in total Unvegetated area. The increase in area was accompanied by a large increase in the number of polygons, but a decrease in the average size of these areas.

The data shown in Figure 25 support these observations. The increase in the number of polygons is apparent. Several Unvegetated areas were delineated on the interior of the central dunes complex in 1973 that were absent in 1938. The amount of Unvegetated land around the Dune Climb area expanded greatly between 1938 and 1973. This could be an indication of the increased recreational use of the dunes complex that occurred during this time period.

Another noticeable change in this cover class was the narrowing of the strip of Unvegetated bluffs and beach along the western edge of the dunes complex from 1938 to 1973. This strip was not continuous along the whole shoreline in

TABLE 8

Acreage of Average, Minimum, and Maximum Polygons for Each Class: 1938, 1973, and 1987

	1938			1973			1987		
CLASS	AVG	MIN	MAX	AVG	MIN	MAX	AVG	MIN	MAX
1 Unvegetated	57	4	519	25	3	172	26	3	360
2 Discontinuous Grass	34	3	168	15	3	82	18	3	157
3 Continuous Grass	121	3	926	29	4	68	31	3	179
4 Grass and Shrubs	11	3	51	85	5	402	28	3	132
5 Grass, Shrubs, and Trees	5	3	7	13	5	23	11	3	23
6 Forest	8	3	16	5	5	5	4	3	7

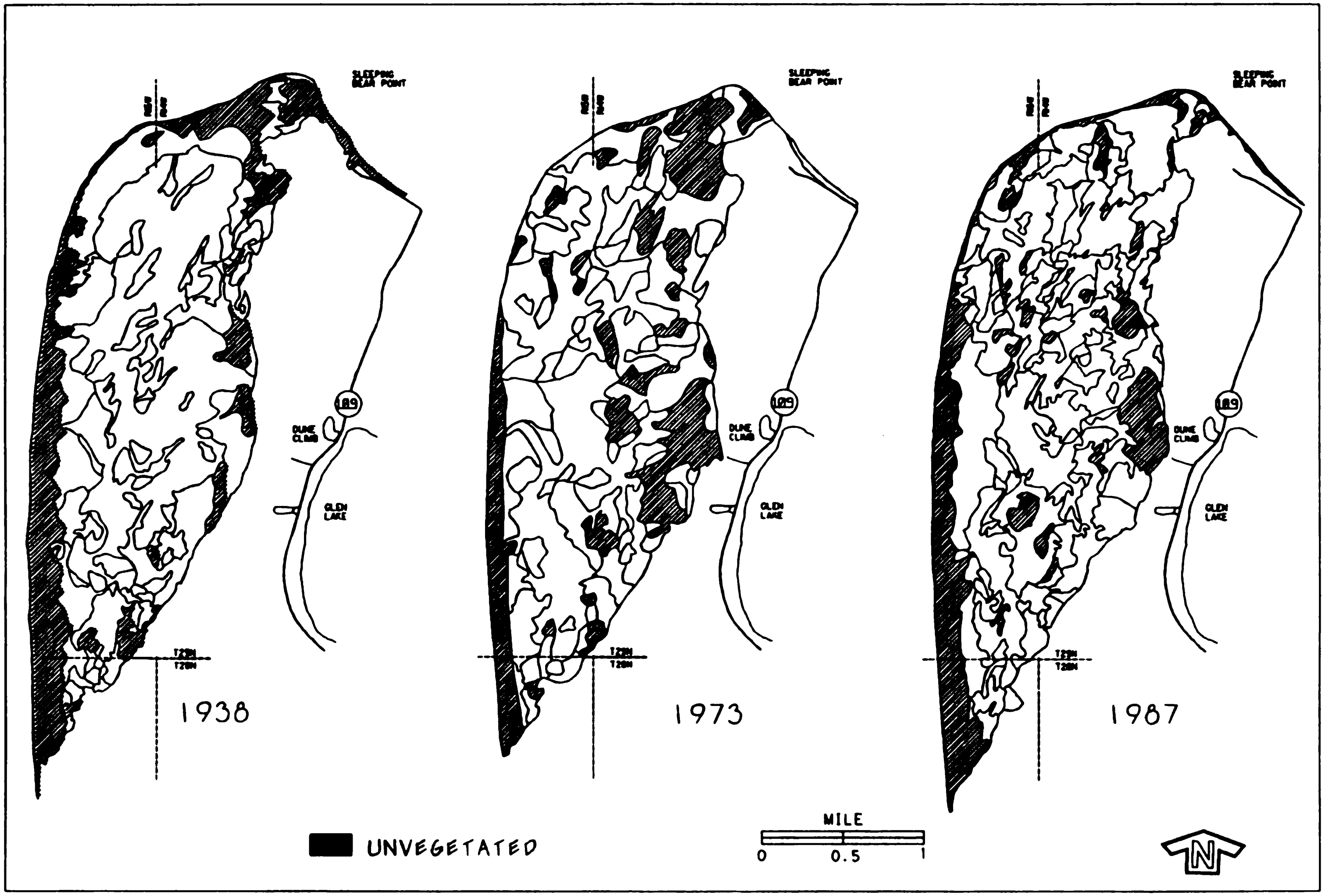


Figure 25 Map Comparing Unvegetated (Class 1): 1938, 1973, 1987

1973 as it was in 1938. The Unvegetated area ended about two thirds of the way up the shoreline in 1973, and the next Unvegetated area along the shoreline occurred on Sleeping Bear Point.

An examination of Sleeping Bear Point indicates a noticeable change in the shape of the shoreline from 1938 to 1973. This may be partly the result of the 1971 landslide.

1973 to 1987.--During this period, the acreage classified as Unvegetated decreased 13% (a loss of 88 acres) and the number of polygons decreased 15% (Table 7). The size of the average and minimum areas Unvegetated land were unchanged, but the maximum area increased (Table 8).

The following list describes some of the more obvious changes that occurred to Unvegetated land during this period.

- The western shoreline was once again a continuous Unvegetated area in 1987.
- A large area on Sleeping Bear Point that was mapped as Unvegetated in 1973 was mapped as mostly Discontinuous Grass (Class 3) in 1987.
- The Unvegetated area in the vicinity of the Dune Climb had decreased in size by 1987 and was surrounded by areas of Discontinuous and Continuous Grass (Classes 2 and 3).
- There were more and smaller Unvegetated areas in the interior of the dunes complex in 1987 than there were in 1973.

- There were fewer Unvegetated areas of on the southern dunes complex.

In summary, the total acreage of Unvegetated land on the dunes complex decreased from 1973 to 1987 accompanied by a decrease in the number of Unvegetated areas. This indicates a net increase in the amount of vegetative cover on the dunes complex during this period.

1938 to 1987.--The trend of increased fragmentation that occurred from 1938 to 1973 appeared to be somewhat slowed from 1973 to 1987. In comparing just 1938 and 1987, the number of polygons doubled and a decrease of 57 acres in land classified as Unvegetated occurred. There were more but smaller areas of Unvegetated land in 1987 than in 1938. There was a larger Unvegetated area in the vicinity of the Dune Climb in 1987 than there was in 1938, but when compared with the 1973 map the trend toward increased Unvegetated land in this area appeared to be reversing.

Discontinuous Grass (Class 2)

1938 to 1973.--The acreage mapped as Discontinuous Grass decreased by 21% (144 acres) but the number of polygons of this cover type increased by 85% (20 to 37) during this period. The average and maximum areas also decreased. In addition to a loss of acreage, these values suggest a trend toward more and smaller areas of Discontinuous Grass on the dunes complex.

A comparison of the 1938 vegetative cover map (Figure 22) and the 1987 vegetative cover map (Figure 23) indicates that some areas mapped as Discontinuous Grass in 1938 were mapped as higher biomass cover types (Continuous Grass or Grass and Shrubs) in 1987 and other areas were mapped as Unvegetated in 1987.

Figure 26 indicates that large areas along the western lakeshore and on the southern dunes complex mapped as Discontinuous Grass for 1938 were mapped as much smaller areas for 1973. In 1973, many of these smaller fragments were surrounded by areas of Continuous Grass (Class 3) and Grass and Shrubs (Class 4) suggesting indicating a gain in vegetative cover. Areas around the Dune Climb that were classified as Discontinuous Grass in 1938 were Unvegetated in 1973 suggesting a loss of vegetative cover.

An increase in areas identified as Discontinuous Grass occurred on the northern part of the dunes complex. A small area along the eastern edge in 1938 had expanded westward onto the dunes complex by 1973. There was also an increase in the number of areas of Discontinuous Grass on the interior of the dunes complex during this period.

1973 to 1987.--During this period, the trend toward an increased number of polygons of Discontinuous Grass continued, but the trend of decreasing acreage was reversed. There was a 42% increase (227 acres) in acreage mapped as Discontinuous Grass from 1973 to 1987 (Table 7). The size of the average area increased slightly and the size of the

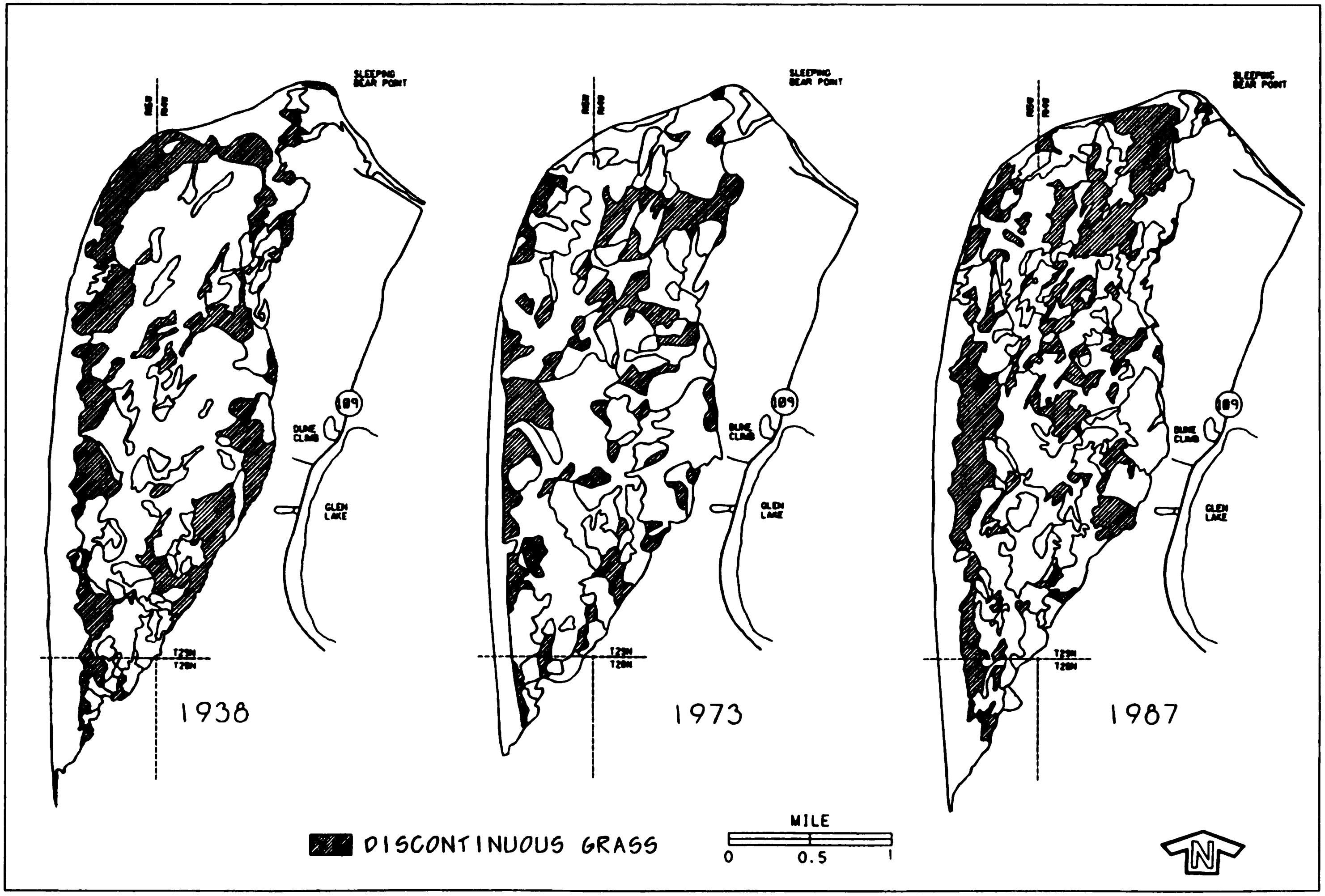


Figure 26 Map Comparing Discontinuous Grass (Class 2): 1938, 1973 and 1987

maximum area increased by 91% (75 acres) from 1973 to 1987.

Figure 26 depicts the locations of areas of Discontinuous Grass during this period; the increased number of areas from 1973 to 1987 is apparent. An increase from 1973 to 1987 in areas mapped as Discontinuous Grass occurred on the northern dunes complex, on the interior of the dunes complex, and in the Dune Climb area.

1938 to 1987.--During this period, the number of polygons of Discontinuous Grass increased by 120% and the acreage increased by 12% (83 acres). The acreage of the average and maximum area decreased slightly from 1938 to 1987. The trend was toward increasing number of smaller areas of this cover type.

The trend of increasing numbers of areas identified as Discontinuous Grass was continuous throughout this period. The trend toward decreasing acreage from 1938 to 1973 was reversed from 1973 to 1987, when an increase in acreage occurred.

A loss of acreage in this cover class does not necessarily mean a loss in vegetative cover. Some of the acreage lost to Discontinuous Grass was identified as Continuous Grass or Grass and Shrubs. An increase in acreage of Discontinuous Grass may be at the expense of higher biomass vegetative cover, or Unvegetated areas may acquire some vegetative cover.

Continuous Grass (Class 3)

1938 to 1973.--As shown in Table 7, the number of areas mapped as Continuous Grass increased by 150% (8 to 20) but the amount of acreage decreased by 41% (394 acres). In 1938, a very large area (926 acres) of Continuous Grass covered most of the interior of the dunes complex. In 1973, the largest continuous area of this cover type was 68 acres.

Figure 27 depicts the change from a very large area of Continuous Grass on the central dunes complex in 1938 to several smaller areas scattered across the dunes complex in 1973. Some of this large area from 1938 was mapped as Grass and Shrubs (Class 4) in 1973. A loss of Continuous Grass to Unvegetated land occurred around the Dune Climb during this period.

Increased acreage or new areas mapped as Continuous Grass in 1973 included the northwestern edge of the dunes complex from the shore inland, on Sleeping Bear Point, and on the southern part of the dunes complex along the bluff edge.

1973 to 1987.--The trend of an increased number of areas of Continuous Grass continued from 1973 to 1987, but the increase was very small (from 20 to 22). The trend of

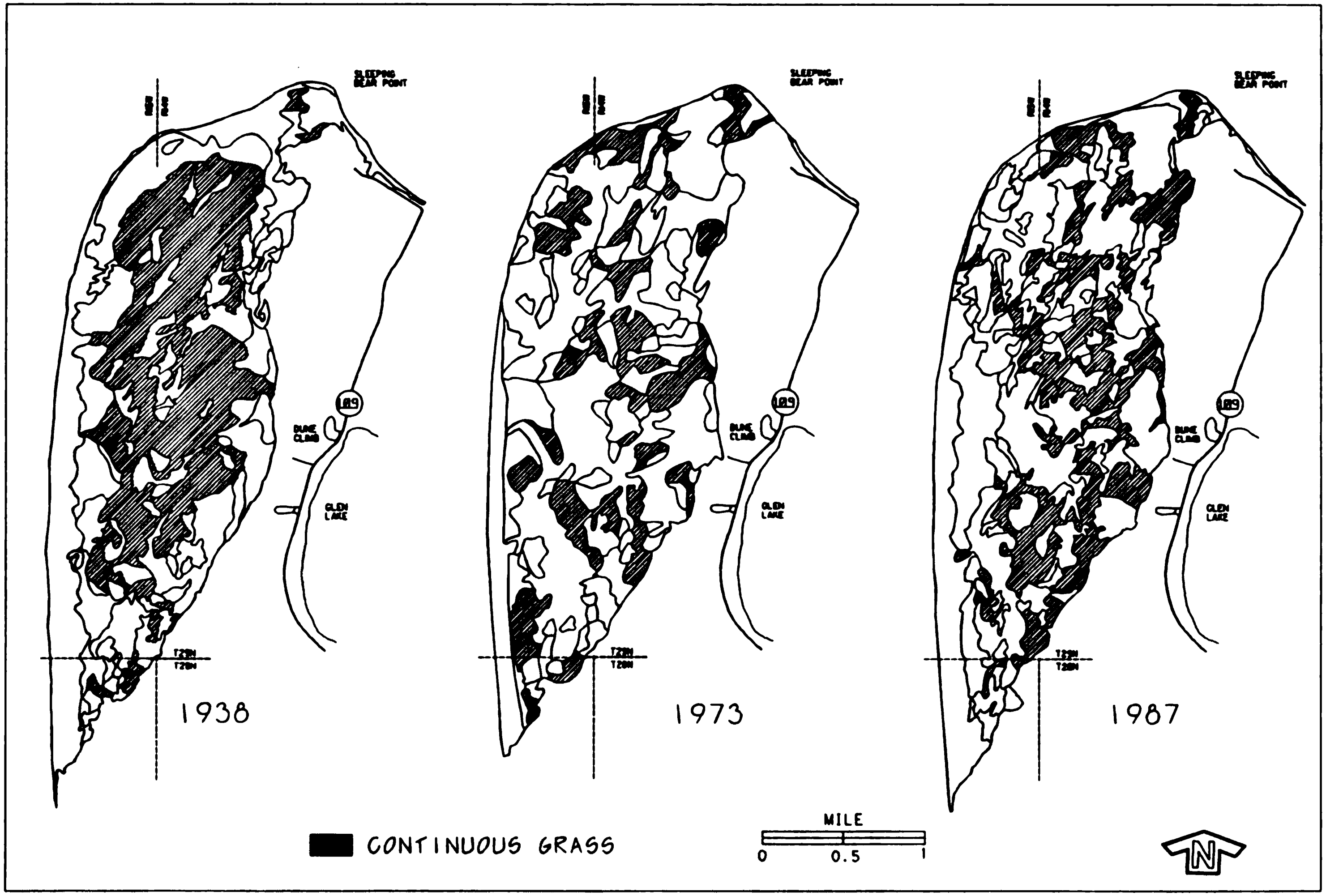


Figure 27 Map Comparing Continuous Grass (Class 3): 1938, 1973, and 1987

decreased acreage that occurred for this cover type from 1938 to 1973, was reversed from 1973 to 1987. An increase of 19% (111 acres) occurred from 1973 to 1987 (Table 7). The size of the average area increased slightly; the size of the maximum area increased significantly from 68 acres to 179 acres (Table 8).

A comparison of the 1973 and 1987 maps in Figure 27 depicts the more widespread occurrence of Continuous Grass cover on the dunes complex in 1987 than in 1973. In particular, the north central part of the dunes complex had more and smaller areas of Continuous Grass in 1987. An increase in area mapped as Continuous Grass is evident in the Dune Climb area.

1938 to 1987.--A comparison of the 1938 and 1987 data indicates a 200% increase in the number of polygons (8 to 22) accompanied by a 29% decrease (283 acres) in area mapped as Continuous Grass over this period (Table 7). The size of the average and maximum areas of Continuous Grass also decreased (Table 8).

The trend of an increasing number of areas was consistent from 1938 to 1973, and 1973 to 1987, however the amount of increase was much smaller from 1973 to 1987 than from 1938 to 1973. The trend of a decrease in acreage of Continuous Grass that occurred from 1938 to 1973 was reversed from 1973 to 1987. Although an overall decrease in acreage occurred from 1938 to 1987, the most recent trend from 1973 to 1987 indicated that acreage of this cover type was increasing.

Grass and Shrubs (Class 4)

1938 to 1973.--During this period the number of areas mapped as Grass and Shrubs decreased 65%, but the amount of acreage increased 161%, a gain of 471 acres (Table 7). The acreage of the average, minimum and maximum polygons of Grass and Shrubs all increased over this period (Table 8). Figure 28 depicts the locations of areas of Grass and Shrubs in 1938 and 1973; the increase in area classified as Grass and Shrubs is obvious.

The largest area mapped as Grass and Shrubs in 1973 was a 402 acre area that occupied the central and southern interior of the dunes complex as shown on the 1973 map in Figures 23 and 28. In 1938, this part of the dunes complex was mostly Continuous Grass with several small areas of Grass and Shrubs scattered around (Figure 22).

Another notable area of increase in Grass and Shrubs cover during this period occurred along the northwestern edge of the dunes complex. This area was mapped as mostly Discontinuous or Continuous Grass in 1938.

1973 to 1987.--The number of areas mapped as Grass and Shrubs increased 144% but the total acreage decreased 18%, a loss of 135 acres (Table 7). The size of the average and maximum areas of Grass and Shrubs also decreased. The

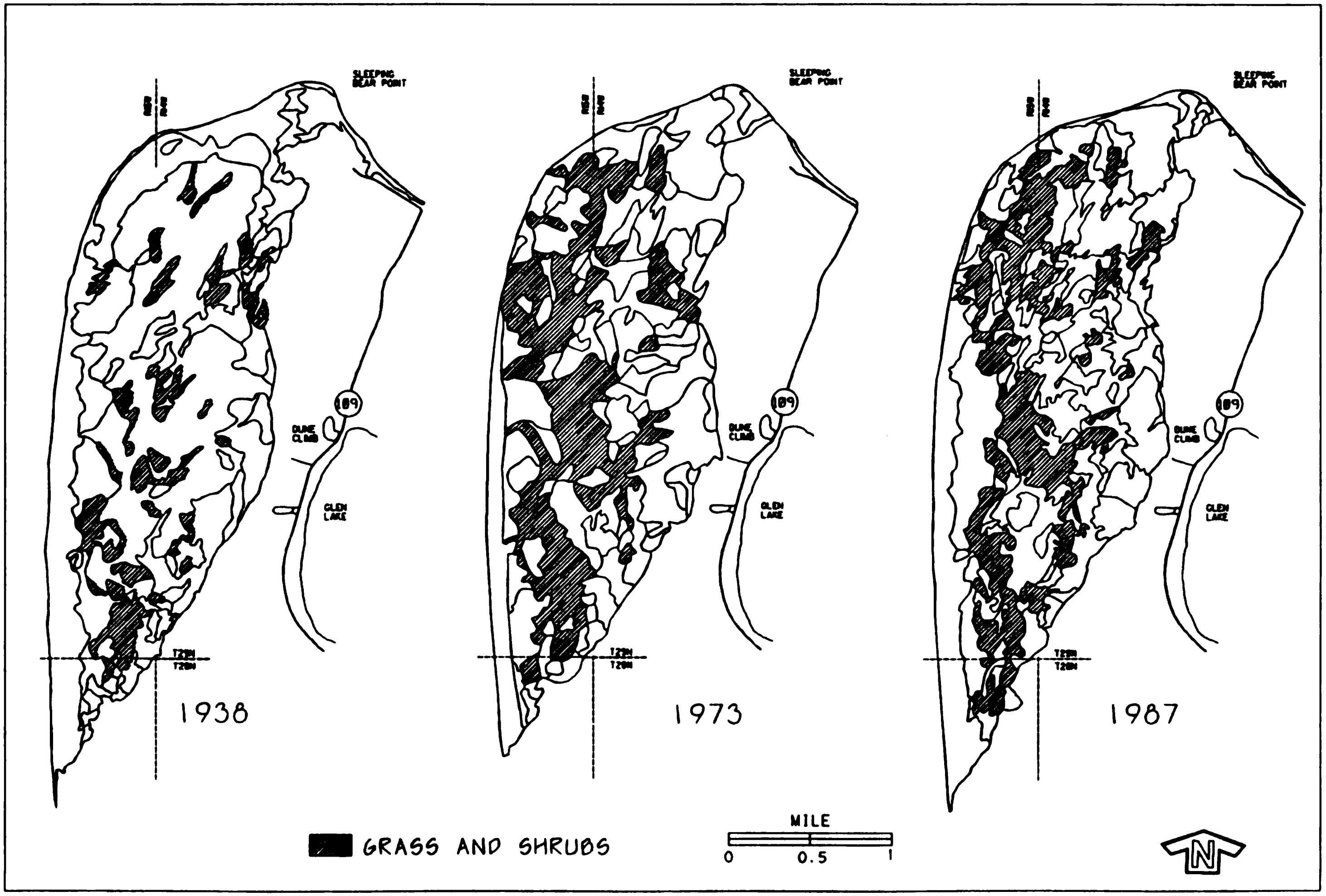


Figure 28 Map Comparing Grass and Shrubs (Class 4): 1938, 1973 and 1987

largest area of Grass and Shrubs mapped in 1987 was 132 acres, compared to 402 acres in 1973 (Table 8).

Figure 28 illustrates the increase in smaller areas of Grass and Shrubs in 1987 compared to 1973. This was most evident on the northern and central areas of the dunes complex. The large area identified as Grass and Shrubs in 1973 on the central and southern dunes complex was smaller and more fragmented in 1987, although Grass and Shrubs still covered a somewhat continuous area.

<u>1938 to 1987</u>.--Although there was only a slight decrease in the number of areas mapped as Grass and Shrubs from 1938 to 1987, the total acreage of this cover type increased 53% (336 acres). However, the trends of change for Grass and Shrubs were not consistent throughout this period. The trend from 1938 to 1973 was toward fewer but larger areas of Grass and Shrubs, accompanied by a large increase in acreage. From 1973 to 1987, the trend was toward an increase in the number of areas accompanied by a slight decrease in total acreage.

A comparison of the 1938 and 1987 maps in Figure 28 illustrates the large increase in acreage mapped as Grass and Shrubs, most notably on the central and northern parts of the dunes complex.

Grass, Shrubs and Trees (Class 5)

1938 to 1973.--In 1938, seven relatively small areas of Grass, Shrubs and Trees cover were scattered across the dunes complex, three of them occurring on the southern part of the complex. In 1973, there were a total of four areas of this cover type, three on the southern dunes complex and one on the east central edge of the dunes complex. The total area of this cover type increased from 34 to 50 acres during this period.

The area of Grass, Shrubs and Trees along the east central edge of the dunes complex in 1973 was located in the same area as two smaller areas of this cover type in 1938 (Figure 29). This suggests that Grass, Shrubs and Trees cover expanded in this area during this period.

The areas mapped as Grass, Shrubs and Trees on the central dunes complex in 1938 were mapped as part of larger areas of Grass and Shrubs (Class 4) in 1973, indicating a loss of trees during this period. The relatively large area of Grass, Shrubs and Trees on the southeastern edge of the dunes complex in 1973 occupied a location that was mapped as small areas of Discontinuous Grass (Class 2), Continuous Grass (Class 3) and Forest (Class 6) in 1938.

1973 to 1987.--During this period, the number of areas classified as Grass, Shrubs and Trees decreased from 4 to 3, and the total area decreased from 50 to 32 acres. The maps in Figure 29 indicate the loss of this cover type on the southern dunes complex from 1973 to 1987, and the occurrence of this cover type in small pockets on the interior of the dunes complex in 1987 that were absent in 1973. The area

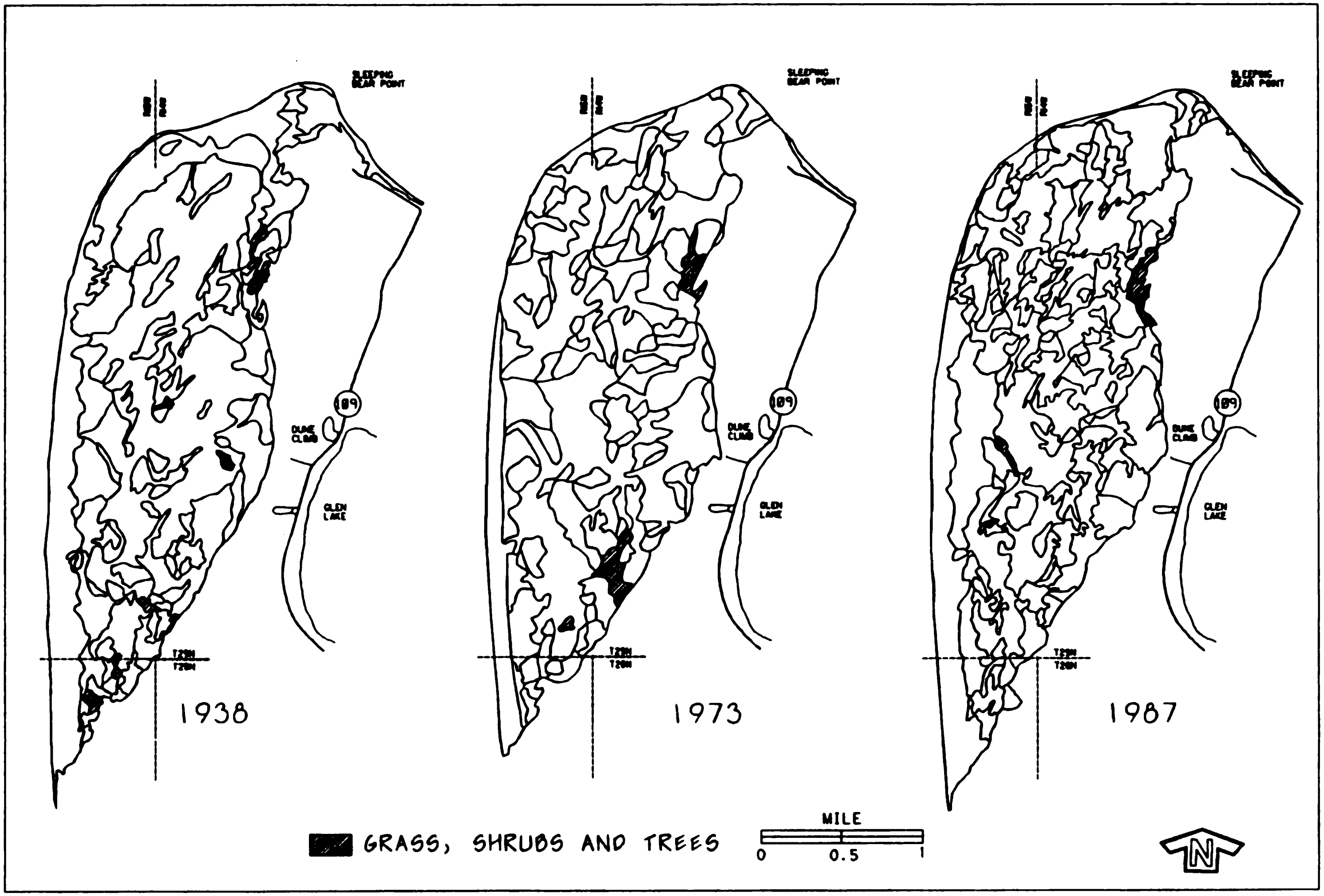


Figure 29 Map Comparing Grass, Shrubs and Trees (Class 5): 1938, 1973 and 1987

classified as Grass, Shrubs and Trees along the east central edge of the dunes complex in 1973 was slightly larger on the 1987 map.

1938 to 1987.--From 1938 to 1987, the number of areas classified as Grass, Shrubs and Trees decreased from seven to three, and there was a loss of two acres of this cover type. The trend of increasing acreage from 1938 to 1973 was reversed from 1973 to 1987. The trend toward fewer and larger areas of Grass, Shrubs and Trees that occurred from 1938 to 1973 was also reversed from 1973 to 1987, with smaller and more scattered areas in 1987 than in 1973.

Figure 29 illustrates the changes that occurred to areas classified as Grass, Shrubs and Trees. The change in location of these areas is evident and loss of this cover type from the southern part of the dunes complex between 1938 and 1987 is also shown.

Forest (Class 6)

1938 to 1973.--In 1938, five areas covering 48 acres were mapped as Forest cover. Four of the five areas occurred on the southern part of the dunes complex, and included the "arms" of the horseshoe-shaped Sleeping Bear Dune. For 1973, only one area, covering five acres, was mapped as Forest.

The maps in Figure 30 indicate the location of these areas. One area on the southernmost part of the dunes complex was mapped as Forest in both 1938 and 1973. The

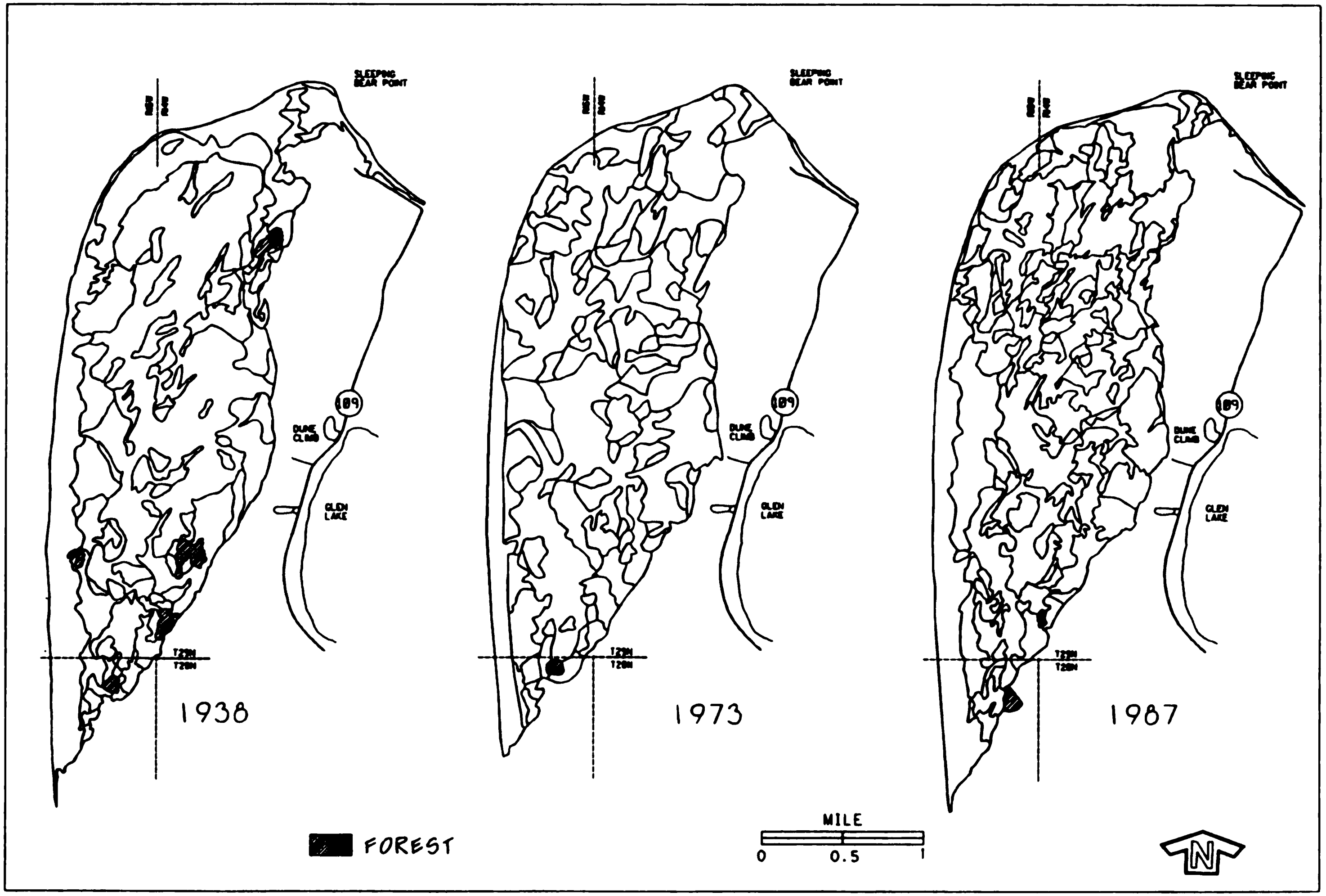


Figure 30 Map Comparing Forest (Class 6): 1938, 1973 and 1987

Sleeping Bear Dune that was mapped as Forest in 1938 was mapped as part of a large area of Grass and Shrubs (Class 4) in 1973 (Figures 22 and 23). The other two areas on the southern dunes complex and the area on the northeastern part of the dunes complex classified as Forest in 1938, were included in areas of Grass, Shrubs and Trees (Class 5) or Discontinuous Grass (Class 3) in 1973.

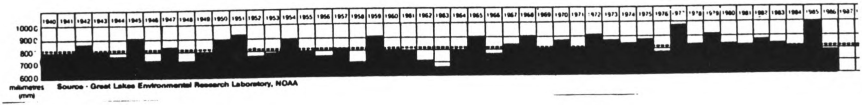
1973 to 1987.--The number of areas interpreted as Forest increased from one to two in this period, and the total area increased by four acres. Both areas in 1987 were located on the southern dunes complex (Figure 30), but they were in a different location than the area of Forest classified on both the 1938 and 1973 maps.

1938 to 1987.--The trend of Forest cover on the dunes complex over this period was a decrease in the number of areas and acreage. Although there was a slight increase in acreage from 1973 to 1987, the 1987 total of 8 acres is significantly smaller than the 1938 total of 48 acres.

Factors Possibly Influencing Results

Environmental factors that may have influenced the results discussed above include, but are not limited to, the variation in the water level of Lake Michigan and the variation in amount and timing of precipitation prior to the date of the imagery. The hydrograph of Lake Huron-Michigan lake levels from 1916 to 1986 (Figure 31) illustrates the

GREAT LAKES BASIN
PRECIPITATION



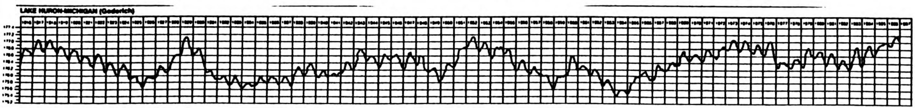


Figure 31 Lake Michigan Water Levels: 1916 to 1986 (EPA, 1988)

variation in lake levels over a long period. "The irregular long-term cycles correspond to long-term trends in precipitation and temperature, the causes of which have yet to be adequately explained" (EPA, 1988 p. 12).

Annual or seasonal variations in lake levels result from changes in precipitation and runoff to the Great Lakes. According to the Environmental Protection Agency:

> Generally the lowest levels occur in winter when much of the precipitation is locked up in ice and snow on land and dry winter air masses pass over the lakes enhancing evaporation. Levels are highest in summer after the spring thaw when runoff increases. (1988, p. 12).

Sand nourishment of the dune field on the dunes complex may adversely affect some areas of vegetation and favor the growth and stability of vegetation in others. Marsh and Marsh (1987) studied eolian processes in perched dune environments and found that the primary sources of sand on perched dunes complexes were the bluffs and escarpment areas, and that most of the sand erosion and movement onto the dune field occurred in the winter. Relative to lake levels, they stated:

> High lake levels are associated with the greatest rates of wave erosion of beaches and bluffs. This in turn raises the magnitude and frequency of bluff failure which inhibits development of vegetative and gravel lag covers on the bluff faces. Therefore, during high water periods sand exposure on bluffs is at its maximum, and all other things being equal, wind erosion and dune nourishment should also be at their greatest (p. 390).

As can be seen from Figure 31, the water level of Lake Michigan was relatively low in the 1937-1938 period, and relatively high in the 1972-73 and 1986-87 periods. The long-term trends prior to the dates of the imagery indicate that the lake level was relatively low throughout the 1930s, was on a continual rise in the late 1960s and early 1970s, and although lower in the late 1970s and early 80s, was rising to record levels by 1986. This suggests that the 1973 and 1987 imagery may reflect more beach and bluff erosion and increased sand movement on the dunes complex than is reflected in the 1938 imagery.

Vegetation can reflect short- and long-term precipitation trends. The long-term climatic trends were discussed in Chapter 1, but the amount and timing of precipitation in the few months preceding the date of the imagery may have influenced the vigor and thus the appearance of the vegetation in the imagery. After a particularly dry spring, the vegetation of early summer may be less vigorous than that after a very wet spring. When attempting to draw conclusions about long-term vegetation trends, it is important to consider short-term factors that may alter or obscure long-term trends.

The total precipitation values for the 12 months preceding the date of the imagery were as follows:

- July 1937 to June 1938: 29.29 inches
- July 1973 to June 1973: 36.68 inches
- July 1986 to June 1987: 49.04 inches

As expected, based on the lake levels for this period, record high precipitation amounts occurred in the mid 1980s, and the driest period was the 1930s.

It is not within the scope of this study to determine the influence of these environmental factors on the results obtained. However, it is important to realize that these factors may have influenced the findings.

In the following chapter, a summary of the results of this investigation are presented along with suggestions for further research.

CHAPTER 4

SUMMARY AND RECOMMENDATIONS

The objective of this thesis was to determine the general trends in vegetative cover on the Sleeping Bear Dunes complex over the period 1938 to 1987. To facilitate this objective, a vegetative cover classification system was developed. The vegetative cover on the dunes complex was then classified and mapped based on the interpretation of aerial imagery from 1938, 1973, and 1987. Digitization, area measurements, data tabulation, and mapping were completed using the C-MAP geographic information system. Thematic maps of the vegetative cover for each period were produced and compared.

A comparison was made between the 1938 and 1987 data based on an eight-class vegetative cover system. A second comparison was made between the 1938, 1973, and 1987 data. Because the 1973 imagery had a small scale (1:40,000), the eight-class vegetative cover system was modified to a six-class system for interpretation and comparison.

Measurements were made of the number of polygons and acreage of each vegetative cover type for each period, and the comparison between periods was based on these values. This type of comparison provided information about the general trends of vegetative cover on the dunes complex. It does not provide information about what has happened to each specific area of vegetative cover over time. That type of information could be gathered from an overlay analysis, but it was not within the scope of this study to do such an analysis.

General Trends: 1938 to 1987

The most noticeable trend from 1938 to 1987 was the break up of large areas of one vegetative cover type into many smaller areas of the same or different vegetative cover. Some of this fragmentation resulted from shrubs invading areas previously classified as Unvegetated or Grass cover types. Cover types that lost acreage (based on 6 classes) included Forest (Class 6), Continuous Grass (Class 3) and Unvegetated (Class 1). Cover types that had an increase in acreage included Discontinuous Grass (Class 2) and Grass and Shrubs (Class 4).

The percentage of the acreage occupied by each cover type is presented in Table 9. Continuous Grass (Class 3) was fairly dominant on the dunes complex in 1938 (37%) whereas Grass and Shrubs cover accounted for only 11% of the acreage. In 1987, Continuous Grass covered only 26% of the dunes complex, but Grass and Shrubs cover had increased to 23% of the cover.

Cover types that included trees (Grass, Shrubs and Trees and Forest) accounted for a very small percentage of the acreage in all time periods, and the decrease in acreage was very slight. The percentage of area with Discontinuous Grass cover or Unvegetated land was relatively consistent over the period. A slight decrease in Unvegetated land and a slight increase in Discontinuous Grass cover occurred.

TABLE 9

Percentage of Acreage For Each Class: 1938, 1973, 1987

	1938	1973	1987
Bare Sand	24%	25%	21%
Discontinuous Grass	26%	21%	29%
Continuous Grass	37%	22%	26%
Grass and Shrubs	11%	29%	23%
Grass, Shrubs, Trees	1%	2%	1%
Forest	1%	<1%	<1%

Summary of Change for Each Class: 1938 to 1987

Unvegetated (Class 1)

The amount of acreage of Unvegetated land decreased from 1938 to 1987. The trend from 1938 to 1973 was an increase in Unvegetated land, but this trend was reversed from 1973 to 1987, for a net loss of Unvegetated land. The amount of Unvegetated land increased in the interior of the dunes complex and around the Dune Climb area. It decreased on Sleeping Bear Point and the beach area bordering the dune complex.

Discontinuous Grass (Class 2)

The trend from 1938 to 1973 for Discontinuous Grass cover was a decrease in acreage and an increase in the number of areas with this cover type. From 1973 to 1987, the amount of acreage increased for a net gain in acreage of this cover type from 1938 to 1987. Some of the acreage lost to this cover type was gained by the Continuous Grass (Class 3) and the Grass and Shrubs (Class 4) cover types. This suggests an overall gain in vegetative cover.

Continuous Grass (Class 3)

The amount of acreage classified as Continuous Grass (Class 4) decreased significantly over this period. Although the net change is a loss of acreage, the most recent trend, from 1973 to 1987, was an increase in acreage of this cover type. The loss of acreage of Continuous Grass was accompanied by a significant increase in areas with Grass and Shrubs cover.

Grass and Shrubs (Class 4)

The amount of acreage classified as Grass and Shrubs increased from 1938 to 1987. Much of the increase appeared to occur in areas that were mapped as having Continuous Grass cover in 1938. The data suggest that this cover type gained in importance (based on amount of acreage) on the dunes complex over this period.

Grass, Shrubs and Trees (Class 7) and Forest (Class 8)

The amount of acreage classified as either Grass, Shrubs and Trees or Forest decreased over this time period. Both of these cover types accounted for very little of the vegetative cover on the dunes complex in any time period. The single most common tree species on the dunes complex is cottonwood, which has a relatively short life span. Eroded dune environments are not conducive to tree growth because of sand movement.

Suggestions for Future Research

This investigation provides initial baseline information regarding temporal trends in vegetative cover types on the Sleeping Bear Dunes complex. Field investigation, including biogeographic analysis of the type and location of species on the dunes complex, would be a very useful addition to knowledge of the Sleeping Bear Dunes complex ecosystem. According to Olson (1958), knowledge of the presence of certain indicator species, both present and past, can lead to a further understanding of what environmental changes have occurred, and can offer clues as to why these changes may have occurred.

Aerial imagery provides an economical and efficient source of natural resource data, especially for use in temporal analysis. One of the major limitations of this investigation was the scale and quality of available imagery. A long term plan for monitoring the vegetative cover on the dunes complex should include periodic aerial imagery taken at a large scale, at the most advantageous time of the year, and meeting certain minimum quality standards. The 1987 imagery used in this study was of very high quality and provided more information than I was able to use, because I was unable to interpret similarly detailed information from the older imagery. Based on my experiences with these sets of imagery, I suggest that imagery at a 1:15,840 or larger scale, taken in mid-summer every five to ten years, using black and white infrared (BWIR) film would meet the minimum standards necessary to effectively monitor and assess change in the vegetative cover of the Sleeping Bear Dunes complex.

There is a critical need for establishing fixed reference points on the dunes complex. Because of the lack of cultural features such as buildings and roads, or any other stable, unchanging marks on the dunes complex, it is difficult to compare data from different time periods and be certain that the data sets are geographically referenced to the same points. This need could be addressed by re-surveying the Congressional Survey System lines and marking section and half section corners with fixed markers that could be made visible on aerial photographs.

Natural resource managers and decision makers need timely, accurate information regarding the temporal change and current condition of the resources they are managing.

The Sleeping Bear Dunes complex is an example of an area for which both preservation and recreational goals exist. The availability of periodic, high-quality, geographically referenced imagery in conjunction with a fully functioning geographic information system (GIS), could provide unprecedentedly usefulinformation about this dune environment including how, where, and possibly even why it is changing.

APPENDICES

APPENDIX A

APPENDIX A: AGENCY SOURCE FOR AERIAL IMAGERY

USDA/AAA	United States Department of Agriculture Agriculture Adjustment Administration
USDA/PMA	United States Department of Agriculture Production and Marketing Administration
USDA/ASCS	United States Department of Agriculture Agriculture Stabilization and Conservation Service
SCS	Soil Conservation Service
MDNR	Michigan Department of Natural Resources

APPENDIX B

APPENDIX B: PHOTOGRAPH SET-UP PARAMETERS

TABLE 10

1938 Photo Set Up

Map or Image Set Up	Average Error	Average Scale	Comments
Glen Haven Quad	4 ft.		Used to set up #3-27;
Photo 3-27	28 ft.	1:20,985	Digitized; used to set up #3-3;
Photo 3-3	20 ft.	1:21,251	Digitized; used to set up #3-4;
Photo 3-4	20 ft.	1:21,555	Digitized; used to set up #3-5;
Photo 3-5	10 ft.	1:21,319	Digitized;

TABLE 11

1973 Photo Set Up

Map or Image Set Up	Average Error	Average Scale	Comments
Glen Haven Quad	7 ft.		Used to set up #173-79;
Photo 173-79	22 ft.	1:41,371	Digitized; used to set up #173-78;
Photo 173-78	20 ft.	1:41,095	Digitized;

TABLE 12

1987 Photo Set Up

Map or Image Set Up	Average Error	Average Scale	Comments
Glen Haven Quad	4 ft.		Used to set up #136 and #135;
Photo 136*	8 ft.	1:15,598	Digitized; used to set up #141;
Photo 141*	9 ft.	1:15,565	Digitized; used to set up #142;
Photo 142*	13 ft.	1:16,248	Digitized;
Photo 135	11 ft.		Used to set-up #142 & #134; not digitized;
Photo 142	20 ft.		Used to set up #143; not digitized;
Photo 143	19 ft.		Used to set up #144; not digitized;
Photo 144*	19 ft.	1:15,628	Digitized;
Photo 134*	14 ft.	1:15,723	Digitized;
Empire Quad	7 ft.		Used to set up #133;
Photo 133*	10 ft.	1:15,145	Digitized;

*Photographs that were digitized

LIST OF REFERENCES

LIST OF REFERENCES

American Society of Photogrammetry. (1983). Manual of remote sensing (2nd ed.). Falls Church, VA: Author.

Avery, T. E., & Berlin, G. L. (1985). Interpretation of aerial photographs. Minneapolis: Burgess.

Buckler, W.R., & Winters, H.A. (1983). Lake Michigan bluff recession. Annals Assoc. Amer. Geographers, 73, 89-110.

Cowles, H. C. (1899). The ecological relations of the vegetation on the sand dunes of Lake Michigan. Botanical Gazette, 27, 95-117, 167-202, 281-308, 361-391.

Daniels, S. M. (1976). Applications of remote sensing to resource classification and inventory of a national shoreline park. Unpublished master's thesis, American University, Washington, D.C.

Dorr, J. A., & Eschman, D. (1970). Geology of Michigan. Ann Arbor: University of Michigan Press.

Enslin, W.R. et al. (1991) C-MAP user's manual. East Lansing: Center for Remote Sensing, Michigan State University.

Gates, F. C. (1950). The disappearing Sleeping Bear dune. Ecology, 31(3), 386-392.

Gillis, W. T., & Bakeman, K. (1963). The disappearing Sleeping Bear Sand Dune. The Michigan Botanist, 2(1), 45-53.

Hazlett, B. T. (1986). The terrestrial vegetation and flora of the mainland portion of Sleeping Bear Dunes National Lakeshore (Technical Report No. 13). University of Michigan Biological Station.

Jacobberger, P. A., & Hooper, D. M. (1991). Geomorphology and reflectance patterns of vegetation-covered dunes at the Tsodilo Hills, north-west Botswana. International Journal of Remote Sensing, 12(11), 2321-2342.

Johnson, L.B. (1990). Analyzing spatial and temporal phenomena using geographical information systems: A review of ecological applications. Landscape Ecology, 4(1), 31-43.

Johnston, C. A., & Naiman, R. J. (1990). The use of a geographical information system to analyze long-term landscape alteration by beaver. Landscape Ecology, 4(1), 5-19.

Kelsch, S. W., & Hendricks, F. S. (1982). Temporal analysis of aerial photographs for environmental assessment. The Texas Journal of Science, 34(3&4), 219-231.

Kuchler, W. A. (1953). Some uses of vegetation maps. Ecology, 34(3), 629-636.

Lillesand, T. M., & Kiefer, R. W. (1987). Remote sensing and image interpretation (2nd ed.). New York: Wiley.

Lovis, W. A., Mainfort, R., & Noble, V. E. (1976). An archaeological inventory and evaluation of the Sleeping Bear Dunes National Lakeshore, Leelanau and Benzie Counties, Michigan (Contract No. CX-6000-4-0150). East Lansing: Michigan State University.

MacConnell, W. P. (1973). Remote sensing 20 years of change in Plymouth County Massachusetts, 1951-1971. (Planning and Resource Development Series No. 23, Publication No. 95). Amherst: University of Massachusetts, Cooperative Extension Service.

MacEachren, A. M. (1987). The evolution of computer mapping and its implications for Geography. Journal of Geography, 86(3), 100-108.

Marsh, W. M., & Marsh, B. D. (1987). Wind erosion and sand dune formation on high Lake Superior bluffs. Geografiska Annaler, 69(A), 379-391.

Mueller-Dombois, D., & Ellenberg, H. (1974). Aims and methods of vegetation ecology. New York: Wiley.

Muhn, J. (1984). Historic resource study: Sleeping Bear Dunes National Lakeshore, Michigan. Washington DC: U.S. Department of the Interior, National Park Service.

Olson, J. S. (1958). Lake Michigan dune development. II. Plants as agents and tools in geomorphology. The Journal of Geology, 66(4), 345-351.

Snyder, F. S. (1985). A spatial and temporal analysis of the Sleeping Bear Dunes Complex, Michigan (A contribution to the geomorphology of perched dunes in humid continental regions). Unpublished doctoral dissertation, University of Pittsburgh.

Sprague, E., & Smith, G. M. (1903). Sprague's history of Grand Traverse and Leelanau counties. B.F. Brown.

Strahler, A. N., & Strahler, A. H. (1984). Elements of Physical Geography (3rd ed.). New York: Wiley.

Strommen, N. D. (1972). Climatic summaries of resort areas: Sleeping Bear Dunes National Lakeshore. U.S. Dept. of Commerce, NOAA, National Weather Service (No. 21-20-4). East Lansing, MI.

Thompson, P. W. (1967). The vegetation and common plants of Sleeping Bear (Institute of Science Bulletin No. 52). Bloomfield Hills, Michigan: Cranbrook Institute of Science.

Tueller, P. T. (1989). Remote sensing technology for rangeland management applications. Journal of Range Management, 42(6), 442-453.

Turner, M. G. (1990). Spatial and temporal analysis of landscape patterns. Landscape Ecology, 4(1), 21-30.

U.S. Department of the Interior, National Park Service. (1961). A proposed Sleeping Bear National Seashore: natural history report. Washington, DC: Author.

U.S. Department of the Interior, National Park Service. (1974). Draft environmental impact statement, master plan: Sleeping Bear Dunes National Lakeshore, Michigan. Omaha, NE: Author.

U.S. Department of the Interior, National Park Service. (1988). Sleeping Bear Dunes natural resources management plan. Omaha, NE: Author.

U.S. Environmental Protection Agency & Environment Canada (1988). The Great Lakes: An environmental atlas and resource book. Chicago: Author.

U.S. Surveyor General, (1839 & 1850). Field notes N. & W. Michigan. Available at the State of Michigan Library and Archives, Lansing, Michigan.

Waterman, W. G. (1926). Ecology of Glen Lake and Sleeping Bear Region. Michigan Academy of Science, Arts and Letters Papers, 6, 351-376.

Weber, W. L. (1973). Soil survey of Leelanau County, Michigan. Washington, DC: U.S. Department of Agriculture, Soil Conservation Service and Michigan Agriculture Experiment Station.