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The Vegetation and a Landsat Assisted Land Cover Map

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Patrick J. Webber

Major professor

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THE VEGETATION AND A LANDSAT ASSISTED LAND COVER MAP OF THE BARROW REGION, NORTHERN ALASKA

By

Brian M. Noyle

A THESIS

Submitted to
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ABSTRACT

THE VEGETATION AND A LANDSAT ASSISTED LAND COVER MAP OF THE BARROW REGION, NORTHERN ALASKA

By

Brian M. Noyle

Landsat Thematic Mapper (TM) and Multispectral Scanner (MSS) imagery at two different spatial scales were employed during this research effort to provide two medium scale (1:63,360) vegetation maps of the Barrow Region on Alaska's North Slope. Detailed field sampling facilitated a site specific accuracy assessment of the digital classification to provide clues as to the reliability of each map. A comparison of the resultant map products was conducted to assess the effect of the resolution of satellite data on the investigator's ability to accurately interpret vegetation pattern in Arctic tundra.

Accuracy assessment of the TM and MSS derived map products indicates that both types of remotely sensed imagery are limited in their ability to accurately represent specific vegetation types at the chosen map scale. The TM instrument, with its improvements in spatial, radiometric, and spectral resolution over the MSS sensor, produced a significantly more accurate vegetation map than that derived from the MSS data. It is concluded that the Landsat derived land cover maps prepared during this investigation provide information on the distribution of general vegetation types across the Barrow Region, but do not provide accurate site-specific vegetation data.

ACKNOWLEDGEMENTS

This thesis would not have been possible without the support and friendship of my advisor, Dr. Patrick J. Webber. I wish to thank him, first and foremost, for the opportunities he has presented to me and for his support throughout this research project. I am also indebted to Mr. Robert Hollister who introduced me to the tundra at Barrow, Alaska, has spent long hours teaching me the plant species of the Barrow Peninsula and has facilitated the logistics of long summers in the Arctic. In addition, I could not have seen this project to its end without the support, encouragement, advice, and hard work of the many students who helped me out along the way. I wish to thank all of these individuals, most notably Chris Brunner, William Chu, Ian Ramjohn, Sharon Osborn, MaryGrace Villanueva, Steve Rewa, Theresa Thomas, and Christy Klimas. Dr. Jerry Brown, Dr. David Lusch, Mr. Christopher Kroot, Dr. Skip Walker, Mr. Scott Drzyzga, and Mr. Jeffery Duh have all been extremely generous with their time and resources. Special thanks must be given to the community at Barrow, particularly Mr. Dario Lieba, Dr. Glenn Sheehan, and Richard Glenn of the Presidential Arctic Commission for shelter and logistical support. I owe my statistical knowledge to Dr. Oliver Schabenberger and my knowledge of remote sensing and Geographic Information Systems (GIS) to Dr. Dan Brown. In addition, I would be remiss if I did not thank Dr. Stuart Gage and Dr. Patricia Norris for their support and encouragement as members of my graduate committee. Funding for this

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Chapter 1

INTRODUCTION AND RATIONALE

I.A. CONTEXT OF THE RESEARCH

Information regarding the characteristics and spatial distribution of the Earth's land cover is critical to many aspects of current and future environmental research conducted at a variety of spatial and temporal scales. Fleming (1988) has noted that, "In all disciplines...there exists a need for timely, reliable information on which to base resource management decisions." Studies of the Earth's land cover and resources are often undertaken for several basic reasons including the satisfaction of scientific curiosity, a contribution to economic inventories, the gathering of data for political and legal discourse, and the facilitation of sound resource management (Hickok 1984). Development of the capabilities to inventory and map a variety of land cover conditions, to monitor changes in land cover and land use through time, and to forecast future land cover and land use scenarios is a necessity for many management and research initiatives. Among others, such initiatives include the modeling of biogeochemical cycles, the study of land-atmosphere interactions, and the provision of a framework upon which to base sound, informed land and resource management decisions in both the public and private sectors (Nelson et al. 1978, Klein 1984).

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While interest in land and resource characterizations has risen dramatically over the past thirty years, the concept is not a new one. It must be pointed out that even before legislative mandate required the preparation of Environmental Impact Statements, public lands management plans, or resource inventories for a variety of related purposes, many responsible policymakers and land managers regularly required significant volumes of similar information upon which to base their regulatory decisions.

The surge of interest in landscape characterization since the mid-1970's has occurred primarily because land and resource managers, following the implementation of such legislative acts as the Rangeland and Renewable Resources Planning Act of 1974, the National Forest Management Act of 1976, the National Land and Resource Policy Act of 1976, and the Soil and Water Conservation Act of 1977 (McGraw-Hill 1992) are now being held accountable for the sum total of environmental impacts resulting from their decisions. Additionally, interest in land and resource classifications has soared following the development of a variety of systems designed for the regular acquisition of remotely sensed data (in both digital and photographic format) and modern data handling systems including geographic information systems (GIS) for the processing, manipulation, and visualization of land cover and natural resource data. Techniques of clustering and ordination, coupled with rapid improvements in computing technologies have resulted in a direct incorporation of new technologies into the resource inventory and land cover classification process over the course of the past 30 years (Bailey et al. 1978, Stone and Ek 1984).

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Sokal (1974) asserts that these methods have changed not only the *common* practices involved in land management and land cover study, but also the very principles involved in classification.

Each of these developments occurred in a political and environmental climate that had just awakened to the concept of the integrated nature of ecosystems. The concept that examination of individual resources, organisms, or other environmental characters in isolation was insufficient to characterize the nature of the landscape became firmly established (Bailey et al. 1978). Furthermore, the environment was now considered to be a resource in its own right. These shifts in thinking drew upon and contributed to the growing concern for the quality of the environment at large. Resource managers and planners began to recognize the multiple resource values placed on particular land units and the interrelationship of resources, biotic and abiotic factors, physical features, and the total environment. Following this line of thinking, the goals of land and resource characterization and classification have been in a continuous process of refinement since the 1950's.

The traditional approach to obtaining information about the landscape, and the resources therein has been through a separate inventory of each of the resources of interest and has thus led to a fragmented perception of the environment. Peterson (1975) has proposed that our efforts to achieve environmental quality and sound management of natural areas must be ecologically based. The use of different frameworks by different administrative agencies results in duplication of effort and an inability to integrate and co-refer

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reference data across agencies and disciplines (Rubec 1979). An ecological framework that integrates many environmental characteristics diminishes problems and assists in the exchange of information (Bailey et al. 1978). A key feature of this approach is the development of a classification scheme based upon known functional relationships between landscape elements (Ellis et al. 1977). Classification and mapping of the distribution of landscape characters has evolved as a means to strengthen the ecological foundation of land and resource management through the viewing of many characteristics and resources concurrently as unique but inseparable components of the landscape (Nelson et al 1978). Methods and stated goals have been expanded to account for not only physical features or quantitative descriptions of a single resource, but also the distribution of resources and the nature of interactions with the study site and its immediate surroundings.

Significant historical developments in techniques for land classification and land cover mapping have led to the use of electronic and photographic remote sensing systems that provide data primarily through the use of aircraft or earth-orbiting satellites. Remote sensing is traditionally defined as the science or process of obtaining information about an object or area through the analysis of data acquired by a device which is not in intimate contact with the object or area under study (Driscoll et al. 1984, Lillesand and Kiefer 1979, Jensen 1986). Following the early developments of the science of remote sensing and photogrammetric image interpretation during World Wars I and II, the techniques of land characterization or classification through exhaustive ground sampling ha

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have been gradually superceded by techniques of electronic or photographic remote sensing coupled with statistical analysis of the resultant data on computers. The readily obvious advantages of data acquisition through remote sensing are the aerial perspective and the wide coverages afforded the investigator, particularly in inaccessible areas (Driscoll et al. 1984, Jensen 1986, Fleming 1988). Land and resource managers, academics, and members of the private sector were quick to recognize the financial and time-scale benefits of the use of remotely sensed data in land and resource classifications. With the development of organized photogrammetric mapping programs in several offices within the U. S. Department of Interior (Ellis et al. 1977, Brooks and O'Brien 1986, Markon 1995) and the launch of the United States Earth Resources Technology Satellite (ERTS) initiative (retroactively named the Landsat Program) by the National Aeronautics and Space Administration (NASA) in 1972 (NASA 1972, Lunetta et al. 1993, Sheffner 1994), it rapidly became possible to map resource distributions, land cover types, cultural features, and a myriad of other details describing terrestrial and aquatic systems over millions of acres with the time and monetary resources it once took to map a fraction of this area. Bones (1984) has noted that prior to the widespread use of remotely sensed data in land cover classification and mapping, the field access costs for resource inventories and surveys often equaled or exceeded the total costs for all other components of the given project. Conversely, Fleming (1988) and Markon (1992) have noted that costs as low as $0.01 to $0.16 per acre have recently been obtained through the use of Landsat Multispectral Scanner (MSS) data duri

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during land classification and cover type mapping efforts in remote portions of Alaska. These new technologies have brought about a revolution in vegetation classification, mapping, and modeling. In addition to facilitating novel research in the arenas of plant community and ecosystem dynamics, these technologies have contributed to a renewed interest in vegetation pattern and process on regional and global scales (Walsh and Davis 1994). However, even as methods and goals of land classifications and resource inventories have changed, the logic behind the process has remained consistent:

> "It is more difficult to implement wise management policies than it is to state them. At the very least one ought to know...what are the natural ecosystems which tend to dominate a region in a rather stable fashion before he embraces a particular management policy for that region. If we don't know what is there now, how can we say what it should be replaced with or what should be preserved?" (Miller and George 1976)

I.B. History of Remote Sensing in Alaska

Significant settlement and development of lands in Alaska did not begin until approximately 1867, following the purchase of the territory from Russia (Brooks and O'Brien 1986). In light of this relatively late initiation of development and the fact that Alaska remains, to this day, sparsely populated relative to the mid-latitudes, many of Alaska's natural resources remain intact. State and federal public resource managers have been presented with the unique opportunity to avoid many of the environmental abuses and problems which have come to pass in the continental United States. Recognizing the opportunity presented them, natural resource managers and policy makers have sought to preserve Alaska's natural areas since the late 1800's.

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Interest in the conservation or preservation of resources in Alaska first manifested itself in 1891 with the creation of the Afognak Forest and Fish Culture reserve to guarantee the continued existence of the state's red salmon stocks (Markon 1995). A short time later, the Chugach and Tongass National Forests were established to provide for recreation, preservation of critical wildlife habitats, maintenance of the timber industry, and protection of the watersheds in each area (Johnson and Jorgensen 1963, Rakestraw 1981). Denali National Park and Preserve (created in 1917 as Mt. McKinley National Park) and Katmai National Park and Preserve (established in 1918 as Katmai National Monument) were subsequently established to ensure the preservation of critical ungulate habitats in addition to significant aesthetic resources and natural areas (Markon 1995). Continuing until 1969, the designation of a great many other protected areas in Alaska, by the U.S. Department of Interior, was undertaken in an attempt to protect wildlife populations victimized by habitat loss and overhunting and to provide for additional preservation of Alaska's natural resources (U.S. Department of Interior 1986,1988,). It was during this last time interval that many of the National Wildlife Refuges were created in Alaska.

Following the purchase of Alaska from Russia, historical events including the discovery of gold, the second World War, the designation of Alaska as a state, and the discovery of oil on the North Slope have all triggered phases of increased activity and hence have contributed in an immense way to Alaskan development (Brooks and O'Brien 1986). As the use of lands in Alaska for development and recreation began to increase, the need for significant amounts

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of natural resource information became apparent. With a total land area of 151.8 million ha covered today by only approximately 23,000 km of roads, a majority of Alaskan water and terrestrial resources continue to be considered “remote”, with access available only by air transportation in many cases (Markon 1995, Fleming 1988, Brooks and O’Brien 1986). Extensive surveys to ascertain resource availabilities and distributions are simply impractical due to the expense and inconvenience of transporting personnel and materials to remote sites and attempting to complete the needed measurements within the constraints of a very short growing season (Anderson et al. 1973). Over time, Alaskan federal and state land management officials have come to recognize the value of remote sensing in the documentation and inventory of the location, extent, and quality of Alaskas’s natural resources. Recently, the techniques of remote sensing and subsequent data analysis, mapping, information dissemination, and archiving have been employed in widespread fashion to aid in addressing the issues involved in development scenarios and resource management planning (Fig. 1-1).

I.B.I. Aerial Photography

Aerial photography has seen extensive use in Alaska in relation to habitat and wetland mapping, management planning and implementation, land cover change analysis, forest inventories, and scientific research efforts. The widespread use of aerial photography in the study of Alaskan terrestrial systems

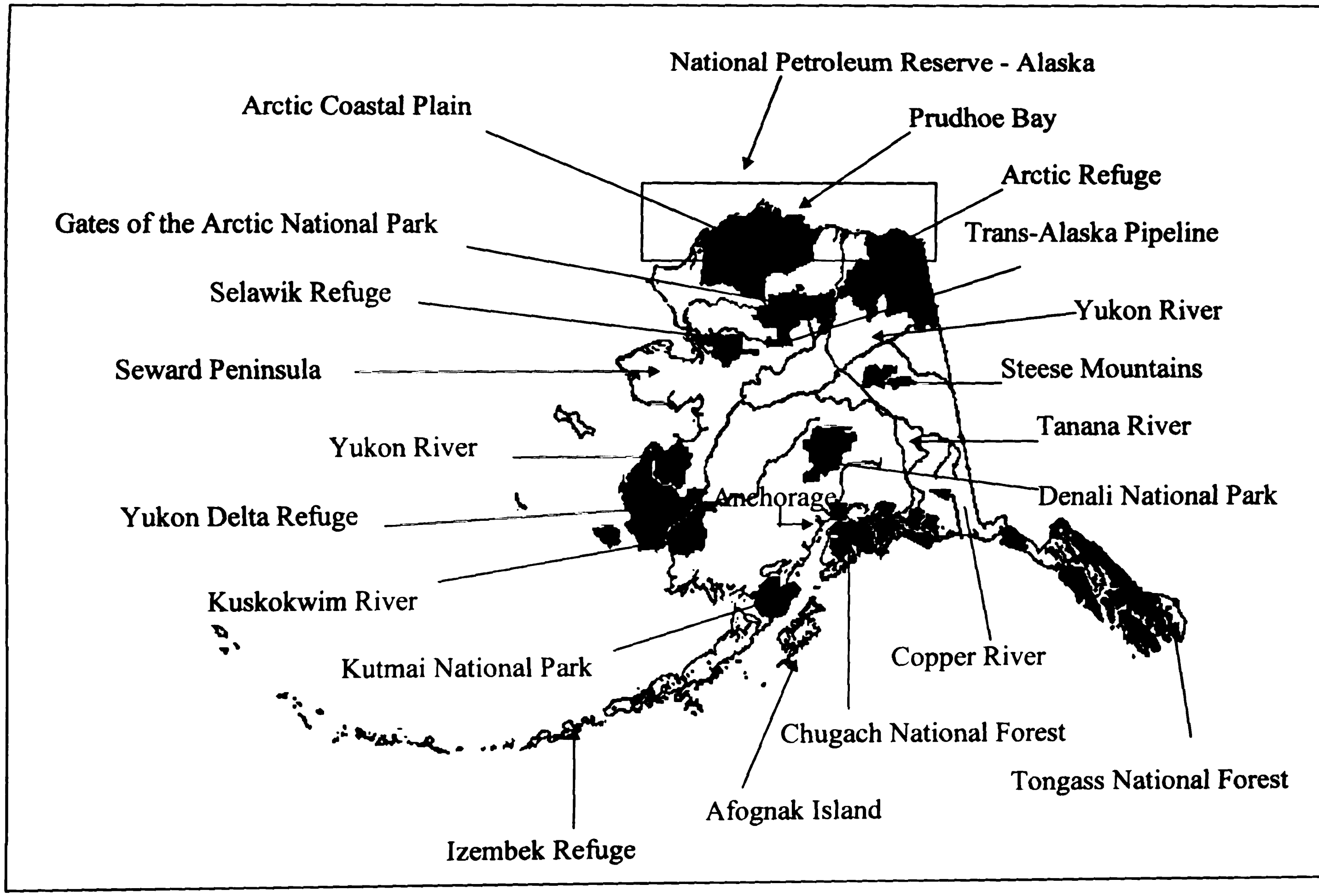

Figure I-1: Map of Alaska showing those areas (shaded) in which remote sensing has played a role in management initiatives. (redrawn from Markon (1995)).

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did not begin until the late 1940's when the U.S. Navy began to photograph large portions of Alaska at the 1:30,000 and 1:60,000 scale. These black and white photographs were instrumental in the completion of the Alaskan Reconnaissance Topographic Maps Series published in 1953 (Brooks and O'Brien 1986). While many of these photographs, all taken with single lens cameras, have not been subsequently updated, the original materials continue to serve as an important historical archive useful in land cover change detection and other landscape studies (e.g., Brown and Berg 1980, Komarkova and Webber 1980).

The U.S. Forest Service used aerial photography to begin statewide forest inventories from 1954 to 1962 following the modification of the McSweeney-McNary Act of 1928 to include the state of Alaska in those areas to be managed for reforestation and timber production. By 1970, it was apparent that the photography collected by the Forest Service was inconsistent in scale and was becoming outdated. With the passage of the National Environmental Protection Act of 1969, the Federal Land Planning and Management Act of 1976, the Forest and Rangeland Renewable Resources Act of 1974 (McGraw-Hill 1992), and other similar legislation (see section I.A.), the need for new medium and large scale aerial photography of the entire state of Alaska was obvious as pressure mounted requesting considerable public lands resource information. Consistent with the recommendations of the Joint Federal-State Land Use Planning Commission for Alaska (Joint Federal-State Land Use Planning Commission 1979), the state of Alaska and eight Federal agencies signed a contract to fund the Alaskan High Altitude Aerial Photography Program (AHAP) to be flown by

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NASA. By the late 1980's, over 95% of the state had been photographed using both black and white and color infrared film (Brooks and O'Brien 1986). The U.S. Forest Service and a variety of investigators have made extensive use of the medium to large scale aerial photography obtained under the AHAP initiative. For example, conventional black and white and color infrared photographs at the 1:30,000 and 1:60,000 scales have been used to map the Chugach and Tongass National Forests, the Tanana River Basin, the Koyukuk River Area, the Juneau Inventory Unit, and several other areas in Alaska's interior (Hutchinson 1968, LaBau and van Hees 1982, Smith and Larson 1984, Winterberger 1984). In addition, 1:48,000 scale photography was used in the study of floodplain succession on the Susitna River in south-central Alaska (Helm et al. 1984). Statewide color-infrared photographs served as the primary data source for the National Wetlands Inventory mapping effort undertaken by Hall (1991). It should also be noted that this photography serves to provide reference information on sampling areas used in the Landsat-assisted mapping of National Wildlife Refuges and Resource Management Areas (Fleming 1988) (see section I.B.II.).

In response to the widespread market interest in Arctic Alaska, particularly for hydrocarbon development, the scientific community, in conjunction with the U.S. Environmental Protection Agency (EPA), the National Research Council (NRC), the Alaska Department of Fisheries and Wildlife, the U. S. Army Corps of Engineers, and numerous other parties, has made significant attempts over the past thirty years to gain an understanding of the Alaskan Arctic through the use of low altitude, large scale aerial photography. The discovery of the Prudhoe Bay

Oilfield in 1968 and its estimated contents, 20 billion barrels of crude oil, guaranteed a continuing interest in the discovery and exploitation of northern Alaska's resources and the influence of aerial photographic studies in the ongoing debate has been considerable. Markon (1980) mapped terrestrial and aquatic habitat along the Alaska Natural Gas Pipeline System to provide baseline data against which to measure environmental impacts of development in a variety of Alaskan ecosystems. Webber et al. (1978) and Walker and Webber (1979) produced large scale vegetation maps of the area along the Yukon River-Prudhoe Bay Haul Road. Swanson et al. (1984) have mapped considerable caribou habitat areas to assist in the development of appropriate wildlife management plans. In addition, Lawson (1982) and Lawson et al. (1978) employed large scale aerial photography in the study of disturbance and recovery processes following exploratory petroleum drilling in the National Petroleum Reserve in Alaska (NPRA). Komarkova and Webber (1980) produced two vegetation maps of the Low Arctic Tundra in the Meade River Quadrangle to provide baseline data for the Research on Arctic Tundra Environments (RATE) project (Batzli 1980). Maps of the vegetation and terrain of the Department of Energy (DOE) study site in the Arctic Foothills Province of Alaska were prepared from large scale aerial photographs as well (Walker et al 1989). Raynolds and Felix (1989) employed aerial photography and photointerpretive methods in the quantification of disturbance due to winter seismic studies in northern Alaska.

The most extensive mapping employing large scale aerial photography in Alaska is that conducted in the mid- to late 1970's in the Prudhoe Bay Oilfield.

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Between 1970 and 1974, the International Biological Programme conducted detailed studies within a small portion of the Prudhoe Bay Oilfield producing large scale maps of the vegetation and terrain (Webber and Walker 1975). Under contract from the U.S. Army's Cold Regions Research and Engineering Laboratory, Walker et al. (1980) produced detailed vegetation maps at two scales in the form of a detailed geobotanical atlas of the entire Prudhoe Bay Region using 1:12,000 scale black and white photography. This resource has served many uses including studies of the cumulative impacts of developments in Arctic Alaska, preparation of Environmental Impact Statements associated with further oil and gas leasing and exploration, and a variety of terrestrial and aquatic habitat mapping applications within the oilfields (U.S. Fish and Wildlife Service 1983, Walker et al. 1984, 1986, 1987, Meehan and Webber, unpub.).

The above descriptions of the uses of aerial photography in Alaskan land and resource management are not exhaustive but point to the important uses of aerial photographs in many situations. Aerial photographs provide detailed, site-specific information and can be examined as a historical baseline for environmental studies as well as providing updated information regarding the state of the landscape. The high geometric and radiometric fidelity of modern aerial photographic systems provide remotely sensed data from which detailed measurements of a variety of environmental parameters can be made. In addition, Shafer and Degler (1986) have suggested that even imprecise 35mm photography may be employed in an inexpensive manner if detailed measurements or observations of the landscape are not necessary.

I.B.II. Digital Satellite Imagery

While resource managers in Alaska have often preferred aerial photography for mapping and resource inventories due to the high spatial resolution they provide and their familiar format, this data source covers only small portions of the landscape. A simple areal calculation reveals that about 5,000 conventional large scale aerial photographs (approximately 1:15,000 scale) are required to encompass a single Landsat scene. Because mapping in Alaska is commonly conducted over large areas, digital satellite data are clearly more practical. The automation of digital satellite data interpretation and land cover mapping has resulted in tremendous benefits in terms of time and money in the mapping of the immense Alaskan landscape (Table I-1).

Feasibility studies for the use of satellite data for land conservation and mapping in Alaska began shortly after the launch of the ERTS-1 (retroactively named Landsat 1, see section I.D.I.) satellite in 1972 (Anderson et al. 1973). While initial image interpretation methods were similar to those employed in the manual interpretation of aerial photography, automated image processing techniques gradually became the norm during the mid-1970's. Several studies conducted during the 1970's have contributed to the widespread use of Landsat data in the classification and mapping of Alaska's natural resources. Anderson et al. (1973) published the results of a study exploring the ability of the ERTS-1 satellite to convey earth and water resources information and recommended the satellite data for a variety of natural resources applications. In addition, a large scale vegetation mapping project was undertaken as a cooperative effort

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Author(s)	Year	Purpose	Res.	Accuracy Assessment?
Anderson et al.	1973	•Landsat feasibility tests	80X80m	None
Miller and George	1976	•Alaskan resource mgt.	80X80m	None
Nodler et al.	1978	•Assessing caribou and reindeer herd potentials	80X80m	None
Morrissey and Ennis	1981	•Vegetation mapping of NPRA	80X80m	None
Walker et al.	1982	•Mapping of USGS quadrangle	80X80m	Felix and Binney 1989
Henderson	1984	•Mgt. of wildlife refuges	Various	None
Swanson et al.	1984	•Reindeer habitat mapping	80X80m	None
Winterberger	1984	•Forest and vegetation inventory	80X80m	None
Talbot et al.	1984	•Vegetation mapping of wildlife refuges	80X80m	None
Shasby and Carneggie	1986	•Statewide vegetation mapping	80X80m	None
Talbot and Markon	1986	•Vegetation mapping of wildlife refuges	80X80m	None
Fleming	1988	•Vegetation mapping in remote areas	80X80m	Yes
Stowe et al.	1989	•Vegetation mapping in support of research	15X15m	Yes
Binnian and Ohlen	1992	•Seasonal phenology analysis	1X1km	None
Markon	1992	•Vegetation of resource mgt areas	80X80m	None
Markon and Derksen	1994	•Waterfowl habitat mapping	15X15m	Yes
Pacific Meridian Resources	1995	•Land cover inventory of NPRA	80X80m	Yes
Muller et al.	1998	•Vegetation mapping in support of research	80X80m	Yes

Table I-1: Summary of literature citations, ground resolutions, and accuracy assessment information from selected major projects involving the use of digital satellite data in Alaska.

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between the Alaska Bureau of Land Management (BLM), the National Aeronautics and Space Administration (NASA), and the U.S. Geological Survey (USGS) (Krebs 1980, Shasby and Carneggie 1986). The project produced a vegetation map for approximately 2 million acres of land along the Denali Highway and provided a comparison of costs, personnel time, and accuracy of mapping using Landsat digital data relative to conventional mapping techniques. A third project involved the mapping of the vegetation covering 23 million acres of land within the National Petroleum Reserve in Alaska (NPRA) in the late 1970's (Morrissey and Ennis 1981). This mapping project, conducted using 10 Landsat scenes, is one of the largest employing Landsat data and, together with the findings of the two studies mentioned above, led to the decision by Alaskan resource management agencies such as the BLM and the Fish and Wildlife Service to continue the use of Landsat digital data in the study and mapping of the state's natural resources.

Two of the most influential events in the history of Alaskan resource management and land cover mapping occurred in concert in 1980 with the passage of the Alaskan National Interest Land Conservation Act (ANILCA) (Brooks and O'Brien 1986, Shasby and Carneggie 1986, Fleming 1988) and the establishment of the Earth Resources Observing System (EROS) Field Office in Anchorage (Shasby and Carneggie 1986). The opening of the EROS Field Office established the first permanent digital image processing computer system in Alaska facilitating the training of users, image processing on cooperative projects, and eventual opening of the system for use by any qualified cooperating

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governmental agency (Shasby and Carneggie 1986). The ANILCA legislation increased the amount of protected lands in Alaska by more than 40 million ha and required federal and state land management agencies within Alaska to update management plans for all lands under their jurisdiction. The ANILCA also instructed the U.S. Secretary of the Interior to produce management plans for each of Alaska's immense National Wildlife Refuges within seven years of the passage of the Act. Because minimal land cover information were available for Alaskan wilderness at the time, Landsat digital data were judged the most appropriate for mapping huge tracts of land.

Databases and Landsat-derived thematic maps were soon prepared to support Environmental Impact Statements written in conjunction with oil and gas exploration and leasing on Alaska's North Slope (USFWS 1983, USDI 1986). In addition, information was produced to supplement a report on caribou and reindeer range potentials (Nodler et al. 1978). The U.S. Geological Survey undertook a mapping of several quadrangles on the North Slope as well (Walker and Walker 1985, Walker and Acevedo 1987). A cooperative agreement between the EROS Field Station staff and the U.S. Fish and Wildlife service signed in 1981 led to the mapping of land cover in 14 of the 16 National Wildlife Refuges in Alaska by the late 1980's (e.g., Walker et al. 1982, Talbot et al. 1984, Talbot and Markon 1986, Fleming 1988). The land cover and terrain data for these projects was produced at a cost of between \$0.01 and \$0.05 (in 1984 dollars) per acre (Henderson 1984). The National Park Service and U.S. Forest service have also made great strides in using Landsat digital data to map many res

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resource management areas and national forests in Alaska to aid in land management and summer and winter animal habitat identification (Markon 1992, Markon 1995). Data were also used for development of predictive models involving fire management and human impacts analyses. Computer processed Landsat data also aided in the identification of wetlands for the National Wetland Inventory Project prepared by Hall (1991).

It should be noted that Landsat data has not been the only source of digital data employed in land and resource management and mapping initiatives in the state of Alaska. SPOT High Resolution Visible and Multispectral (HRV-XS) data have also been used by Markon and Derksen (1994) to map tundra land cover near Teshekpuk Lake and by Stow et al. (1989) to map tundra vegetation in the Arctic Foothills Province on Alaska's North Slope. While the high spatial resolution of SPOT data recommends itself for detailed mapping of vegetation in Arctic Alaska, the relatively low spectral resolution makes it unsuitable for the accurate detection of vegetation types (Stow et al. 1989). In addition, multispectral data from the National Oceanic and Atmospheric Association (NOAA) AVHRR satellite have been employed by several researchers in the mapping of large areas to produce regional estimates of biomass, to track the progression of phenology over the course of the growing season, and to examine the habitat preferences of several wildlife populations (e.g., Binnian and Ohlen 1992, Douglas 1992). AVHRR data, with a spatial resolution of 1.1km, is too coarse for detailed cover type mapping required by most resource managers, but the t

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the twice daily coverages provided by the satellite make the data very useful for other ecological applications and the use of such data is growing (Markon 1995). Resource and land cover data acquired through the analysis of digital satellite data have yielded important information for researchers and land/resource managers as they provide a means of obtaining documentation, classification, and inventory of environmental conditions over large areas in a relatively short time period. Between 1980 and 1995, over 109 million ha of Alaskan land and water were mapped through the use of digital multispectral data, accounting for 72% of the 151.8 million ha of the state's total land area (Markon 1995). Because much of Alaska is considered to be included in the Arctic or Subarctic zones, the databases resulting from the variety of mapping efforts discussed above will undoubtedly serve as a valuable research base for those interested in global change research, land use and land cover change, cumulative impacts analysis, and general biophysical information regarding pattern and process in cold-climate landscapes (Jensen 1983, Walker and Walker 1991).

I.C. Research Rationale

Over the course of the next several decades, the Arctic System will continue to be affected by a variety of factors, from both within and outside the system, including global climate change, cumulative impacts resulting from resource development, pressures from an increasing human presence in the Arctic, and other agents. The potential exists for Arctic ecosystems to be profoundly altered through changes in vegetation cover, thawing of ice-rich permafrost, and wildlife habitat destruction. Such changes are often closely co

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correlated with changes in land cover or land use and may have profound effects on wildlife populations, native subsistence lifestyles, renewable and non-renewable resource management practices, cold-regions engineering technologies, as well as feedbacks and interactions with global biogeochemical cycles. Vegetation or land cover maps of Arctic Systems are necessary to satisfy a wide variety of needs in relation to global change research, land and resource management, and educational priorities over the next several decades.

The general importance of vegetation maps has been repeatedly emphasized in the literature (e.g., Kuchler 1967, Komarkova and Webber 1980, Kuchler and Zonneveld 1988). Brown (1976) and Webber and Ives (1978) have highlighted the importance of vegetation or land cover maps in the development of land management plans and scientific research programs in Arctic regions. Changes in the composition and structure of ecosystems are currently driven largely by management practices. Future effects of Global Climate Change and human-induced disturbance will be superimposed upon these present trends. One essential ingredient in any cold regions land management plan is an inventory of the resources. Fundamental to this inventory are maps of soils, vegetation, cultural resources, and wildlife distributions. While our understanding of pattern and process in Arctic tundra communities is increasing, pressures from Global Climate Change and human development will not wait for the scientific community to establish the ideal understanding necessary for effective land and resource management. With these concepts in mind, inventory and mapping of Arctic tundra vegetation has been promoted because Arctic vegetation compo

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composition is highly correlated with a variety of environmental variables including hydrology, slope and aspect, soil nutrient status, and permafrost properties (Brown 1976, Everett et al. 1978, Walker 1983). Maps of Arctic vegetation are thus capable of conveying information regarding a suite of other factors operating at a variety of spatial scales within a region.

I.C.I. Arctic Vegetation Mapping for Management and Research Initiatives

The city of Barrow (Fig. I-2) is one of eight centers of development on Alaska's North Slope and is home to the administrative body of the North Slope Borough, the world's largest municipality. The presence of this significant infrastructure has made Barrow the focus of many Arctic research efforts subsequent to the establishment of the Naval Arctic Research Laboratory (NARL) in 1947 (Reynolds and Tenhunen 1996). The legacy of the NARL is a rich history of scientific investigation. This commitment to research was recently renewed with the setting aside of significant acreage in 1992, termed the Barrow Environmental Observatory (BEO), for scientific research and with the celebration of the 50th anniversary of the NARL in 1997 (National Arctic Research Laboratory 1997). Despite the considerable research conducted in the Barrow area, a detailed map of the vegetation of the region, which provides information useful to researchers and resource managers in the area, is conspicuously lacking.

The efforts of Morrissey and Ennis (1981) yielded a Landsat Multispectral Scanner (MSS) derived map of the entire National Petroleum Reserve in Alaska (NPRA) which includes the Barrow Region. This map however, has been judged

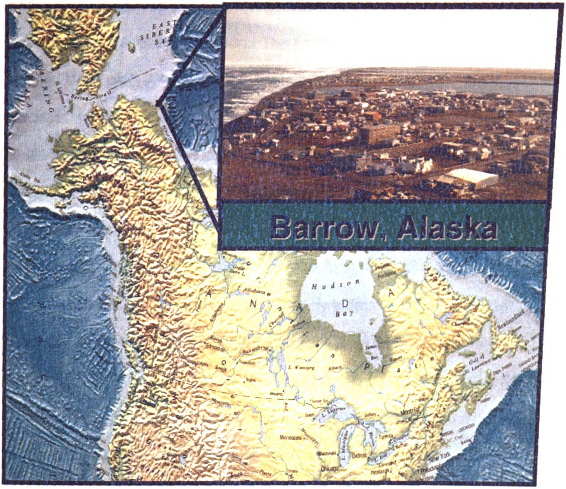

Figure I-2: Map of the North America illustrating the location of the city of Barrow on the North Slope of Alaska.

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to be of insufficient resolution for the identification of specific important vegetation communities (Markon and Derksen 1994). Walker (1977) mapped a narrow strip of vegetation within the Tundra Biome Site of the International Biological Programme (IBP) using a television scanning photodensitometer. In addition, Webber (1978) produced a detailed vegetation map of the entire Tundra Biome study area within the Barrow Region. The limited areal extent of the Walker (1977) and Webber (1978) maps has limited their use by resource managers and researchers who have traditionally been concerned with multisite or regional scale management issues. In addition, no land cover map of this region of northern Alaska has been accompanied by an accuracy assessment providing information on the potential utility of the resultant product.

A medium to large scale land cover map, integrated with existing maps of soils and cultural resources and accompanied by a detailed accuracy assessment, would serve as a valuable reference for current and future investigators in the Barrow region. Bliss and Matveyeva (1992) have noted that without background knowledge of floristic and vegetation patterns in a given region, detailed studies of plant processes in such a region become less meaningful. In addition to providing detailed information on vegetation types and landforms for land use planners and resource managers of the North Slope, the outputs of this effort may prove useful to programs such as the recently established Arctic System Science (ARCSS)/Land, Atmosphere, Ice Interactions (LAII)/Arctic Transitions in the Land-Atmosphere System (ATLAS) program which has voiced the need for medium and large scale vegetation maps of the Barrow area.

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area. Additionally, the vegetation maps discussed herein may serve as a platform for proposed studies of land cover change in the Arctic, the effects of disturbance on the adaptation of plant communities to climate change, and other recently discussed scientific research initiatives.

I.C.II. Vegetation Maps and Global Climate Change Research

In addition to facilitation of localized management and research initiatives discussed above, Arctic vegetation maps contribute to an examination of the direct consequences of global climate change on ecosystem health, structure, and function, which is the subject of intensive research. The study of global climate and its interactions with the Earth's ecosystems is a complex research focus involving a myriad of feedbacks, interactions and other complex processes. The best available method for estimating future climate is with numerical climate models known as Global or General Circulation Models (GCMs) (Etkin and Agnew 1992). GCMs are numerical models consisting of equations, both diagnostic and prognostic in nature, designed to represent the Earth's atmosphere, surface, and immediate subsurface. Given a set of initial equations and forcing functions, GCMs simulate how the Earth's atmosphere may change through time.

Perhaps most important in the development in GCM's has been the recognition that significant changes in vegetation, wildlife, and larger scale landscape characteristics will accompany changes in climate (Edlund 1992, Etkin and Agnew 1992). Most notably, vegetation prediction has become an integral part of GCMs, permitting feedback from calculated vegetation descriptions to cli

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climate. Specific inputs to recent models include: general vegetation type; vegetation stature; patch roughness; vegetation surface albedo in the visible and near-infrared portions of the electromagnetic spectrum; net carbon gain or loss by vegetation; transpiration rates; stomatal resistance; root resistance to soil water uptake; and canopy-ground/canopy-atmosphere radiative and sensible heat exchanges (Henderson-Sellers 1993). Continental climates in current GCMs are highly dependent upon the outputs from equations using the above variables where vegetation is then permitted to feed back into climate model simulations in each subsequent iteration. Vegetation has thus become one of the most important and dynamic inputs into GCMs (Henderson-Sellers 1993).

Current modeling efforts using GCMs take a variety of formats and all still contain considerable sources of error. Despite the variety of approaches and outcomes to these methods, there are some points upon which all GCM outputs agree. Predictions of ambient temperature increases accompanying an atmospheric doubling of CO_2 range from 1.5° to 4.5°C as a global average (Maxwell 1992, Rizzo and Wilken 1992). All major GCM working groups in North America predict warming to be exacerbated at the high latitudes where temperature increases may range from 4° to 16°C during the winter months with more modest increases during the summer (Koerner 1992, Rizzo and Wilken 1992). In addition it has been noted that certain ecosystems, by their very ecological makeup or location are very sensitive to climatic change (Rizzo and Wilken 1992). Such ecosystems include Arctic Systems which are frequently comprised of wetlands or often represent plant communities at or near the fringe

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of their ecological range. While the entire land area of the Arctic is only 4% of the Earth's surface, the Arctic System is traditionally regarded as a net carbon sink (Maxwell 1992) and thus the land surface of this biome has the potential to significantly affect trophospheric CO_2 concentrations and in turn, Global Climate Change outcomes. Too little attention has so far been paid to the carbon balance of ecosystems north of 60° which have low annual productivity and low standing crops of above ground biomass, but have large areal extents, massive accumulations of peat, and high sensitivities to climatic change (Kelley and Gosink 1984).

It is widely accepted dogma in the literature that climatic change will have widespread and noticeable impacts on the Arctic environment. Edlund (1992) has noted that a warming of 2°-4°C would affect Arctic vegetation at all spatial scales. The impacts of climate change in the Arctic are potentially great simply because vegetation distribution is controlled largely by temperature and hydrology, two factors which stand to be altered significantly by and provide feedbacks to an accumulation of greenhouse gases and corresponding atmospheric warming (Edlund 1986, Edlund and Alt 1989). Precisely how Arctic climate will evolve in the future is uncertain both because of gaps in scientific understanding and a lack of knowledge of how quickly atmospheric greenhouse gasses will increase. The urgency in resolving the net effect of the myriad of feedbacks in the Arctic is evident in the discrepancies between various computer simulations for the general circulation of the atmosphere (LaDrew and Barber 1992). Because the current conditions of permafrost landscapes, including vegetation cover, influence the response of such regions to Global Climate Change, vegetation maps of Arctic Systems represent a critical link in the chain of modeling equations and forcing functions used in the formulation of modern GCMs. The land cover characterization provided by the vegetation maps presented in this thesis, coupled with such research efforts as the Circumpolar Arctic Vegetation Mapping Project (CAVM) (Walker and Lillie 1997) and the northern Alaskan component of the International Tundra Experiment (ITEX) (Walker 1997, Hollister 1998) stand to make a significant contribution to the study of the effects and feedbacks resulting from climatic amelioration in the Arctic System.

I.D. Research Framework

I.D.I. The Landsat Program

The efforts to achieve the goals of this thesis (see section I.D.II.) employ the use of Landsat Multispectral Scanner (MSS) and Landsat Thematic Mapper (TM) digital satellite data and automated image processing techniques. The Landsat Program is the longest running effort for the collection of multispectral, digital data on the earth's surface features from space (Sheffner 1994). A detailed history of this space-based remote sensing program can be found in the *Landsat Data User's Notes* published by the Earth Resources Observing System (EROS) Data Center (NOAA 1984). At the urging of the U.S. Department of the Interior, the National Aeronautics and Space Administration (NASA) initiated the Earth Resource Technology Satellite (ERTS) Program in 1967 (Jensen 1986). This program was retroactively named the Landsat Program to distinguish it from the Seasat Oceanographic Satellite Program which was launched in 1978. ERTS 1, later renamed Landsat 1 prior to the launch of Landsat 2 in 1975, was launched on July 23, 1972 beginning a legacy of (to this point) five satellites carrying a variety of remote sensing systems designed primarily for the acquisition of earth resources information.

Since the launch of Landsat 1, over 3 million Multispectral Scanner (MSS) and Thematic Mapper (TM) images (Sheffner 1994) have been acquired and stored at the National Satellite Land Remote Sensing Data Archive (NSLRSDA) at the EROS Data Center (EDC) in Sioux Falls, SD and at various Landsat international ground receiving stations. The temporal extent of the data collection, the characteristics and quality of the Landsat data, and the ability to collect new data directly comparable to that already in the archive, make the Landsat data a unique resource used extensively in the examination of a broad range of issues involving earth science, global change research, and the monitoring and assessment of land and coastal zone resources (Sheffner 1994). In addition, the regional perspective provided by a single Landsat scene facilitates consistent classification of land cover over large areas based upon spectral reflectance. Also important for consideration in the mapping of Arctic regions, the processing methods used with satellite data are well adapted for application to wildland areas composed of complex mosaics of ground cover. The 1:250,000 scale maps produced by traditional photointerpretive methods seldom have a resolution of less than 16 ha (40 acres). The 0.45 ha resolution of Landsat MSS, and even finer grain size of Landsat TM, preserve much of the co

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complexity of Arctic tundra vegetation patterns. This fact is important for the practical application of the maps to Arctic land use planning. The several other advantages associated with the use of Landsat multispectral digital data have been variously discussed above.

All five Landsat satellites operate in circular, near-polar, sun-synchronous orbits. Landsats 1-3, flying at a nominal altitude of 919km imaged the same 185kmX185km swath of the earth every 18 days while Landsats 4 and 5 flying at an altitude of 705km experienced a shorter repeat time of 16 days with the same swath width. Landsats 1-5 were all equipped with the Multispectral Scanner (MSS) sensor while Landsats 4 and 5 were also equipped with the Thematic Mapper (TM) instrument (Fig. 1-3). The Landsat MSS and TM sensors are optical mechanical systems in which discrete detector elements record the reflected solar radiant flux from the earth's surface as an electronic signal after this electromagnetic energy has been passed through a series of filters designed to pass discrete, broad portions of the electromagnetic spectrum. The MSS has four sets of filters and detectors, yielding four bands of information per image, while the TM provides seven bands of information with its seven sets of filters and detectors (Fig. I-4). Information regarding the spatial, spectral, radiometric, and temporal resolutions of the Landsat MSS and TM sensors is provided in Table I-2. While the ground resolution of the MSS instrument in commonly listed as 79mX79m, the data is provided to the user by the EROS Datacenter (EDC) at a ground resolution of 57mX57m due to resampling during image rectification. The first three Landsat satellites, equipped with the Multispectral Scanner or

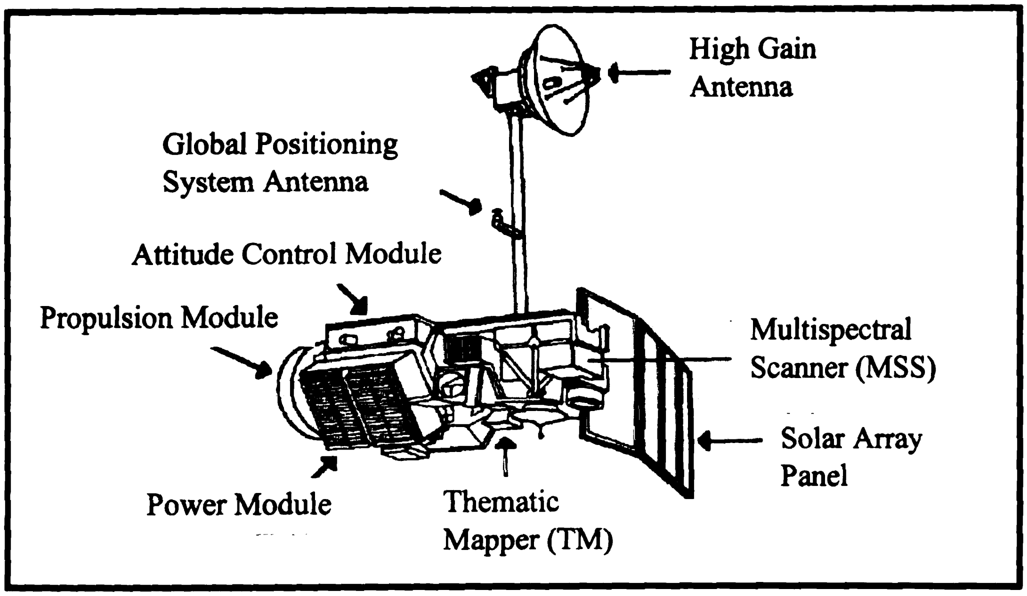
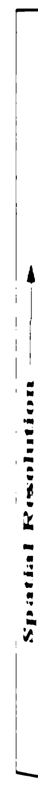


Figure I-3: Diagram of a Landsat satellite showing principle components and location of the Multispectral Scanner (MSS) and Thematic Mapper (TM) instruments.


Spatial Resolution

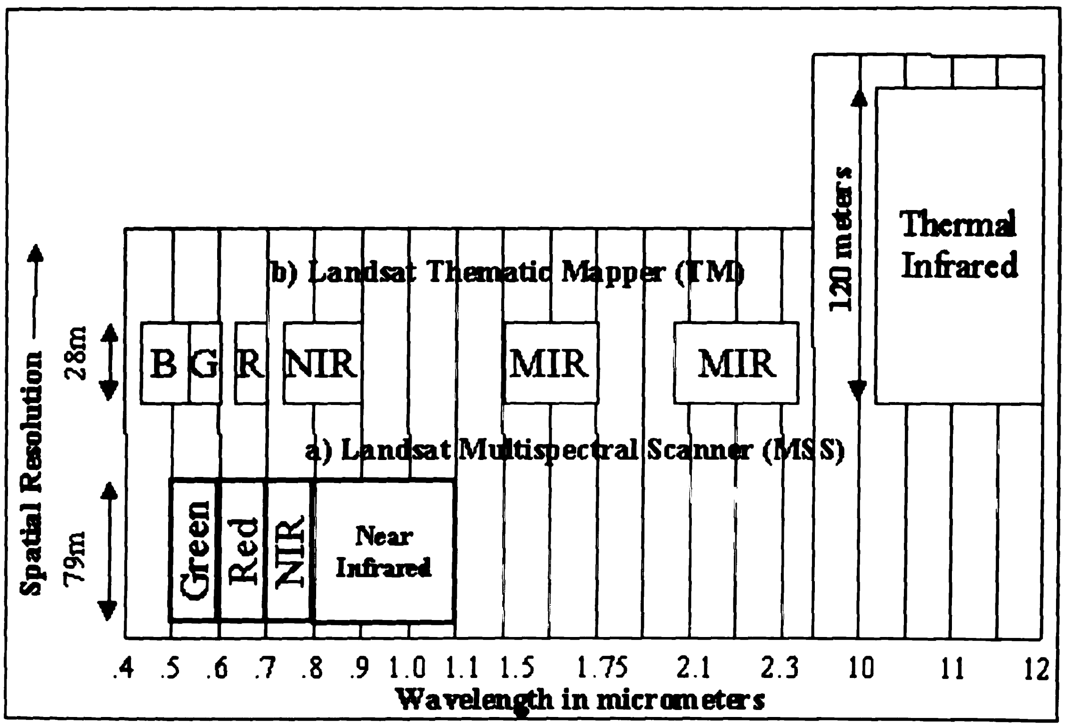


Figure I-4: Diagram showing spatial and spectral characteristics of the Landsat a) Multispectral Scanner (MSS) with its 4 spectral bands and 79m pixels and b) Thematic Mapper (TM) with its 7 spectral bands and 30m pixels.

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	Multispectral Scanner (MSS)		Thematic Mapper (TM)	
	Band Number	**Micrometers**	**Band Number**	**Micrometers**
	1[a]	0.5-0.6	1	0.45-0.52
	2	0.6-0.7	2	0.52-0.60
	3	0.7-0.8	3	0.63-0.69
	4	0.8-1.1	4	0.76-0.90
	5	10.4-12.6	5	1.55-1.75
			6	10.40-12.5
			7	2.08-2.35
IFOV at nadir	79m X 79m bands 1-4[b] 240m X240m band 5[c]		30m X 30m bands 1-5, 7 120m X 120m band 6	
	6 bits, 64 levels		8 bits, 256 levels	
Quantization levels	15MB/s		85MB/s	
Earth coverage	18 days Landsats 1,2,3; 16 days Landsats 4,5		16 days Landsats 4,5	
Altitude	919km		705km	
Swath width	185km		185km	
Inclination	99°		98.2°	

[a]=MSS bands 1-4 were originally numbered bands 4-7 on Landsats 1-3.
[b]=MSS data obtained as 79mX57m pixels and supplied to the user at 57m resolution.
[c]=MSS band 5 was present only on Landsat 3.

Table I-2: Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM) Sensor System Characteristics.

MSS, recorded data in four wavelength bands in the visible and near infrared portions of the electromagnetic spectrum. Landsat's 4 and 5 retained the MSS instrument and were also equipped with the Thematic Mapper or TM sensor which had capabilities similar to the MSS but also provided for sensing in the middle and thermal infrared portions of the electromagnetic spectrum. Note that, with the exception of TM band 6 (thermal or emitted infrared wavelengths), the TM instrument boasts significant improvements in spectral, spatial, and radiometric resolution over the MSS sensor.

It has been noted in the literature (Walker 1983, Walker and Acevedo 1987) that the landscape of the Arctic Coastal Plain Province of Alaska's North Slope (which includes the Barrow Region) has several characteristics which make it particularly suitable for the use of Landsat imagery in land cover mapping. First, the major vegetation types of the landscape are all related to environmental gradients that are predictable from spectral information. For instance, the Arctic Coastal Plain is patterned by suites of plant communities which respond to changes in moisture. The moisture regimes of soils in the summer largely determine which types of plant communities occur within each temperature range and soil type. Wetland areas in the Barrow Region are dominated by sedges and grasses. Mesic sites will have a nearly complete vegetation cover with varying proportions of graminoids, forbs, and woody dicot vascular species. Well drained sites will have sparse vegetation with higher proportions of lichens. In addition to following spectrally identifiable environmental gradients, the vegetation of the Arctic Coastal Plain is low-growing

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tundra vegetation with no trees. Thus, the ground cover is readily visible by satellite remote sensing. Finally, the region is flat, with few topographically induced shadows that may modify the spectral signature of specific vegetation types.

While Landsat multispectral digital data is an excellent resource for the mapping of Arctic land cover on the basis of cost, areal coverage, consistency in classification, and vegetation characteristics, a classification of Landsat data for the purposes of vegetation mapping must recognize the limitations of the data. First, the spatial resolution of both MSS and TM digital satellite data is insufficient to resolve complex microtopographical characteristics that are often important in determining plant community distribution in Arctic tundra. Many vegetation complexes associated with patterned ground, including polygonized tundra, strangemoor, frost scars, hummocks, and reticulate patterned ground, are not discernible on the satellite images selected for use in this thesis. The major limitation of Landsat data and the related land cover classification methods is that the final mapping units are based solely upon surface reflectance and not on the presence or absence of any specific vegetation type. There are two characteristics of northern Alaskan vegetation that affect its spectral reflectance and thus are most important with regards to Landsat-derived vegetation classifications: the amount of water on the surface of the landscape; and the percent of deciduous shrubs in the vegetation canopy (Walker et al. 1982, Walker and Acevedo 1987). Numerous other factors including the total percentage of plant cover, the amount of erect, dead graminoid vegetation, the substrate color, the amount of lichen cover, and the nutrient status of the site will also affect the reflectance values recorded at the satellite sensor (Walker et al. 1982, Walker and Acevedo 1987). Despite the aforementioned limitations, Landsat digital data provide an attractive alternative to traditional photointerpretation methods in remote and extensive regions such as Alaska's North Slope. Mapping from satellite imagery is proving extremely useful in classifying large areas, representing large scale tundra vegetation pattern, and representing seasonal variation of tundra environments. Landsat satellite imagery and the associated image processing techniques have been applied with considerable success in tundra environments (see Markon 1995 for a summary) and have consequently been selected for use in this research.

I.D.II. Research goals

During the summer of 1997, members of the BEO management committee approached the Michigan State University Arctic Ecology Laboratory and expressed their desire that a vegetation map be prepared for the Barrow Region to aid in the development of a BEO management plan, to serve as a resource to the Planning Commission of the North Slope Borough, and to facilitate ongoing environmental research and education in the Barrow area. The goal of this thesis is the production of a map of the vegetation of the Barrow Region on the North Slope of Alaska through the use of remotely sensed data. The principle products of this research are two 1:63,360 scale vegetation maps of the Barrow Region prepared from multispectral, digital data of two different spatial scales. Each map is accompanied by a detailed accuracy assessment summarizing the utility of the information contained in the final products. In addition, the resultant maps will be incorporated into a digital geographic information system (GIS) including digital cartographic data and a map of soils for the region. Incorporation of the GIS created during this project into the databases of the North Slope Borough, the National Snow and Ice Data Center (NSIDC), and the Institute for Arctic and Alpine Research (INSTAAR) will provide a detailed inventory of topography, vegetation, soils, and cultural resources which will be useful to investigators and resource managers requiring information on land cover in this area of northern Alaska.

Observational studies on the general vegetation types dominating a particular region do not lend themselves to traditional scientific experimentation involving the proposal of hypotheses followed by rigorous statistical testing. Nevertheless, it is still useful to keep in mind key research questions that may guide one's efforts and provide a framework within which to discuss key results. With this in mind, the underlying question driving this research project is as follows: *What discrete vegetation types, identifiable based upon their multispectral signatures, dominate the landscape of the Barrow Region, northern Alaska and in what proportions are these vegetation types present upon the landscape?*

The ultimate goal of this thesis is the production of vegetation maps that will prove useful to planners and resource managers working in the Barrow Region, several of the current National Science Foundation (NSF)/Arctic System Science (ARCSS)initiatives, the National Aeronautics and Space Administration

(NASA) sponsored research initiatives, the Circumpolar Arctic Vegetation Mapping (CAVM) effort, and ongoing Global Climate Change modeling. Proposal of hypotheses relative to the information content and derived map accuracy of the satellite data of different spatial and spectral resolutions is important to ensure maximum utility of the resultant map products.

For the sake of clarity in presentation, research questions and hypotheses are discussed under two headings: general applicability of Landsat digital data to mapping the Barrow landscape and comparison of the accuracy or information content of Landsat TM and MSS satellite sensors. Each of these issues is discussed in turn in relation to general research questions, specific hypotheses, and rationale.

Question 1: Can Landsat digital satellite data from the Thematic Mapper (TM) and Multispectral Scanner (MSS) instruments be employed to accurately represent the dominant vegetation types present on the landscape in the Barrow Region?

Hypothesis: Both the Landsat TM and MSS sensors provide data enabling the preparation of vegetation maps which will accurately represent the general vegetation types present on the landscape in the Barrow Peninsula.

Rationale: A feasibility study conducted by Anderson *et al.* (1973) in addition to early Landsat assisted mapping efforts within the National Petroleum Reserve in

Alaska (NPRA) (Morrissey and Ennis 1981) and a cooperative resource mapping effort between the Alaska Bureau of Land Management (BLM), the National Aeronautics and Space Administration (NASA), and the U.S. Geological Survey (USGS) (Krebs 1980, Shasby and Carneggie 1986) have suggested that Landsat digital satellite data are particularly suitable for mapping large remote regions in northern Alaska. In addition, the widespread use of Landsat data in northern Alaskan mapping efforts subsequent to initial exploratory studies (see section I.B.II.) points to the general applicability of digital multispectral data in mapping land cover and other natural resources in the Arctic. Unfortunately, while a myriad of mapping efforts employing Landsat digital data have been undertaken in the Alaskan Arctic, only three studies, that the author is aware of, have been accompanied by statistically valid estimates of the accuracy of the resultant maps (Muller *et al.* 1998, Fleming 1988, Felix and Binney 1989).

If land cover maps prepared from digital satellite data are to be of use to resource managers, planners, and scientists, such maps must be accompanied by metadata or some other quantitative indication of the accuracy or utility of the information contained therein. The U.S. Geological Survey suggests that the minimum level of accuracy for land use and land cover information derived from remote sensor data should be at least 85% (Fitzpatrick-Linz 1981, Anderson *et al.* 1976) to provide maximum utility to a variety of user groups. It is thus the working hypothesis for this thesis that Landsat digital data from both the TM and MSS instruments can be employed to produce land cover maps of Alaskan Arctic

Tundra at an overall accuracy level of 85% at the 0.95/0.05 confidence level. Methods for statistical testing of this hypothesis will be explored in Chapter 4.

Question 2: Are land cover maps derived from Landsat Thematic Mapper (TM) data, with it's increased spatial, spectral, and radiometric resolution, able to provide information at a higher level of accuracy relative to maps derived in an identical manner from Landsat Multispectral Scanner (MSS) data?

Hypothesis: Maps produced from Landsat TM data will provide information on land cover in the Barrow Region that is more accurate than maps of the same area, derived in the same manner using Landsat MSS data.

Rationale: With the exception of the studies by Markon and Derksen (1994) and Stowe *et al.* (1989), all efforts to map vegetation on the Arctic Slope of Alaska using digital satellite imagery (see section I.B.II.) have employed Landsat MSS data. Even after the addition of the TM instrument to the Landsat arsenal with the launch of Landsat 4 (NOAA 1984), researchers have persisted in the use of Landsat MSS data to map tundra vegetation in Arctic Alaska. As the TM sensor boasts significant improvements in spatial, spectral, and radiometric resolution relative to the MSS instrument, the question becomes one of why researchers would persist in using an inferior instrument in the face of improved technology which provides significantly more information. It is not within the scope of this thesis to hypothesize on trends in digital satellite information usage but rather to show that the Landsat TM sensor is capable of producing more accurate maps of Arctic tundra vegetation that the MSS instrument.

The increase in spatial resolution from approximately 80m in the case of the MSS instrument to approximately 30m with the TM instrument (Jensen 1986) yields a finer grain size over the landscape and thus should reduce errors in classification due to mixed pixels at the boundary between land cover classes. In addition, the TM instrument has 7 spectral bands of information in contrast to the 4 spectral bands of information present in MSS data. Furthermore, band 3 of MSS data is focused on a portion of the near infrared spectrum in which all vegetation undergoes a transition in reflective properties (Fig I-5), thus reducing the value of information in this band when mapping vegetation is of primary interest (Lusch and Hudson 1998). Finally, quantization of radiance values recorded at the MSS instrument is conducted using 6 bit encoding allowing only 64 possible values. The TM instrument encodes recorded radiance values using 8 bit encoding which allows digital numbers to be scaled from 0 to 255 thus reducing instances of assigning identical digital numbers to differing radiance values (NOAA 1984). For these reasons we would expect that the increased information available in a TM digital image will yield more accurate vegetation maps than the identical MSS image when the image processing steps are performed in the same manner on each image. Models for statistical testing of this hypothesis are presented at length in Chapter 4.

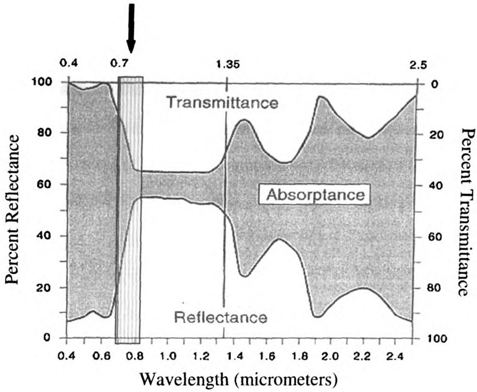

Figure I-5: Graph of generalized reflectance and transmittance properties of green vegetation in a portion of the electromagnetic spectrum. Note the arrow indicating the region of the spectrum covered by MSS band 3 (Near Infrared). Vegetation differentiation in this region is confounded by the rapid transition in vegetation reflectance values.

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Chapter 2

LAND COVER CLASSIFICATION AND ITS APPLICATION TO THE BARROW REGION

II.A. LAND COVER CLASSIFICATION: BACKGROUND

Inventorying and classifying data or information represents one of the fundamental beginnings of human knowledge (Lynch 1984). Classifications label and show relationships among items, while inventories simply produce and summarize information (Driscoll et al. 1984). Numerous authors (e.g., Grigg 1965, Shimwell 1971, Sokal 1974) agree on the basic principles involved in classification. It is the everyday task of intentionally grouping objects that are similar and separating those that are dissimilar (Nelson et al. 1978, Driscoll et al. 1984). Classification is an information technology which serves to systematically name and illustrate relationships among objects under consideration and, in this manner, bring order to our communication and thinking (Nelson et al 1978, Bailey et al. 1978, Frayer et al 1978). Thus, any classification system may be viewed as providing a framework, within which we may organize knowledge regarding any number of things and allow generalizations to be made regarding those things being classified. In addition, classifications provide structure for large data sets and permit rapid interpretation of large quantities of information which can subsequently be presented in a concise manner. Classification of land cover is often conducted in concert with mapping efforts on a variety of spatial scales in an effort to present the resultant data in a form conducive to rapid visual interpretation by the user community.

Wide acceptance of the general description of the principles of classification described above paints a rather optimistic picture of the present science and process of land classification and mapping. Despite widespread agreement on the principles and potential uses of land classifications, the diversity of uses of the resultant data has led to a corresponding diversity of systems of classification (Ellis et al. 1977, Loveland et al. 1991, Viereck et al. 1992). Considered holistically, land classification and mapping is an extremely complex problem requiring several types of classification schemes based upon such things as inherent land cover characteristics, potential land uses, recommended uses, etc. (National Resources Planning Board 1941). In addition, wildland areas require the collection of information regarding timber resources, hydrology, recreation potential, cultural features, and other details. The result is that a staggering number of resource and land classification systems have been developed. Apparently, each new work group has often forged ahead with a classification procedure and vocabulary development to meet its own unique and often narrow requirements. Such a disorganized approach to classification and mapping is inefficient, wasteful in terms of time, effort and financial resources, and inadequate to address the needs of land and resource managers in search of a standard approach to description of the terrestrial environment.

It has been acknowledged that it is unlikely that a single system of classification, applicable to all needs in the public and private sector, will be developed in the near future (National Resources Planning Board 1941, Gilmour 1951, Hirsch et al. 1978, Nelson et al. 1978, Lent 1984). It is however, entirely possible to construct a classification system in a manner which will serve a considerable proportion of the needs of the user community (Walker 1983, Driscoll et al. 1984). The characteristics of such a classification scheme warrant discussion.

Development of classification systems for use in resource management and land cover mapping exercises is distinct from those classifications developed to describe vegetation consistent with phytosociological or phytocenological principles. Phytosociology, or more correctly phytocenology (Kuchler 1967), attempts to study and classify vegetation based primarily on floristic rather than life form or other characteristics. While floristic criteria, as well as the numerical relations within vegetation communities play a significant role in several land cover mapping efforts (Troll 1939, Pina and Albuquerque 1954, Gaussen 1948, Ellenberg and Zeller 1951 as cited in Kuchler 1967), a detailed discussion of phytosociological objectives and methods is beyond the scope of this thesis. A summary of the basic approaches to classification from a phytosociological or phytocoenological standpoint can be found in Oosting (1956), Kuchler (1967), or Shimwell (1971).

The purpose of a classification system from a land or resources management perspective is to collect, organize, and communicate information useful in management and policy making decisions. In this context a classification system is expected to provide a framework for policy planning and implementation, an information resource for research and development initiatives, and a management decision-making tool, among other things (Frayer et al. 1978). Following a consideration of the needs of the major players in the user community, Bailey et al. (1978), Frayer et al. (1978), and Nelson et al. (1978) presented several criteria for classification designed to produce a system for characterizing and mapping land cover and/or resources which would provide maximum utility. First, the system should be flexible, general and of wide geographic applicability so as to facilitate the presentation of several types of information at a variety of geographic and administrative levels and in a variety of environmental situations. Classification and mapping units should be relatively homogeneous and should respond more or less uniformly to experimental treatments. The system should be based upon concepts and logic which can be explained to the non-technical user and quantified for incorporation into empirical computer-based information systems. To provide maximum utility on a variety of scales, units within the classification system must be identifiable at a variety of scales including by close inspection of ground plots, and by use of aerial photography and smaller scale remote sensing systems.

The ideal classification system should also be ecologically based according to Driscoll et al. (1984) and Gallant et al. (1995). Basing the system upon observable, quantifiable, ecological phenomena increases the chances that the system can be applied in a variety of geographic settings, at several spatial scales, and in a manner that can be experimentally validated as being professionally credible. There is also much concern on the part of land and resource managers that an ideal classification system be designed as a hierarchy (Walker 1983, Driscoll et al. 1984, Gallant et al. 1995). A hierarchical system of classification lends itself to multiple uses as information can then be presented at a variety of spatial and administrative scales and changes can be made to the system through aggregation or division of levels in the hierarchy as special needs require.

To ensure maximum usefulness, classifications should also be developed using a multitude of factors (Cline 1949, Gilmour 1951, Bailey et al. 1978). Single-factor classifications, as the name implies, use only a single character in the development of the system and prediction of other characteristics of a given site or cover type is completely fortuitous. In contrast, multi-factor systems of classification can summarize several distinguishing characters defining cover type and be interpreted for several purposes. Once a classification scheme has been defined in this manner, cover type classification and mapping can be reduced to an examination of a very few important site characteristics which can then be examined and employed by a multitude of people who need know nothing of the number of characters employed in its initial construction.

While no single system can meet all of the aforementioned criteria, any system should, at minimum, be objective and quantifiable (Frayer et al. 1978).

Following this consideration of the variety of perspectives on classification and the number of characteristics which may be incorporated in their development, it should come as no surprise that the literature is cluttered with a variety of classification schemes. Even when one narrows the focus to the Arctic, or takes the finer view of the state of Alaska, the resulting number of classification schemes is staggering and often confusing.

II.A.I. Broad Descriptions of Arctic Land Cover

Beginning in the mid-nineteenth century (Trautveter 1851), various authors have proposed broad biogeographic divisions of the Arctic tundra system, considered in this thesis to be that region of the globe north of the latitudinal treeline approximated by the 10°C mean July isotherm (Chernov and Matveyeva 1997) (Fig. II-1). Various authors, primarily in Russia and North America, have presented differing views on the biogeographic zonation of Arctic tundra (e.g., Alexandrova 1969, Webber 1974, Alexandrova 1977, Komarkova and Webber 1978, Bliss 1988, 1997, Edlund 1992, Chernov and Matveyeva 1997). Polunin (1951) divided the North American Arctic into High-, Middle-, and Low- subzones while, in the same year, Porsild proposed "ice desert", "rock desert", and "tundra" as alternative terms of classification. In 1969, Young proposed a four-tiered division of the Arctic based primarily on floristics. Webber (1974) divided the Arctic into High-, Low-, and Polar Desert subzones based upon the vegetation characteristics of mesic sites. Tedrow's (1977) classification of broad biogeographic regions within the North American Arctic partitions the biome into "tundra", "sub-polar desert", and "polar desert" based

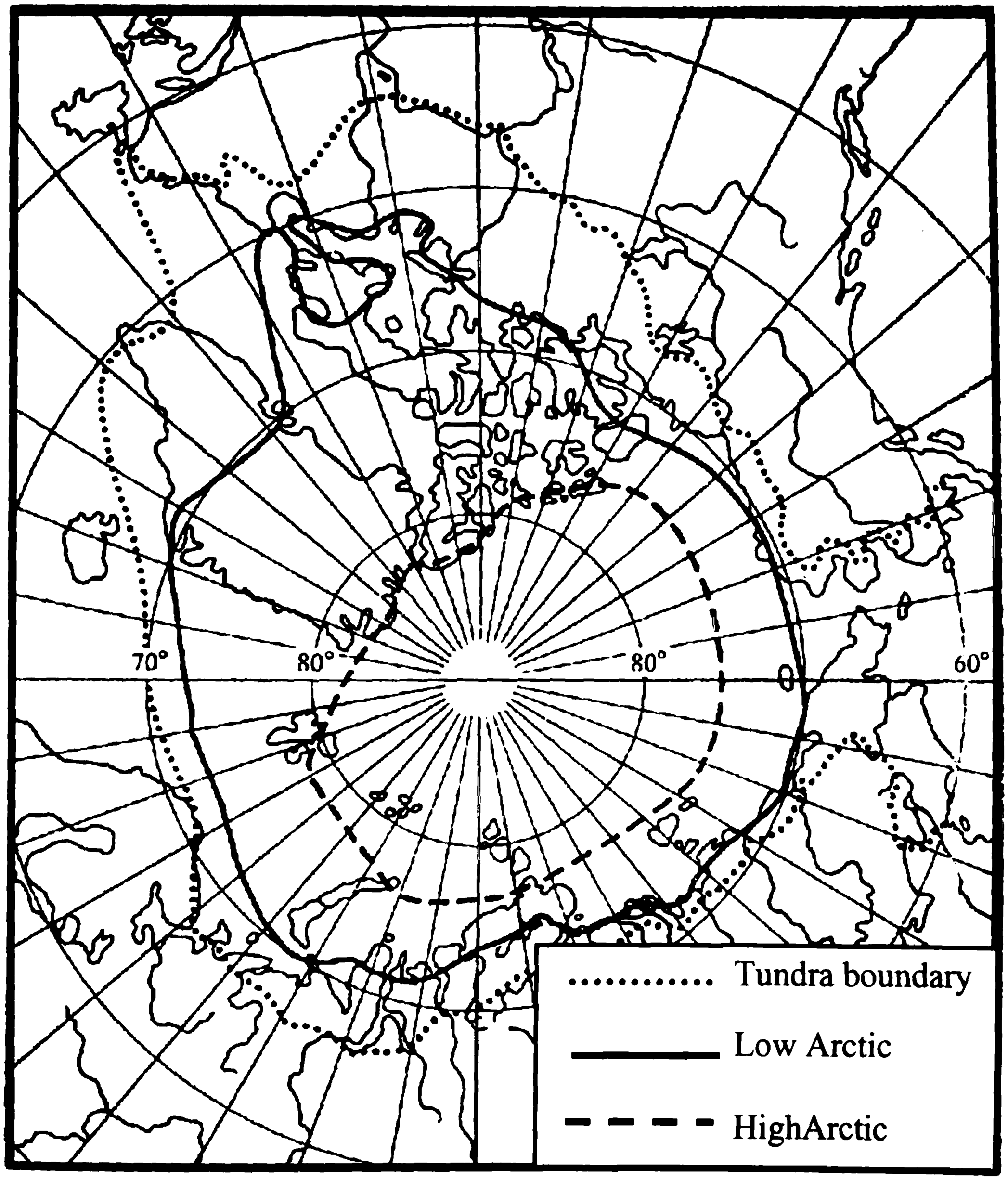

Figure II-1: Circumpolar map showing the southern limits of the tundra ecosystem, Low Arctic tundra, and High Arctic tundra (as described by Alexandrova 1980). The southern tundra boundary coincides roughly with the 10°C mean July isotherm.

upon soil characteristics. To avoid the confusion which invariably accompanies an immersion in the debate surrounding Arctic biogeographic provinces, the list presented here is incomplete. The key point however, is clear: While each of these classifications of the Arctic tundra is important from a general biogeographic standpoint, they are too broad to serve the needs of land and resource managers or the scientific community who require more detailed information regarding local vegetation communities, soils, hydrology, and other land cover characters.

II.A.II. Classification and Mapping of Land Cover in Arctic Alaska

Knowledge of vegetation, more than any other factor, is employed in land-use planning and resource management of tundra regions (Walker 1983). Vegetation cover provides insight into a variety of environmental factors including hydrology, permafrost properties, and soil properties including depth of the active layer, temperature, and winter snow cover conditions (Brown 1976, Everett et al. 1978, Webber and Ives 1978). Accordingly, the following reviews of land cover classification schema developed for use in Arctic Alaska revolve largely around the state of the vegetation covering the landscape.

An examination of the literature dealing with more detailed land cover classification systems useful for application to research or resource management issues in northern Alaska is a daunting task. A search limited to classifications developed for use in the Northwest United States and Alaska revealed a single reference (Ellis et al. 1977) summarizing 55 different classification schemes! The majority of these classification systems were developed for very narrow uses such has broad habitat type delineation or *potential* land use summaries and thus represent subjective cover type categories with little relevance for presenting an integrated ecological view of the present state of the landscape. In addition, at least 15 other systems of classification, used primarily in remote areas in Alaska or employed in broad biogeographic representations, were discovered elsewhere in the literature (Spetzman 1959, Kuchler 1969, Joint Federal-State Land Use Planning Commission for Alaska 1973, Webber and Walker 1975, Bailey 1976, Everett et al. 1978, Lawson 1978, Komarkova and Webber 1980, Brown et al 1980, Walker 1983, Viereck et al. 1981, 1982, 1992, Hall 1991, Bailey et al. 1994, Gallant et al. 1995).

Kuchler's (1969) map delineates the *potential* natural vegetation of Alaska based upon a variety of abiotic factors and thus is not of much use to researchers and land managers interested in the actual present state of the landscape. Land cover maps by Spetzman (1959), the Joint Federal State and Land Use Planning Commission for Alaska (1973), Bailey et al. (1994) and Gallant et al. (1995) represent attempts to delineate broad ecoregion classifications which are also of insufficient detail in terms of information and spatial scale for use in management planning or research initiatives. Webber and Walker (1975), Lawson et al. (1978), Komarkova and Webber (1980), Brown et al. (1980), all developed classification schemes and large-scale map legends for special purpose mapping endeavors, of minimal geographic extent, to facilitate ecological research and environmental planning in the Prudhoe Bay, Fish Creek, and Barrow regions on the North Slope of Alaska. While useful in relation to each of their respective program goals, the classification schemes are not widely used within the state of Alaska and a system for uniform applicability of methods and legends was not proposed in any of the above cases.

Subsequent to the passage of the Alaskan National Interest Lands Conservation Act (ANILCA) of 1980 (see section I.B.II.), there was a significant effort to standardize the classification scheme employed in Alaskan land cover mapping in order to facilitate the development of statewide databases of cover types for all public lands in the state within the seven year period mandated by the legislation. The classification systems developed by Walker (1983) and by Viereck et al. (1981, 1982, 1992) have received the most attention in the widespread mapping of Alaskan lands that has been conducted at a variety of scales (e.g., Shasby and Carneggie 1986, Talbot and Markon 1986, Walker and Acevedo 1987, Stow et al. 1989, Walker et al. 1989, Markon and Derksen 1994) following passage of the ANILCA. Because of their widespread use in the mapping of Arctic Alaskan tundra, it is these two classification systems which will receive the most attention here.

II.A.II.a. The Alaska Vegetation Classification

The final vegetation classification for the state of Alaska, developed by Viereck et al. (1992) over a 16 year period, is a taxonomic system (Bailey et al. 1978) designed to satisfy a variety of needs. Consistent with the recommendations of Cline (1949), Gilmour (1951), and Bailey et al. (1978) (see section II.A.) the resulting scheme is a multifactor system based upon all plants at any location (the relative abundance of individual plant species). The classification system presented by Viereck et al. (1992) is largely based upon characteristics of the vegetation itself with occasional reference to habitat features where needed for clarity. The system is hierarchical and comprised of units at five levels of resolution (levels I through V). The broadest, most general level of classification (level I) is distinguished primarily on the basis of vegetation stature and is divided into forest, scrub, and herbaceous vegetation categories. Level V represents the finest level of resolution and describes individual plant communities while levels II, III, and IV are intermediate between these two extremes.

To be considered as a vegetation type in the Viereck et al. (1992) system of classification, at least 2% of the land cover in a given area must be vegetation. Landscape patches having less than 2% cover are considered unvegetated or barren. Forest land cover units are distinguished based upon crown canopy cover and arboreal species composition down the hierarchy to level IV. Level II classes for forested lands are needleleaf, broadleaf, and mixed forest while level III classes are distinguished on the basis of total tree canopy cover as suggested by Fosberg (1967). In contrast, level IV forest units are determined by those tree species comprising at least 25% of total tree canopy cover. Scrub vegetation classes are based upon shrub height, shrub canopy coverage, and species composition down the hierarchy to level IV. Scrub classes for the level II classification are dwarf tree scrub, tall and low scrub, and dwarf scrub. Level III divisions for dwarf tree scrub vegetation are the same as those described above for forest, while the subunits of tall, low, and dwarf scrub are aggregated based upon dominant plant species associations.

Herbaceous vegetation is comprised of a diversity of non-woody species ranging from aquatic algae, to bryophytes, to terrestrial graminoids. Level II units in the Viereck et al. (1992) system are designated as graminoid, forb, bryoid, and aquatic herbaceous vegetation categories in an attempt to impose order on this tremendous diversity of growth forms and habits. At level III in this hierarchy, graminoid and forb vegetation may be distinguished on the basis of a subjective moisture gradient: Each cover type may be classified as dry, mesic, or wet. Bryoid vegetation is further divided into mosses and lichens and aquatic vegetation becomes subdivided based upon the salinity of the water in which it grows (saline, brackish, or freshwater).

The system developed by Viereck et al. (1992) represents a tremendous effort to develop a multifactor, hierarchical system of vegetation classification that will standardize land cover mapping efforts in the state of Alaska and serve a variety of needs within the user community. A significant portion of the land cover classification and mapping that has been performed in Alaska since the early 1980's has been conducted using this classification system as the basis for the map legends (e.g., Shasby and Carneggie 1986, Talbot and Markon 1986, Fleming, 1988, Markon 1992). For the purposes of this thesis however, this classification scheme has major drawbacks. First, the system incorporates all vegetation communities in Alaska and is thus so lengthy as to be considered inefficient when the primary interest is in the study and classification of tundra vegetation. Secondly, the system is not designed primarily for mapping and thus the proscribed vegetation units are often not consistent with those characteristics which can readily be inferred from Landsat data. The system is also difficult to use in developing Landsat-derived land cover classifications because it is based upon vegetation characteristics which are not traditionally easily identified through examination of Landsat data (see section I.D.I.).

II.A.II.b. The Walker Hierarchical Tundra Vegetation Classification

In contrast to the system developed by Viereck et al. (1992), the Walker (1983) vegetation classification system was especially designed for mapping the tundra of northern Alaska. This classification system describes tundra vegetation in a hierarchical structure employing four levels (A through D). Level A describes very general vegetation types useful in the small-scale mapping of vegetation in northern Alaska. This broad level of classification is made up of water, wet tundra, moist tundra, shrubland, partially vegetated/barren, and ice cover types corresponding roughly to the classes employed by the Joint Federal-State Land Use Planning Commission for Alaska (1973) and the USGS land cover classification system for remote sensor data (Anderson et al. 1976).

Level D represents the finest level of resolution in the classification scheme and describes specific vegetation communities corresponding to the stand type of Marr (1967), the plant community type of Whittacker (1967), the nodum of Komarkova and Webber (1980), or the association of Braun-Blanquet

(1932, 1951). This level of the classification has a multitude of discrete units and is open to inclusion of any newly described vegetation community. Plant community names are consistently derived in accordance with strict guidelines. The community names always contain four parts: a site moisture term, the dominant plant taxa, the dominant plant growth forms, and a general physiognomic descriptor. Detailed instructions for the construction of level D community names can be found in Walker (1983) or Walker and Acevedo (1987).

Level C in the hierarchy is recommended for use in photo-interpretive mapping efforts at scales from 1:6,000 to 1:63,360. Because the species composition of tundra vegetation can rarely be determined from aerial photography, the level C nomenclature drops the dominant plant taxa component from the classification scheme. The remaining characters (the site moisture term, the dominant plant growth forms, and the physiognomic descriptor) employed in the level D classification are still employed at this level of resolution. The number of possible cover types at this level is constrained by the number of discrete moisture regimes and vegetation growth forms present in the area under study.

Level B land cover units in this system are delineated based upon those vegetation characteristics which are commonly employed in classifications based upon Landsat data. The amount of water on the land surface and the amount of deciduous shrubs in the vegetation canopy are the two primary characters of Alaskan tundra vegetation which have a significant impact on surface reflectance properties and thus are most important to consider in Landsat-assisted mapping efforts. While numerous other land cover characteristics including amount of erect dead vegetation, percent cover of vegetation, substrate or lichen color, and soil nutrient regime also affect multispectral reflectance values as recorded by Landsat, the original 12 level B cover types are described based upon site moisture status, proportion of shrubs in the plant canopy, and, in the case of barren or partially vegetated areas, the total percentage of plant cover. Subsequent to the publication of the original classification scheme by Walker in 1983, the system has continued to evolve, primarily through the aggregation of several level B classes which are not easily separated on Landsat images. For example, dark and light colored barren lands can probably be aggregated for the purposes of most cover type mapping without a significant loss of information.

The classification hierarchy of Walker (1983) has been employed with considerable success on the North Slope of Alaska. Walker et al. (1982) mapped the Arctic National Wildlife Refuge (ANWR) using this method. In addtion, the land cover of the Beechey Point (Walker and Acevedo 1987) and Sagavinirktok (Walker and Walker 1985) quadrangles was mapped using the Walker (1983) classification scheme. Level C cover type maps have been prepared for the Imnavait Creek watershed in the foothills of Alaska's Brooks Range (Walker et al. 1989) and the classification has also been used in association with SPOT/XS-HRV digital data to map vegetation in the Arctic Foothills with some success (Stow et al. 1989). Most significantly, Walker and

Walker (1991) have shown that this hierarchical system lends itself particularly well to incorporation into geographic information systems (GIS) at a variety of spatial scales. In an effort to examine the history and pattern of disturbance on Alaska's North Slope, Walker and Walker (1991) used the classification hierarchy in the construction of a three-tiered GIS with five sublevels which presented typical scientific and management initiatives at each level and linked multiple elements between levels.

Neither the Viereck et al. (1992) classification system nor that developed by Walker (1983) address each of the recommendations for an ideal classification system presented in section II.A. above. However, each has addressed a number of the issues which must be considered in the development of an effective classification and mapping scheme. Because the Walker (1983) system was developed specifically for use in the mapping of tundra land cover, it lends itself well for use in the research presented in this thesis. At the second level (level B) in the hierarchy, land cover types are described based upon those characteristics of the vegetation that can be consistently classified from digital multispectral data (see section I.D.III.). At finer scales of classification and mapping, the system attempts to avoid subjectivity through the description of multiple factors and yet remains flexible so as to facilitate recognition of the heterogeneity present within tundra landscapes.

The classification scheme eventually prepared as the legend to the final map outputs is a modified version of the that developed by Walker (1983) as a hierarchical land cover classification system. For application to the Barrow landscape, the *Barren* and *Partially Vegetated* land cover classes were aggregated into a single *Barren or Partially Vegetated Surface* class. In addition, the *Very Wet Tundra* and *Wet Tundra* cover classes have been aggregated into a single *Wet Tundra* class. The spectral resolution of both the TM and MSS sensors makes it difficult to distinguish surfaces with less than 30% cover from unvegetated surfaces. In addition, the vegetation of *Wet* and *Very Wet* tundra classes of Walker's (1983) classification scheme is often the same with the site moisture frequently determining class membership. The distinction between "very wet" and "wet" areas thus becomes blurred over the course of the growing season depending upon the dynamic hydrology which may change with increased depth of thaw and prolonged precipitation or drying events. The final classification scheme selected for use in this research thus includes 8 classes: *water; wet tundra; moist/wet tundra complex; moist or dry tundra; moist tussock sedge, low shrub tundra; moist shrub rich tundra; shrubland; and partially vegetated or barren surfaces* (Table II-1). *Moist tussock sedge, low shrub tundra* and *shrubland* are not represented in the final maps simply because these land cover types do not occur in the study area.

II.B. The Vegetation of the Barrow Peninsula

The research area covers much of the land area loosely referred to as the Barrow Peninsula. The geographic area included in the map area extends from approximately 71° 15' N to 71° 25' N and from 156° 20' W to 156° 55' W and represents the northernmost land area in the United States. The Barrow

Land Cover Class	Brief, General Description	Map Color
Water	Ice, ocean water, all inland fresh water (< 40% vegetation).	
Wet tundra	Marshy areas with ephemeral shallow water or saturated soils.	
Moist/wet tundra complex	Low-centered ice wedge polygon complex.	
Moist or dry tundra	Complete/nearly complete vegetation cover; relatively species rich.	
Moist shrub rich tundra	Dominated by dwarf shrubs often forming a dense mat.	
Partially vegetated or barren areas	Beach gravel, developed or disturbed areas, partially vegetated surfaces.	

Table II-1: A summary of the six land cover classes, derived for the Walker (1983) classification, selected for use in the mapping of the Barrow Region, northern Alaska.

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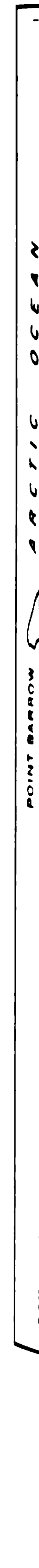
Peninsula is a 25,000 year old (Brown and Selleman 1973) spit of land extending into the Arctic Ocean. It is bordered by Elson Lagoon on the east and the Chukchi Sea on the west. The village of Barrow sits on the west coast of the peninsula at approximately 71° 18' N, 156°40' W (Fig. II-2). The climate of the peninsula (Fig. II-3) is characterized by long, cold winters and a short, cool growing season during which the temperature may fall below zero on any given day. The snow free period is variable but usually lasts from early June to early September each year. The sun does not rise from November 18 to January 24 and is above the horizon 24 hours a day from May 10 until August 2. The coastal tundra of this region is underlain by ice rich permafrost producing a dominant pattern of ice-wedge polygons and shallow tundra lakes. The vegetation of the Barrow Region is characteristic of coastal tundra (Brown et al. 1980) and is dominated by graminoids (principally *Carex aquatilis ssp. stans* and three species of the Genus *Eriophorum*). The Barrow tundra is mainly acidic (Walker et al. 1998) and has a rich bryophyte component with a variety of lichens.

The vegetation classification selected for use in this research (see section II.A.II.b.) divides the tundra of the Barrow Peninsula into several distinct vegetation associations which will be discussed in turn below. For preparation of final vegetation maps of the region, classes defining *water*, *wet tundra*, *moist/wet tundra complex*, *moist or dry tundra*, *moist shrub rich tundra*, and *partially vegetated or barren areas* were delineated and will be described here.



POINT BARROW
ARCTIC OCEAN

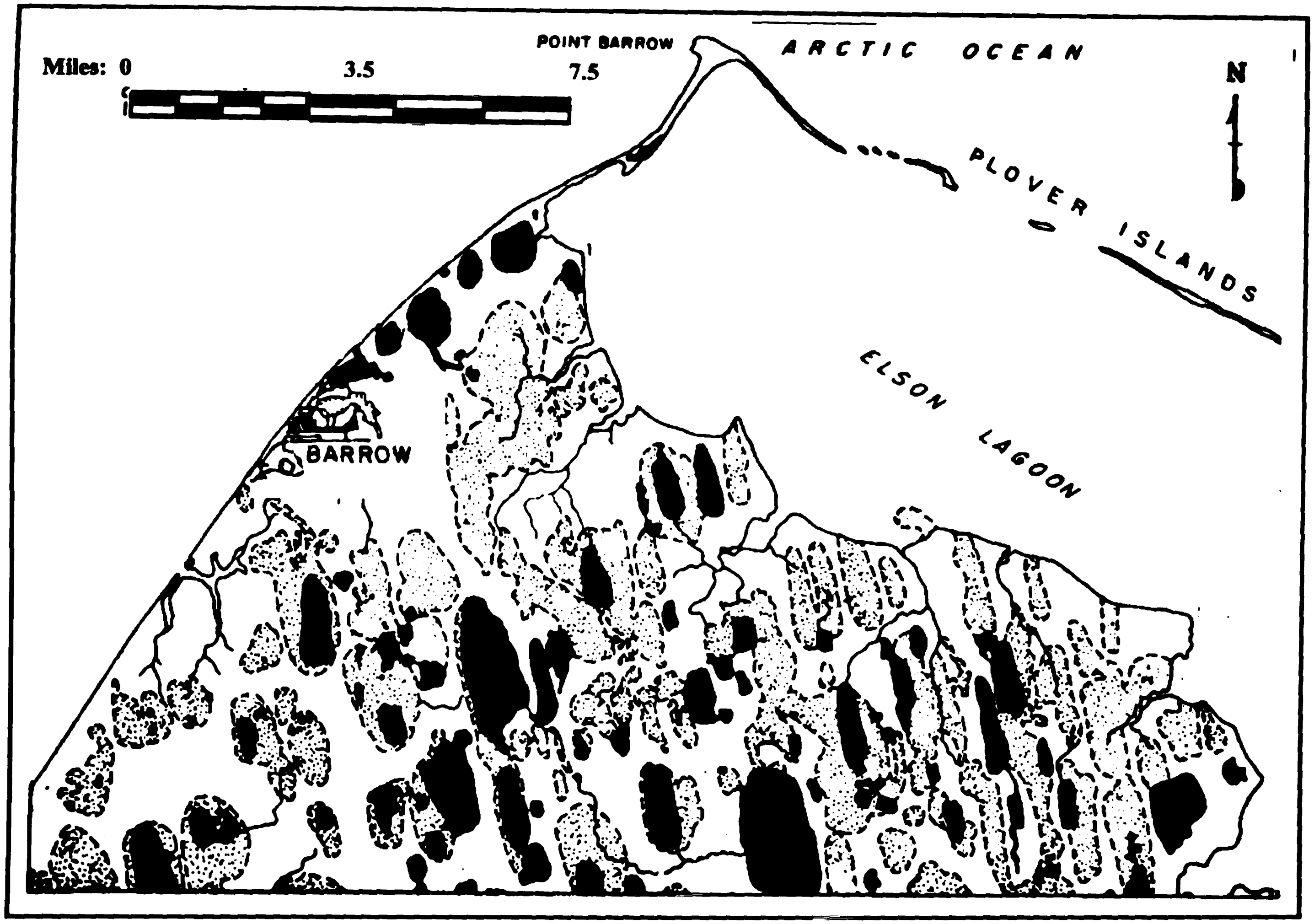


Figure II-2: Map of the Barrow Region showing the location of the city of Barrow on the western coast of the peninsula. Black areas denote ponds and shallow tundra lakes. Stippled areas are marshes occupying the drained basins of former tundra lakes (after Britton (1957)).

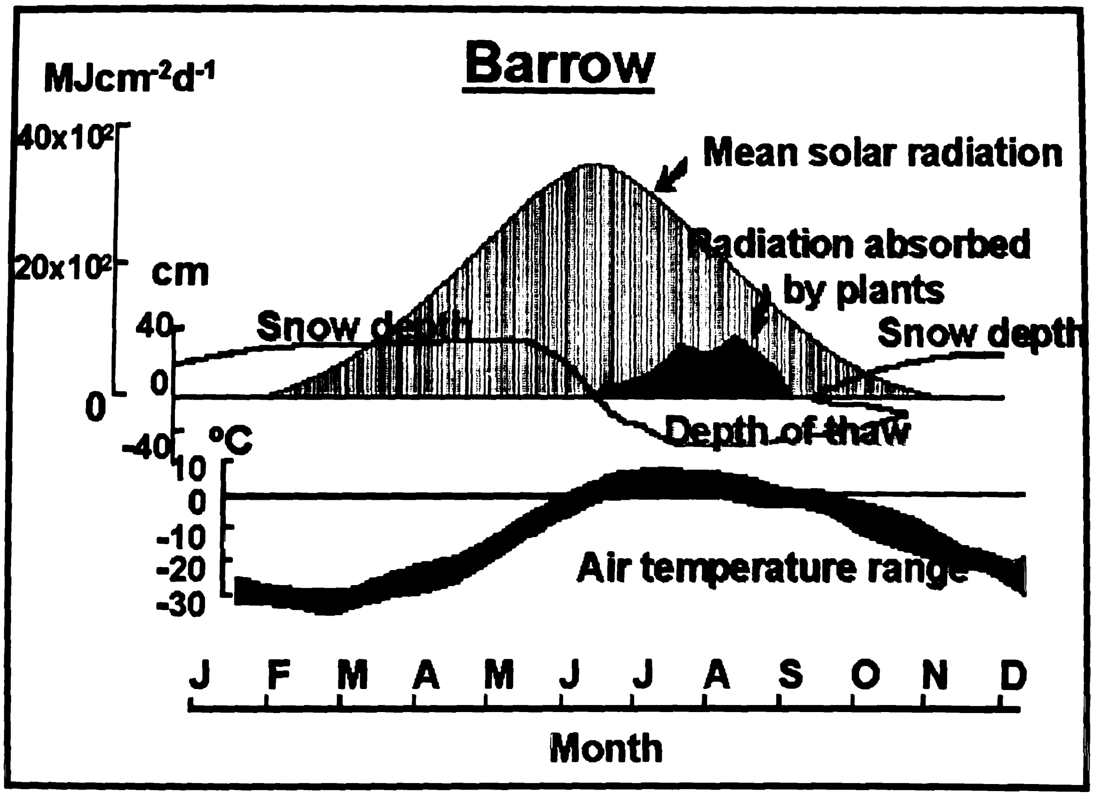


Figure II-3: Schematic summarizing mean, maximum, and minimum temperatures, snow depth, active layer thickness, and solar radiation at Barrow, Alaska (after Chapin and Shaver 1985).

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Taxonomy of common vascular plant species follows that of Hulten (1968). Common mosses and lichens are listed consistent with the naming conventions reported by Murray and Murray (1978).

II.B.I. Water

The water land cover class (Fig. II-4) includes ocean water, inland fresh water (ponds, lakes, rivers, and streams), and ice. In addition, the grass *Arctophila fulva* and *Carex aquatilis ssp. stans*, the dominant sedge in the region, often grow in standing inland fresh water. This aquatic grass or aquatic sedge tundra is classified as water when vegetation cover is less than 40%. In addition to the graminoids mentioned above, *Caltha palustris* and/or *Ranunculus palasii* are occasional dicots. Mosses, lichens and shrubs are absent in this land cover type.

II.B.II. Wet Tundra

Wet tundra (Fig. II-5) includes all marshy areas dominated by sedges. These areas commonly have ephemeral shallow water or consistently saturated soils. While wet sedge tundra is usually dominant in this class, moist/wet tundra complex composed of particularly large low-centered polygons and having greater than 60% cover of wet tundra vegetation is also included in this cover type. Principle graminoids include *A. fulva, C. aquatilis ssp. stans, Eriophorum angustifolium, E. russeolum, E. scheuzeri*, and, *Dupontia fisheri*. In low lying coastal areas where salt water intrusion leads to more saline substrate, *C. aquatilis ssp. stans* is often replaced by *C. subspathacea* and/or *C. ursina*. Forbs are rare in this cover type with the exception of *C. palustris*

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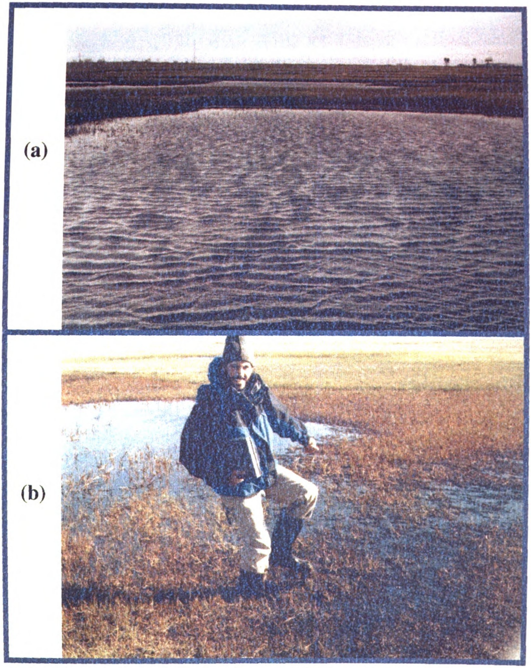

Figure II-4: Photographs illustrating examples of the *Water* land cover class: (a) inland freshwater pond near the U.S. Air Force Distant Early Warning (DEW) Line; (b) aquatic grass tundra with *Arctophila fulva* growing in standing water. (photograph (b) by Chris Brunner)

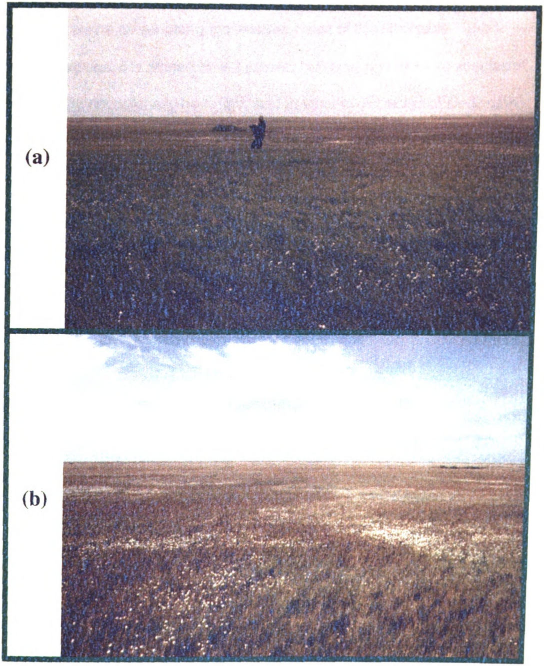

Figure II-5: Photographs illustrating examples of the *Wet Tundra* land cover class: (a) a highly productive wet tundra community comprised primarily of *Carex aquatilis ssp. stans* with some *Eriophorum angustifolium* (white inflorescences); (b) wet tundra community in the drained basin of Footprint Lake. *C. aquatilis ssp. stans* is in the foreground with the reddish *Arctophila fulva* and *Eriophorum Scheuzeri* (white inflorescences being the dominant plants. (photograph (b) by Chris Brunner) and *R. palasii. Cochlearia officionalis and Stellaria humifusa* increase in importance in saline areas along the eastern coast of the peninsula. The bryophyte component is limited in wet tundra; however one or more species of *Sphagnum* may occasionally be found, and at least two species of *Calliergon* can often establish in these wet environments where standing water does not persist for the duration of the growing season. Shrubs and lichens are nearly always lacking in wet tundra in the Barrow Region.

II.B.III. Moist/Wet Tundra Complex

This land cover class represents the low-centered ice wedge polygon complex common on the Barrow landscape. Ice wedge polygons are a distinctly periglacial feature whereby vertically oriented wedges of ice form just below the ground's surface (Fig. II-6) through the process of freezing and thawing. Formation of subterranean ice wedges causes the uplifting of the upper soil layers (usually peat) directly above the ice wedges creating the irregular network of raised polygon rims bordered by comparatively wet polygon troughs and centers as seen in Fig. II-7. The formation and evolution of ice wedge polygons complexes across tundra landscapes is intimately linked to the thaw lake cycle as first described by Britton (1957) and further discussed by Billings and Peterson (1980). While a detailed discussion of the thaw lake cycle is not practical here, it should be noted that this phenomenon is a mechanism of landscape change operating on a scale of thousands of years in the northern high latitudes. As the name implies the draining, revegetation, and eventual refilling of tundra lakes is hypothesized to be cyclic or repeating in nature and

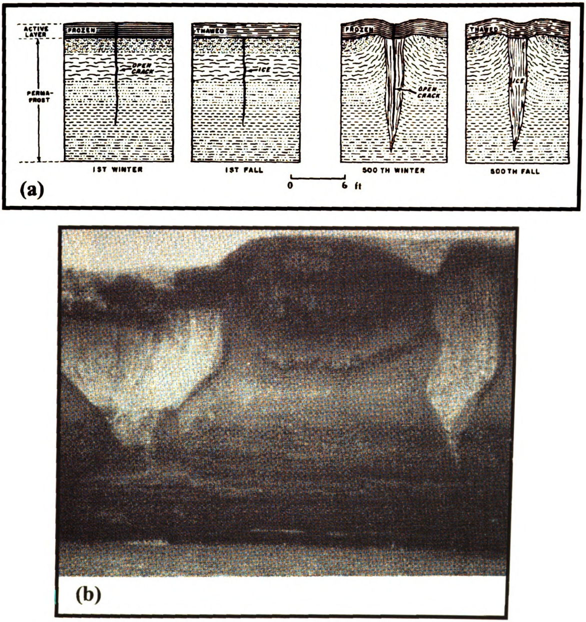

Figure II-6: The evolution and manifestation of subterranean ice wedges: (a) Ice wedge evolution according to the contraction crack theory. Sediments contract and crack in low air temperature. Cracks are expressed at the surface in polygonal forms and frost and water fill the crack and expand the ice mass. This process repeats over time to produce large ice wedges (as seen in (b)) and the surfaces feature shown in Fig. II-7. (b) Large ice wedges exposed near Drew Point Alaska (after Walker et al. 1980). Similar ice wedges occur beneath polygon troughs in the Barrow Region.

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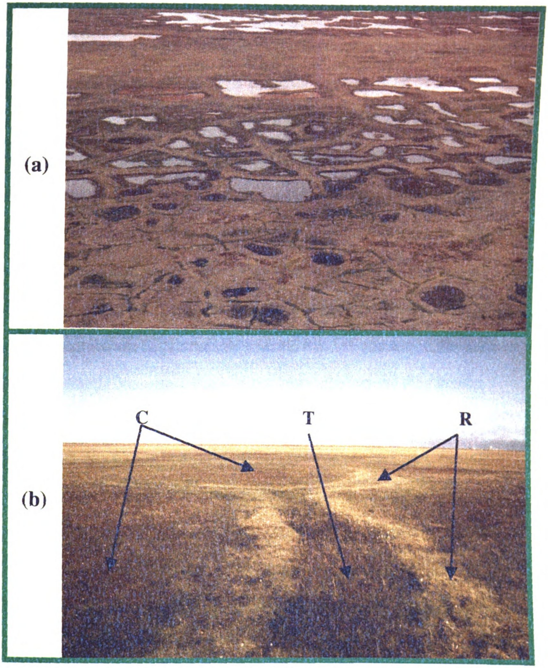

Figure II-7: Examples of *Moist/Wet Tundra Complex* land cover class: (a) low altitude oblique photograph of a low-center ice wedge polygon complex; (b) close up of low-center ice wedge polygons illustrating wet centers (C) and troughs (T) bounded by moist, raised polygon rims (R).

results in a changing mosaic of vegetation types and landforms in Arctic Regions.

The Moist/Wet Tundra Complex land cover unit is common in the Barrow Region and is intermediate between the wet tundra and moist or dry tundra cover types. Spectral signatures of these areas vary based upon the percentage of moist tundra, the season, and summer rainfall. This cover type features wet polygon troughs and centers separated by moist, raised polygon rims. Wet areas in this cover type will have vegetation similar to that described for the wet tundra cover class. Specifically, these wet areas are dominated by sedges with occasional forb species and few mosses and lichens. The moist, raised polygon rims are comparatively species rich. In addition to the grasses and sedges already described, these areas may also include *Poa arctica, Luzula confuza,* and *L. arctica* in the graminoid component. There is commonly a rich assemblage of forbs including several species of *Saxifraga, Petasites frigidus, R. nivalis, R. pygmaeus, Pedicularis kaneii, Senecio atropurpureus,* and at least two species of *Stellaria*. Shrubs often found in moist areas include *Salix rotundifolia, S. pulchra, Vaccinium vitis-idea,* and *Cassiope tetragona*. The bryophyte component of the moist polygon rims is very diverse relative to other land cover types. The variety of mosses present is most often dominated by *Sphagnum spp. and Aulocomium spp.* Lichens, while rare in the wetter areas of this vegetation complex, are well-represented on polygon rims by several species of *Cetraria,* and *Cladonia*, in addition to *Thamnolia subuliformis.*

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II.B.IV. Moist or Dry Tundra

The Moist or Dry Tundra land cover class (Fig. II-8) is the most abundant land cover type in the Barrow Region. Many areas dominated by Moist or Dry Tundra have complete or nearly complete vegetation cover however high-centered polygons and frost boils may be sparsely vegetated. Areas of moist tundra in the Barrow Region have a vegetation cover analogous to that described for the moist polygon rims in the Moist/Wet Tundra Complex. These areas are typically dominated by sedges or other graminoids and have a rich assemblage of forbs and mosses. Shrubs and lichens are also well represented. Dry tundra is dominated principally by dwarf shrubs with lesser amounts of graminoids and dry tolerant mosses. Lichens are an important component in dry tundra. Principle graminoids include species of *Carex* , *Luzula*, and *Eriophorum* as mentioned above in addition to *Arctagrostis latifolia*, and *Alopecuris alpinus* in drier areas. Moist areas have many forbs present including *Saxifraga spp., P. frigidus, Cardamine pratensis, Cerastium beeringianum, Ranunculus spp.*, and others as described for moist polygon rims above. Dry tundra areas feature the addition of *Papaver hultenii, P. lapponicum,* and *Potentilla hyparctica.* Common dwarf shrubs include *S. rotundifolia, S. pulchra, C. tetragona, V. vitis-idea,* and *Dryas integrifolia. Sphagnum spp.* and *Aulocomium spp.* are the principle mosses in moist areas with dry tolerant mosses such as *Polytrichum, Pogonatum, Dicranum,* and *Distichium* establishing in more well drained areas. The lichen community is diverse in Moist or Dry Tundra and includes *Thamnolia subuliformis, Bryocaulon*

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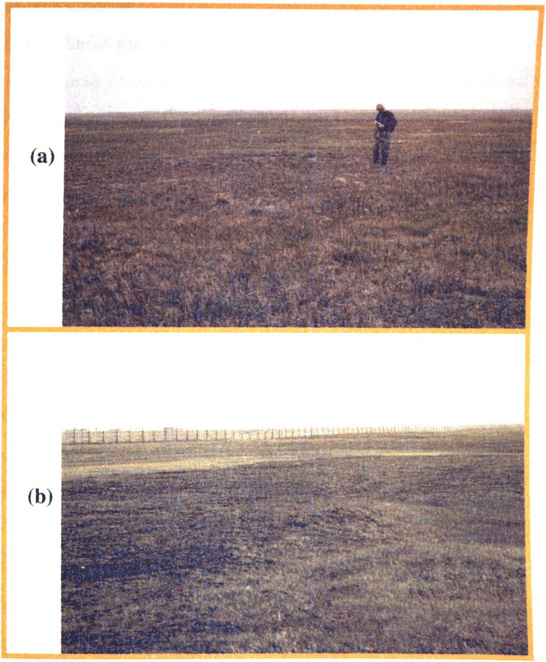

Figure II-8: Photographs illustrating the *Moist or Dry Tundra* land cover type: (a) dry tundra community dominated by *Arctagrostis latifolia*; (b) moist and dry tundra communities on a raised beach ridge. Greener vegetation to the right is moist tundra dominated by graminoids (mainly *Carex aquatilis ssp. stans*) while the darker vegetation on the left is drier and dominated by dwarf shrubs and lichens. (photograph (b) by Chris Brunner)

(Cornicularia) divergens, Sterocaulon alpinum, and several species of *Alectoria, Cetraria,* and *Cladonia.*

II.B.V. Moist Shrub Rich Tundra

Moist Shrub Rich Tundra (Fig. II-9) is similar to Moist or Dry Tundra, but rather than being dominated by graminoid species, a variety of dwarf shrubs form a dense vegetation cover in this land cover class. Graminoid, forb, bryoid, and lichen species in this land cover class are equivalent to those found in moist tundra, however shrubs such as *S. rotundifolia, S. pulchra, C. tetragona, V. vitis-idea,* and *D. integrifolia* comprise the bulk of the vegetation cover and are the primary determinant of this cover type's multispectral signature as detected at the satellite sensor. This cover type is common along the western coast of the Barrow Peninsula and is primarily found along river channels or on moist raised beach ridges having complete vegetation cover and well developed soils.

II.B.VI. Partially Vegetated or Barren Areas

The Partially Vegetated or Barren land cover class (Fig. II-10) primarily encompasses beach gravel along the coast of the Barrow Peninsula. Also included in this land cover type are gravel roads and pads, urbanized/developed areas, barren or partially vegetated river alluvium, and semistabilized gravel or disturbed areas. While few plants can grow in the coarse gravel along the coast of the peninsula, in disturbed areas where the surface organic mat has been stripped away, or in areas where chronic disturbance (natural or anthropogenic) churns the soil surface, there are several

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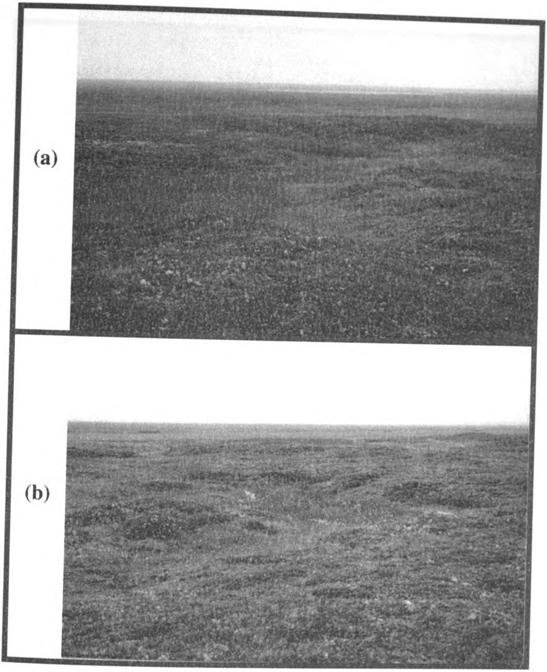

Figure II-9: Examples of the *Moist Shrub Rich Tundra* land cover type: (a) example of moist tundra where *Salix pulchra* is the dominant shrub, forming a dense mat over much of the substrate; (b) moist tundra community similar to photograph (a) but with *S. rotundifolia* as the dominant shrub.

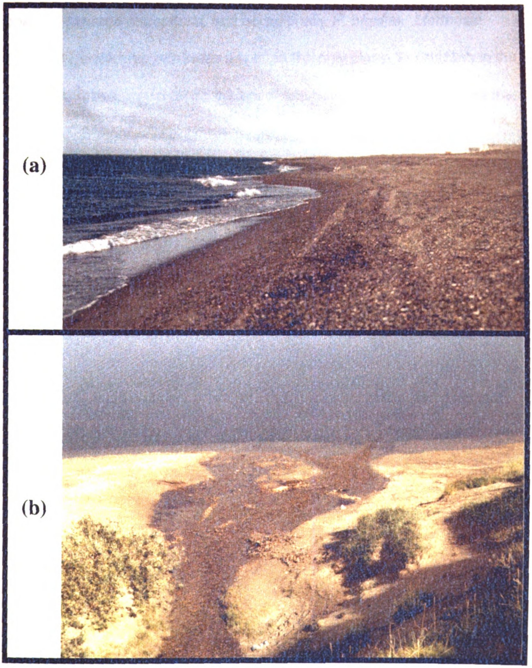

Figure II-10: Photographs illustrating the *Partially Vegetated or Barren* land cover type: (a) beach gravel along the western coast of the Barrow Peninsula; (b) partially vegetated river alluvium. (photo (a) by Chris Brunner)

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occasional plants which can successfully establish in these areas. The grass *Phippsia algida* establishes with some success and may be accompanied by *C. officionalis, Saxifraga caespitosa,* and occasionally *P. frigidus. Mertensia maritima* and *Honckenya peploides* are often the only plants to establish in the chronically disturbed gravel along the coast and have cover values of less than 2%.

Chapter 3

LANDSAT CLASSIFICATION METHODS

III.A. Digital Image Classification Procedures: A Review

The automated categorization of all pixels in a digital image into discrete land cover types or classes is the primary objective of most modern image classification procedures. Fig. III-1 provides a general summary of the process of image processing and classification. Multispectral data (images comprised of $n>1$ spectral bands) are traditionally employed in this process and spectral patterns present in the data and expressed for each individual pixel are commonly used as the numerical basis for classification. Each pixel has a unique n dimensional spectral signature and is examined and assigned to a particular cover class based upon decision processes serving to minimize misclassification errors. Implicit in this process is acceptance of the caveat that different features will manifest different sets of digital numbers based upon the inherent spectral reflectance, or thermal emissivity properties in the case of thermal sensing, of the materials under consideration (Lillesand and Kiefer 1979, Jensen 1986). Note that a spectral "pattern" of cover types does not imply a geometric character but rather a discrete set of radiance measurements recorded in n different spectral bands for each picture element in the landscape.

While the majority of commonly used classifiers and classification methods involve computer-assisted recognition of spectral pattern, two other

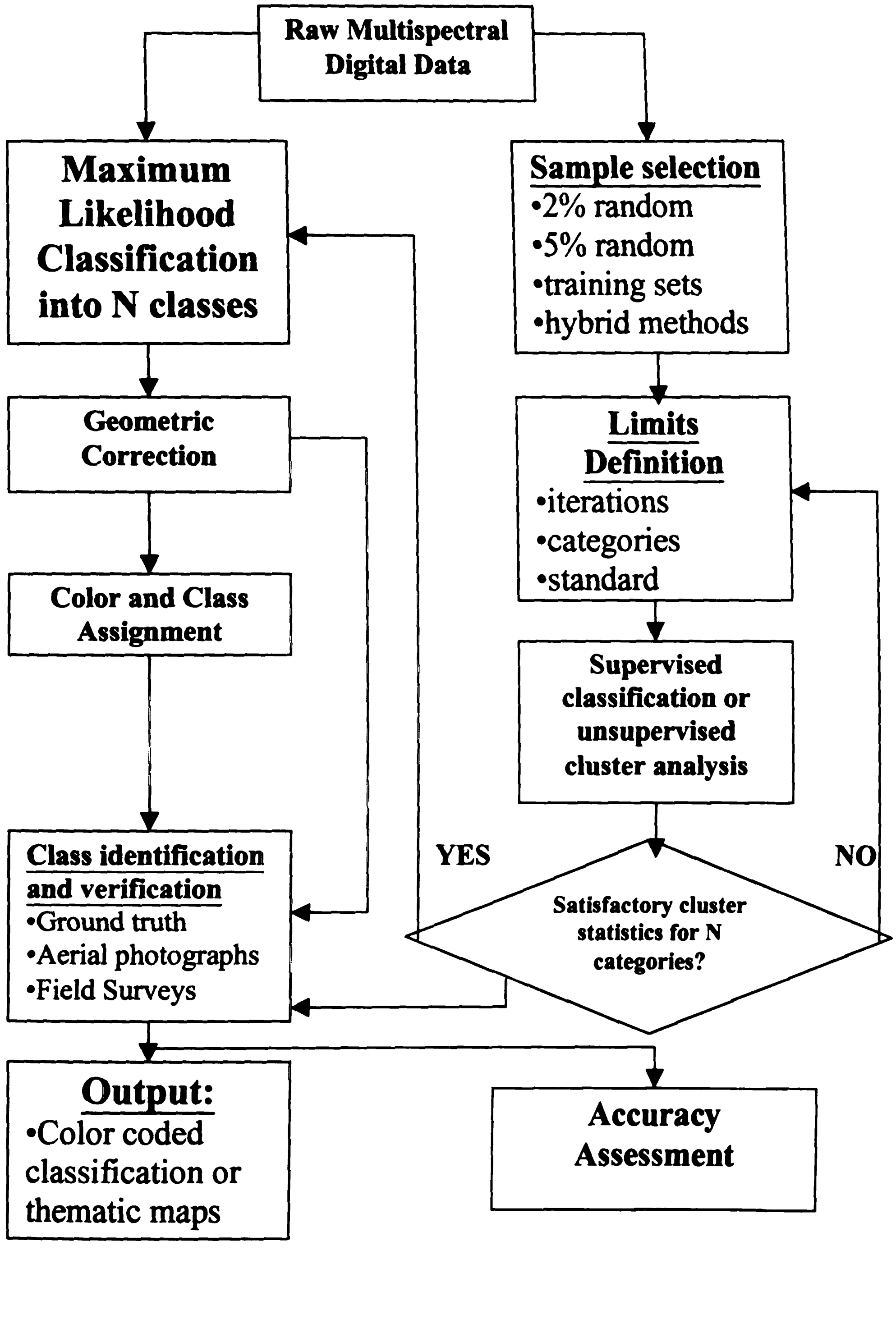

Figure III-1: Flow chart for generating thematic maps from digital multispectral data using modern image processing techniques (redrawn from Miller and George (1976)).

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pattern recognition systems are the subject of current research. Spatial pattern recognition methods are geometric in nature and involve the categorization of image pixels based upon spatial relationships while temporal pattern recognition methods incorporate time as an aid in the classification process (Gurney and Townshend 1983, Bolstad and Lillesand 1992). The methods employed in this research however, are based upon spectral pattern recognition and accordingly, receive considerable attention in the text which follows.

Methods of classification based upon spectral pattern recognition can be divided into the two broad categories of supervised and unsupervised techniques. Supervised classification techniques involve the direct interaction of the investigator in the categorization process as he/she "supervises" the pixel classifications, through the specification of statistical attributes of each feature type of interest (Lillesand and Kiefer 1979, Jensen 1986, Mausel et al. 1990, Cetin and Levandowski 1991) (Fig. III-2). The statistical characteristics of each land cover type in the selected classification scheme are developed as the analyst selects discrete areas, called training areas or training sites, of known cover type which are compiled by a computer algorithm into a numerical interpretation key. The overall goal of the training site selection process is the creation of a set of statistics which will accurately describe the spectral response characteristics, in terms of the mean, the variance, the between band covariance, and the maximum and minimum pixel values for each band, for each land cover type of interest in the image to be classified. Through a variety of possible algorithms which can be selected by the analyst (PCI, Inc. 1997), the computer

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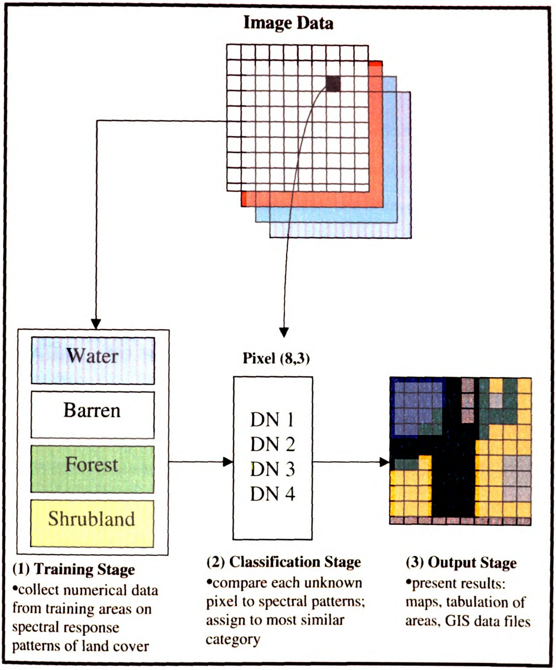

Figure III-2: The basic steps involved in supervised image classification.

then examines the spectral pattern of each pixel in each of the *n* image planes and places the pixel in the land cover class that it most resembles based upon the statistical characteristics assembled for each cover type during the training site selection process.

Alternatively, the investigator may choose to perform an unsupervised classification of the remotely sensed data covering the area under study. In the unsupervised approach to image classification, one of several algorithms is selected to examine all pixels in all *n* bands of an image and aggregate them into a number of spectral classes based upon natural clusters or groupings of pixels in the *n* dimensional spectral space (Walker et al. 1982, Jensen 1986, Walker and Acevedo 1987, Hodgson and Plews 1989) (Fig. III-3). The basic assumption of this process is that the digital number values of all pixels in a cover class should cluster relatively close together in the *n* dimensional spectral space while data in different cover classes should be comparatively well separated (Hodgson and Plews 1989).

Note that in an unsupervised classification of digital data, the output from the process is a group of naturally occurring spectral classes. These spectral classes must then be examined by the analyst to determine their information content. This involves the use of ancillary data such as aerial photography, digital elevation models (DEMs), slope and aspect information, the knowledge of the investigator, and other information to assign land cover classes to each spectral grouping generated by the computer (Hutchinson 1982, Gurney and Townshend 1983, Cibula and Nyquist 1987, Jones et al. 1988, Franklin and

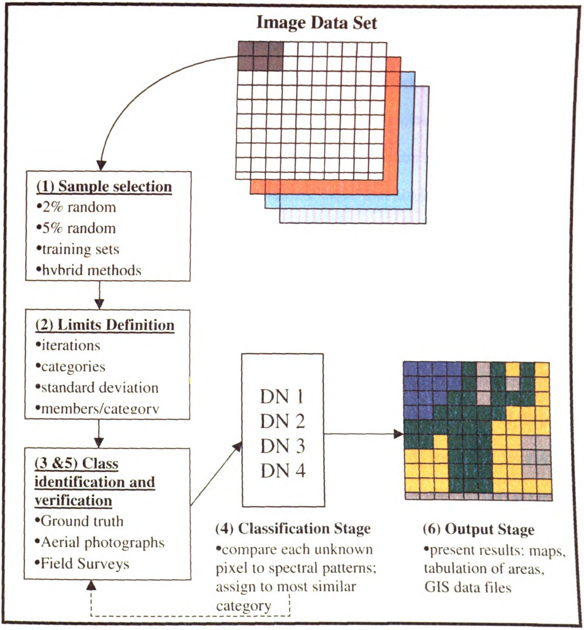

Figure III-3: The basic steps involved in an unsupervised image classification.

Peddle 1989, Janssen et al. 1990). The process is iterative and may involve the grouping of several spectral classes under one cover type or the further division of some initial spectral classes to obtain an acceptable classification (Fig. III-4). One final point must be made: Whichever classification scheme and method is selected for use in a particular investigation, there is a profound difference between spectral classes and land cover types (information classes) (Jensen 1986. Campbell 1987). Spectral classes are those that are inherent in the remotely sensed data and must be identified and labeled by the investigator. Information classes, on the other hand, are those which the analyst defines and undertakes to describe and map.

III.B. Overview of Landsat Classification Methods

Classification of both the Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM) images was performed consistent the methods of Walker et al. (1982) and Walker and Acevedo (1987). The methods were first developed by researchers at the United States Geological Survey (USGS) Western Mapping Center and the NASA Ames Research Center in Moffett Field, California. It must be stressed that while the following methods facilitate automation of several stages of the classification and mapping process, they are "computer-aided" in that intimate interaction is required of the analyst in order to set critical statistical thresholds and other limits which manipulate the data and constrain the processing algorithms (Miller and George 1976). The procedures have been employed with success in several land cover mapping efforts on the North Slope of Alaska (Acevedo 1982, Walker et al. 1982, Walker and Acevedo 1987, Stow et

Spectral class (cluster)	Identity of cluster	Information Category
Possible Outcome 1:		
1	Water	Water
2	Urban	Urban
3	Shrubland	Shrubland
4	Forest	Forest
Possible Outcome 2:		
1	Turbid Water	Water
2	Clear Water	
3	Sunlit Trees	Forest
4	Shaded Trees	
5	Barren land	Urban
6	Urban	
7	Shrubland	Shrubland
Possible Outcome 3:		
1	Water	Water
2	Open Forest	Forest
3	Brushland	Brushland
4	Residential	Urban

Figure III-4: Possible outcomes from an unsupervised image classification. Outcome one leads to a 1 to 1 correspondence between clusters and information classes. Outcome two produces several clusters for each information class. Outcome three illustrates the possibility that a single cluster may represent more than one information class.

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al. 1989) and have been found to yield accurate information regarding tundra landscapes in a format useful to land and resource managers (Muller et al. 1998). The image analysis approach is a hybrid of the supervised and unsupervised methods of land cover classification discussed in section III.A. above. An unsupervised isodata clustering stage, with subsequent editing of spectral groupings and labeling of land cover types is first conducted. The resulting spectral signatures are incorporated into a Gaussian Maximum Likelihood Classifier so that all image pixels are assigned to a given land cover class based upon the edited spectral cluster statistics. Ground reference information of various formats is then used to verify the correct labeling of land cover types. Fieldwork conducted to collect georeferenced, site specific cover type data can subsequently be employed to refine the classification and conduct accuracy assessment of the final maps.

III.B.I. Data Acquisition

The search for appropriate Landsat digital data began with an electronic search of the U.S. Geological Survey's (USGS) Earth Resources Observation Systems (EROS) database in Sioux Falls, SD for appropriate Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM) images providing coverage of the Barrow Region in northern Alaska. The database can be queried via the World Wide Web at <http://edcwww.cr.usgs.gov/webglis> or a search request can be formally submitted to the EROS Data Center via electronic mail or telephone. To ensure that the vegetation classifications reflect the current state of the landscape in the Barrow region, the search was limited to those Landsat

scenes of the study area obtained after 1980. This time interval was deemed appropriate to ensure that significant alteration of the landscape, detectable on the satellite imagery, had not occurred subsequent to the date of image acquisition and, at the same time, that a plurality of appropriate scene choices would be available. The region surrounding the city of Barrow is covered by path number's 79 and 80 and rows 9, 10, and 11 on the Landsat World Reference System 2, a system employed for indexing individual images obtained by Landsats 4 and 5, so these locations were incorporated into the electronic search criteria (Fig. III-5). In addition, the coast of Alaska's North Slope is dominated by fog an average of 115 days a year primarily during the growing season (Shafer and Degler 1986) when remote sensing is most useful in identifying and discriminating land cover types. Even when the fog lifts, it rises only to a height of 1,000–2,000 feet, increasing the effects of atmospheric attenuation of sunlight and effectively impairing the satellite's ability to detect land cover reflectance values in the visible and reflected infrared wavelengths. In attempt to minimize or avoid such complications during image processing, all Landsat images containing more than 10% cloud cover were excluded from the search. The search results yielded 40 Thematic Mapper (TM) images and 23 Multispectral Scanner (MSS) images of the Barrow Region that met the aforementioned criteria with respect to geographic location, date of acquisition, and percent cloud cover.

The TM and MSS sensors aboard the Landsat satellite have unique spatial and spectral resolutions (see section I.D.I.). Because it would be

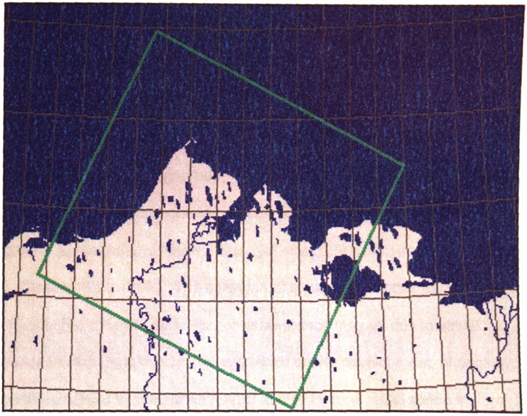

Figure III-5: View of a portion of Alaska's North Slope showing the location and orientation of the Landsat scenes selected for use in this research. The green rectangle corresponds to the area covered by Path 79, Row 10 of the Landsat World Referencing System II.

desirable to explore how such differences affect each sensor's ability to accurately detect land cover types, the final scenes selected for analysis were chosen so that both the TM and MSS image were obtained from the same satellite platform (Landsat 5) on the same date. While selection in this manner does not account for differences in sensor calibration, this does remove the effect of differences in atmospheric constituents, earth-sun distance, and sun angle between scenes, which may produce artificial variations in reflectance values recorded at the sensor not due to any significant difference in land cover type on the ground (Lillesand and Kiefer 1979, Hall et al. 1991, Jensen 1986, Chavez 1988, Olsson 1993, 1995). The selection of same date images also eliminates the chance that differences in sensor performance may be due to actual differences in the condition of the land cover due to development, phenology, or temporal variations in climate and other abiotic factors. MSS scene # LM5079010008618190 and TM scene #LT5079010008635710, both obtained at the same solar time of approximately 9:45am (NASA 1972) on 30 June 1986 and having 0% cloud cover, were selected for use in this study (Fig. III-6). While the late June date for these images is slightly early to take advantage of peak vegetation phenology for the Arctic growing season near Barrow, similar vegetation mapping efforts by Acevedo et al. (1982), Walker et al. (1982), and Walker and Acevedo (1987) conducted in the Beechey Point Quadrangle and the Arctic National Wildlife Refuge in northern Alaska employed similar imagery from early July and obtained satisfactory results.

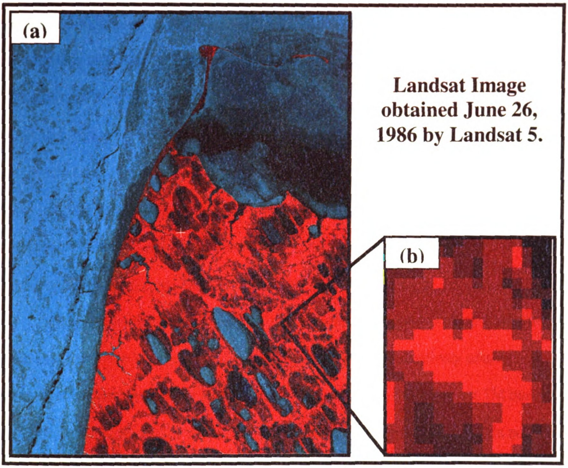

Figure III-6: (a) Subset of the Landsat TM image employed in this mapping effort. The image is displayed as a false color composite overlaying bands 4 (near-IR), 3 (red), and 2 (green). (b) enlarged portion of the digital image illustrating the spatially controlled sampling which aggregates a given area on the ground into a single value. TM pixels are 28.5m on a side while MSS pixels are 57m on a side.

Computer compatible tape (CCT) (for the Landsat MSS image) and high speed recordable compact disk (for the Landsat TM image) formats of the selected scenes were obtained from the EROS data center in band-sequential (BSQ) format. The raw image data were preprocessed by the EROS Data Center Digital Image Processing System (EDIPS) to yield radiometric and geometrically corrected images. To facilitate image analysis, the images were loaded onto a standard UNIX server in the Michigan State University Department of Geography Advanced Computing Laboratory. All four bands of the Landsat MSS image were included in the classification efforts while bands 1-5 and 7 of the TM image were included in the analysis for this image.

Band 6 (thermal or emitted infrared wavelengths) was omitted from the analysis of the TM image for several reasons. While the relatively coarse resolution of the thermal band (120mX120m) relative to the other six TM bands (28.5mX28.5m) did play a role in the decision to exclude it from the data set, the overriding reason was due to the radiant temperature characteristics of earth surface features and the solar time of image acquisition. The overflight time of approximately 9:45am local sun time (NASA 1972) for the Landsat 5 satellite yields a thermal (emitted) infrared image of the landscape at a time when surface features are not highly separable because of the lag in the diurnal radiant temperature variations in the earth's surface features relative to solar insolation (Geiger 1965). Note in Fig. III-7 that the relative radiant temperatures of both water and surface features lag behind solar insolation and that the high specific heat and thermal inertia of water prevent the drastic diurnal temperature

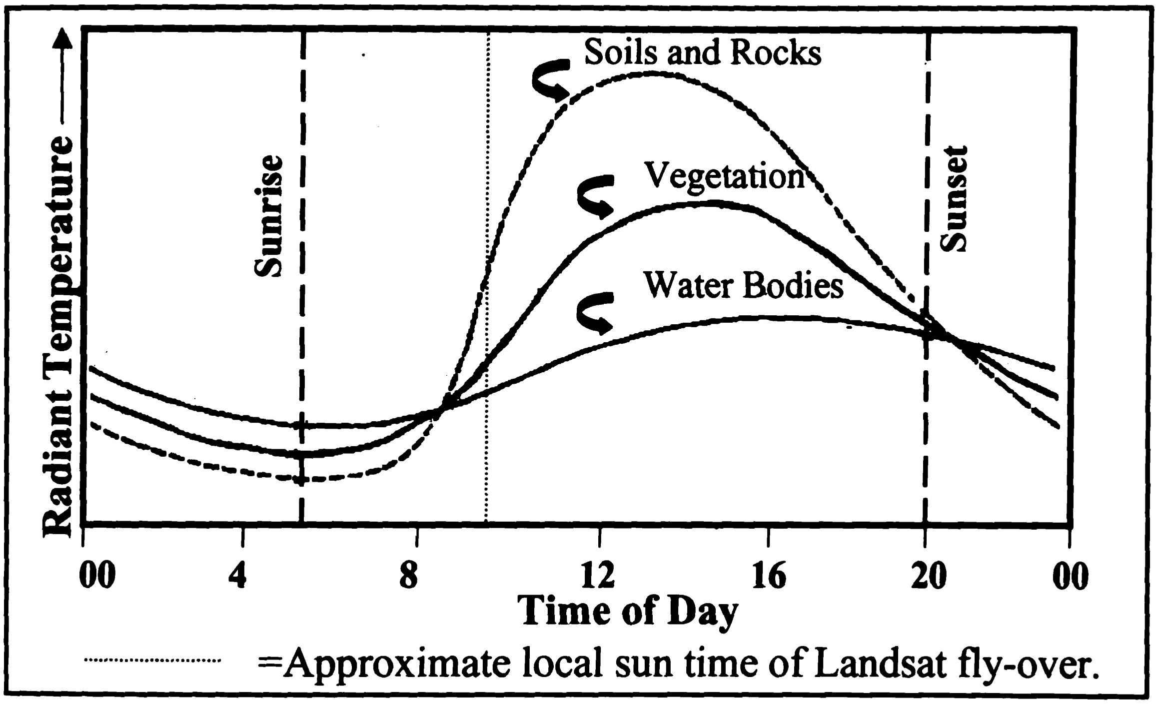

Figure III-7: Generalized diurnal radiant temperature curve for earth's major surface features. Note the relatively small difference in radiant temperature distinguishing surface features at the time of Landsat image acquisition.

oscillations apparent for terrestrial features. This leads to the intersection of the radiant temperature curves for water and terrestrial features shortly after dawn and shortly after sunset. Daytime Landsat 5 images of the earth's surface are obtained just after this morning intersection point when radiant temperatures for a variety of landscape features will not be spectrally distinct. While the sun does not dip below the horizon during much of the growing season in Barrow, this diurnal trend in temperatures is still very apparent (Hollister 1998). The resultant thermal image is thus not very useful for distinguishing cover types due, for the most part, to the time of image acquisition.

During preliminary image processing, it was discovered that image planes 1 and 4 of the Landsat MSS image suffered from a phenomenon known as image banding. The precise reasons for its occurrence are not known, but image banding results from the satellite sensor recording random stripes of pixels in an image plane with identical radiance values. This horizontally oriented corruption of the original radiance values yields conspicuous stripes of color and distorted histograms for those image planes affected. This phenomenon is not easily dealt with, as there is no way to restore or correct pixel values that were originally recorded incorrectly. However, a variety of spatial filters have been developed to deal with this problem. A 7x7 median filter (PCI, Inc. 1997, Jensen 1986) was applied to image plane 4 and a 3x3 median filter was applied to image plane 1 in the Landsat MSS image to reduce the effects of image banding. This interpolation of missing or incorrect data is not ideal but represents one of the "best" ways to deal with such issues based upon the present state of knowledge.

III.B.II. Computer-Assisted Classification

All image-processing steps were performed within the PCI Works software environment (PCI, Inc. 1997). The software is distributed by PCI Remote Sensing Corporation, Arlington, VA and offers a variety of image processing and data analysis/manipulation functions useful in the analysis of remotely sensed data. While the same image-processing procedures were conducted on both the Landsat MSS and Landsat TM images, individual analyses of the images were conducted separately unless otherwise indicated. The mapping methods employed in the research represent an integrated effort comprised of three stages. Acquisition of ground reference data through the use of aerial photography and field studies, preparation of land cover classifications from each of the selected Landsat images, and the composition and output of the final color-coded thematic maps are the three main foci of the method. Following preparation of the final map outputs, a detailed accuracy assessment was conducted for the map produced from each sensor image (Chapter 4).

III.B.II.a. Preparation of land cover classifications

Training areas were selected through a visual interpretation, on a color computer monitor, of false color composite images of the Landsat MSS (band 3=red, band 2=green, band 1=blue) and Landsat TM (band 4=red, band 3=green, band 2=blue) images. Attempts were made to choose training blocks within each image which contained a majority of the spectral variation within the scene. Recommendations, from the literature, on the total proportion of reference image pixels to be included in the unsupervised cluster building exercise range from 2-

20% (Miller and George 1976, Fleming 1988). Ultimately, 21 training blocks were selected (Fig. III-8), representing 2% of the total area under study, for incorporation into an unsupervised classification clustering algorithm. Only 2% of the image was selected as a majority of the map area was determined to be ocean which can be classified rather simply using a binary water mask. The training blocks were delineated in a binary image mask to facilitate their inclusion in the cluster building exercise while excluding the undesired portion of each image.

A clustering algorithm (ISOCLUS) was applied to the training blocks to define discrete groups of pixels (clusters) based upon their multi-spectral reflectance values (in each of the four Landsat MSS spectral bands and in each of the six Landsat TM spectral bands). The selected algorithm groups pixels having similar *n*-dimensional reflectance values, maximizes the statistical distance between classes of dissimilar pixels, and provides statistical descriptors (mean value of the pixel reflectance from each band and covariance matrix as a measure of cluster size and shape) for each individual cluster. While several authors have recommended the arbitrary specification of the number of possible clusters to be generated (Fleming 1988, Talbot and Markon 1986, Markon 1992), the discriminatory power of the unsupervised clustering algorithm is maximized when there is no constraint on the number of spectral classes to be generated (Lillesand and Kiefer 1979). For this reason, the clustering algorithm was run allowing the computer to specify the final number of cluster centers produced.

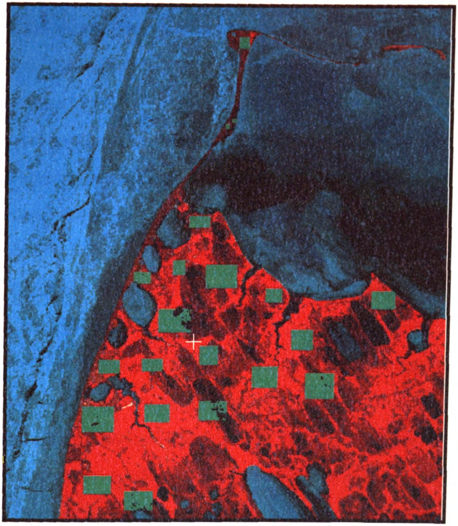

Figure III-8: Portion of the Landsat TM scene of the Barrow Region showing those areas selected for input into the ISODATA clustering algorithm (green).

Following the unsupervised clustering of both the Landsat MSS and Landsat TM images, spectral plots and statistical tables were generated summarizing the information contained in each of the cluster data sets. Information regarding means, variances, and intercluster separability were examined for each image. The preliminary spectral classes for each image were assigned to cover classes with the aid of color infrared aerial photographs, field data from the related International Tundra Experiment (ITEX) project focused on the Barrow region (Walker 1997, Hollister 1998), and from personal knowledge gained in field observations and research experience. Interpretation of cluster statistics in concert with a visual examination of the false color composite for each respective image facilitated the editing of spectral signatures allowing the aggregation, deletion, or further subdivision of spectral classes prior to their use in the classification process.

Following the definition of a final set of statistics for each spectral class in each image, the resulting spectral signatures were submitted to a Gaussian Maximum Likelihood Classification algorithm. This algorithm calculates a probability density function for each spectral class (Fig. III-9) and then assigns each pixel in the image to the cluster for which its probability of being a member is greatest (Lillesand and Kiefer 1979, Jensen 1986). Application of this algorithm to the entire study area in both the MSS and TM images resulted in the separation of all pixels into the spectral classes defined by the cluster statistics generated through the unsupervised spectral clustering algorithm.

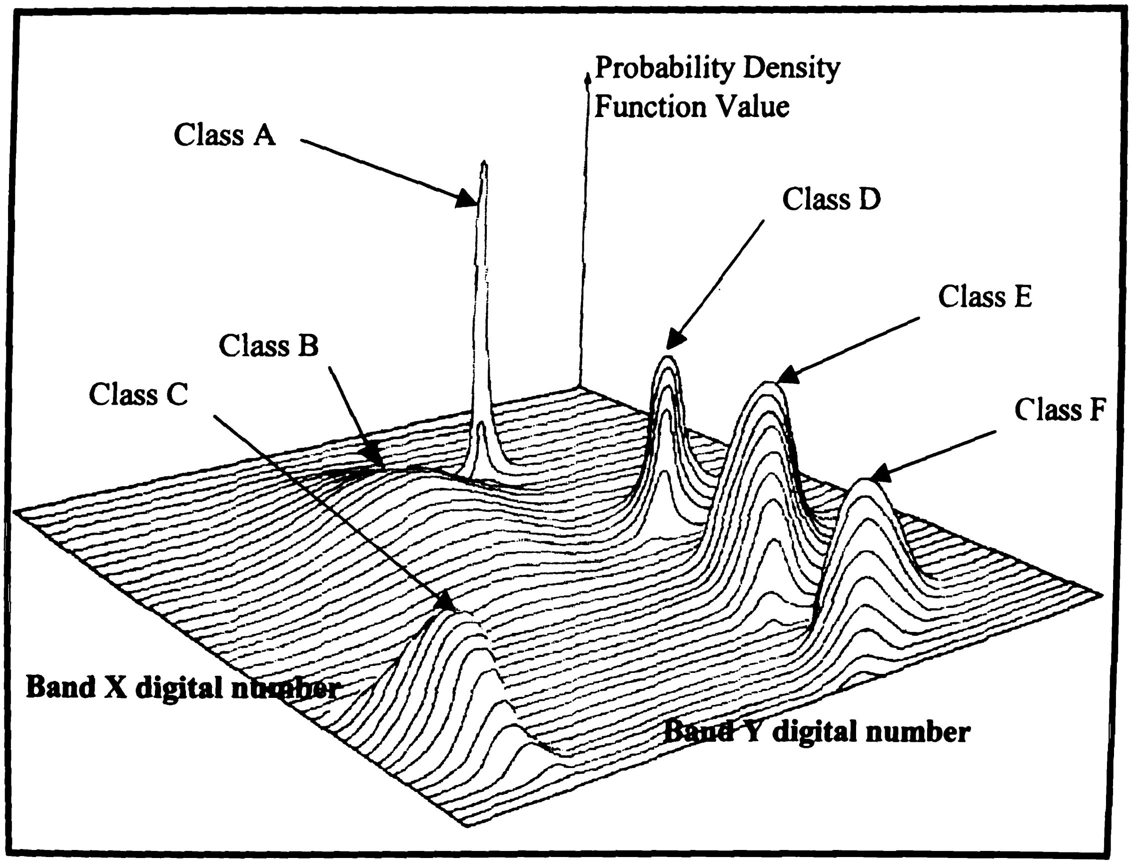

Figure III-9: Probability density functions for a set of theoretical land cover types as defined by a Gaussian Maximum Likelihood Classifier similar to the one used in this mapping effort.

With all pixels in each Landsat image separated into discrete spectral classes, a preliminary attempt to determine the information content of these spectral classes was conducted by assigning each cluster to the land cover type it was thought to represent. This procedure was facilitated through visual interpretation of each Landsat image on the color computer monitor with identification of land cover types from aerial photographs. Each land cover type (represented by one to many clusters) was coded with a distinctive color to produce a preliminary thematic map of the Barrow region for each of the images employed in the analyses. Following field collection of ground reference data (see section III.B.II.b.) each of the clusters was reinterpreted and assigned to the cover class to which it belonged.

III.B.II.b. Acquisition of ground truth polygon data

Because the acquisition of Landsat digital data records not the presence or absence of particular vegetation types but rather characteristic surface reflectance values for the variety of features within the satellite's field of view (see section I.D.III.), it is useful to conduct adequate ground truth exercises to facilitate editing of cover types before map publication to ensure maximum correctness in land cover representation wherever possible. Ground surveys for the Barrow region, Alaska were concentrated in areas covered by 3 frames of 1:60,000 scale color infrared (CIR) aerial photography obtained from Aeromap, Inc. of Anchorage, AK. In addition, larger scale 1:24,000 CIR photographs were available and provided coverage of a significant portion of the Barrow Environmental Observatory (BEO). Information gleaned from aerial photography was supplemented with data found in the literature (Britton 1957, Webber et al. 1980, Morrissey and Ennis 1981, Walker 1997, Hollister 1998).

Before field work was conducted, numerous polygons were delineated on the 1:60,000 and 1:24,000 CIR photographs (Fig. III-10) to highlight areas representing the major cover types of the region. Within the PCI Works environment the area corresponding to each CIR photograph frame was displayed and each cluster category was displayed over the false color composite of each Landsat subscene. Large homogeneous areas of each given cluster which showed up on the color display were then identified, outlined, and numbered on the CIR photographs. Normally only large homogeneous areas with significant geographic separation were selected for field checking of each cluster however, the size and spatial distribution of polygons varied due to the natural heterogeneity of tundra landscapes. Each numbered polygon was recorded on a data sheet with its corresponding cluster identification number and preliminary land cover type according to the Walker (1983) classification scheme (Fig. III-11, see section II.A.II.b.).

Each numbered polygon recorded from the CIR photographs was then visited and examined in the field. Visitation of each polygon included a description of percentage cover of the dominant vegetation, recording of the major surface form, estimates of height of vegetation, and recording of general notes and descriptions of the vegetation within the polygon. Detailed instructions for conducting this relevee sampling can be found in Walker et al. (1979 unpub.) and Shimwell (1971). Chapter 2 provides detailed summaries of the ground

Figure III-10: Portion of 1:60,000 scale color-infrared aerial photograph #3004 showing the location of polygons surveyed to serve as ground truth in the Barrow Peninsula mapping effort. The city of Barrow is visible in the lower left center portion of the photo.

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Field Data From Ground Reference Surveys

Vegetation Mapping Ground Reference Polygon Data

Date of Preliminary Classification: May 1998 **Location:** Barrow Peninsula, Alaska

Observers: Noyle and Brunner **Date of Survey:** 7-23-98

Polygon # 46 **Statistical Cluster(s)** 7, 9, 10 **CIR Frame No.** 3004

Preliminary Classification: Wet tundra

Species Information/Percent Cover of Veg. Types:

Dominant: 90% Wet Sedge Tundra **Secondary:** 5% Moist graminoid tundra

Tertiary: 5% Aquatic Grass Tundra **Others:** —

Surface Form: Large LCP (low relief) **Notes:** —

Principal Plant Species: Salix pulchra, Carex aquatilis ssp. stans, Eriophorum angustifolium Arctophila fulva.

Polygon # 37 **Statistical Cluster(s)** 16 **CIR Frame No.** 3004

Preliminary Classification: Moist/Wet tundra complex

Species Information/Percent Cover of Veg. Types:

Dominant: 60% dry herbaceous tundra **Secondary:** 40% moist graminoid tundra

Tertiary: **Others:**

Surface Form: FCP **Notes:** Moist or dry tundra

Principal Plant Species: Luzula confusa, Carex aquatilis ssp. stans Ranunculus nivalis, Saxifraga cernua, Thamnolia subuliformis, Sphagnum spp.

Polygon # 43 **Statistical Cluster(s)** 6, 7, 8 **CIR Frame No.** 3004

Preliminary Classification: Wet tundra

Species Information/Percent Cover of Veg. Types:

Dominant: 95% Wet sedge tundra **Secondary:** 5% moist graminoid tundra

Tertiary: **Others:**

Surface Form: large LCP **Notes:**

Principal Plant Species: Carex aquatilis ssp. stans, Eriophorum russeolum, Dupontia fisheri, Sphagnum sp., Drepanocladus sp., Saxifraga foliolosa.

Figure III-11: Sample field data from ground reference surveys.

survey data and typical plant communities which may be found within each cover type discernible on the Landsat MSS and TM images. The field data collected in this manner were then applied to the preliminary land cover classification generated for each image so as to facilitate a check of the preliminary classification. It is important to note that this field examination of map polygons to obtain ground truth data for map editing is independent of accuracy assessment data collection as described in Chapter 4.

III.B.II.c. Preparation and output of final land cover maps

Once a final classification was prepared for each Landsat scene, geometric correction of the satellite data was conducted. The data were corrected by selecting corresponding points on each Landsat scene and on U.S. Geological Survey (U.S.G.S.) 1:63,360 scale topographic maps. Geometric correction is a multistep process resulting in the calculation of transformation coefficients necessary to register the digital data to the Universal Transverse Mercator (UTM) map projection for Grid Zone 4 using the North American Datum of 1927 (NAD27). Transformation coefficients were calculated from a second order precision calibration polynomial generated during the geographic referencing process. During registration of each Landsat image to the UTM coordinate projection, a nearest-neighbor rule was used to assign pixels to their correct position on the UTM grid. This process yielded the final, geometrically corrected TM and MSS derived maps with horizontal errors of 34.05m and 52.98m respectively.

Map publication first involved the generation of map layouts for each resultant map in the Environmental Systems Research Institute's (ESRI) ArcView GIS software. The vegetation and landcover maps derived from the Landsat TM and MSS data were plotted at the 1:63,360 scale and subsequently printed on a large format printer in the Michigan State University (MSU) Department of Geography. The final maps, "Landsat TM-Assisted Vegetation Map of the Barrow Region, Northern Alaska" and "Landsat MSS-Assisted Vegetation Map of the Barrow Region, Northern Alaska", are included in the back of this thesis and are also available upon request from the MSU Arctic Ecology Laboratory.

Chapter Four

LAND COVER MAP ACCURACY ASSESSMENT

IV.A. Accuracy Assessment Defined

No land cover mapping effort is complete until the accuracy of the resultant products has been assessed. This last statement has gained importance with the advent of advanced digital remote sensing and innovative image processing techniques. While map accuracy assessment remains an integral part of mapping efforts employing detailed ground survey or more traditional remote sensing techniques such as large-scale aerial photography, the complexity of modern digital classification protocols creates an even greater need to assess the accuracy of the results of these newer initiatives. Jensen (1986) has noted that there must be methods for quantitatively assessing classification accuracy if remote sensor derived land cover maps and their associated statistics are to find application in the user community. The U.S. Geological Survey (USGS) has described the accuracy of spatial data as: "The closeness of results of observations, computations, or estimates to the true values, or the values accepted as being true" (USGS 1990). Accuracy assessment or validation is thus an important step in the processing of remotely sensed data as it determines the value of the resultant data to a particular user.

The term accuracy assessment has evolved to have a number of different connotations depending upon the source(s) of map errors being examined by the investigator. Janssen and van der Wel (1994) and Congalton and Green (1993) have noted at least eight potential sources of confusion between a remotely sensed image classification and the reference data used to test the classification. These potential sources of error include:

- Differences in registration between the reference data and the remotely sensed image classification;
- Delineation error encountered when accuracy assessment sampling sites are digitized;
- Data entry error resulting from incorrect input of reference data attributes;
- Errors in delineation or interpretation of reference data (photointerpretation error);
- Changes in the state of the landscape between the date of remotely sensed image acquisition and the data of reference data collection;
- Variations in classification due to inconsistencies in human interpretation of heterogeneous landscapes;
- Errors in remotely sensed image classification; and
- Errors in remotely sensed image delineation.

Congalton and Green (1993) found that it is the first six factors in this list which have the ability to most profoundly affect the accuracy of remote sensing derived thematic maps and make the classification appear far worse than it actually is. Consistent with the recommendations of the aforementioned authors, measures have been taken over the course of this project to minimize the influence of these first six factors on land cover map classification accuracy. Such measures include: standardization of image processing protocols; performance of all image processing by a single analyst; multiple checks of data entry; substitution of ground visits for photointerpretation of reference data; and the use of ISODATA clustering algorithms to reduce human inconsistencies in dealing with heterogeneous landscapes.

Studies on spatial data accuracy and on errors in the integration of remote sensor data in a Geographic Information System (GIS) have been initiated (Lunetta et al. 1991). Research initiatives 1 (Accuracy of Spatial Databases) and 12 (Integration of Remote Sensing and GIS Technologies) of the National Center for Geographic Information Analysis (NCGIA) stand to enrich the understanding of sources of error in remote sensor data and how these factors affect map accuracy (Lunetta et al. 1991, Goodchild and Gopal 1989). Research on assessment of thematic map accuracy which deals comprehensively with each of the eight sources of error mentioned above is still ongoing and a discussion of how such assessments might be conducted is beyond the scope of this thesis. While attempts have been made to control for a variety of sources of error and to incorporate issues of spatial fidelity into the map validation process presented herein, accuracy assessment will hereafter refer to an examination of a map's thematic accuracy.

Thematic accuracy refers to the non-positional characteristics of spatial data, i.e., the attributes of said data (Chrisman 1997). If these attributes permit some exhaustive classification, then this validation of the non-positional characteristics of spatial objects yields the classification accuracy as suggested by Hord and Brooner (1976). In the case of mapping with remote sensor data, this refers to the agreement between the attribute label assigned during image processing and the actual state of the landscape as observed in the field, either directly or indirectly. Assessments of thematic accuracy essentially ignore the first six sources of image classification error mentioned above (although efforts should be made to minimize their influence on the final classification result) and concentrate instead on errors in classification or errors in map delineation. In fact, the caveat underlying most modern accuracy assessment methods is that all errors will be due to inconsistencies in class assignment or spatial object delineation on the final map (Congalton and Green 1993).

IV.B. A History of Thematic Map Accuracy Assessment

Throughout the 1970's and 1980's, assessment of the accuracy of remote sensor derived thematic maps was treated as an afterthought rather than as an integral component of image processing and mapping efforts (Congalton 1991, Jensen 1986). Even with the recognition of a need for more comprehensive, quantitative map validation techniques in the late 1970's (Ginevan 1979, van Genderen and Lock 1977, Hord and Brooner 1976), most accuracy assessment initiatives through the 1980's would report only a single map accuracy value. These early assessments often employed the same data used to train the classification algorithm and, furthermore, ignored the locational accuracy of thematic class assignments. In so doing, these early attempts at the validation of thematic map information content introduced considerable optimistic bias into reported accuracy values. Subsequent to the recognition of the shortcomings of early attempts at accuracy assessment of thematic maps, many methods for site specific assessment of map accuracy have been developed (e.g., Ma and Redmond 1995, Foody 1992, Congalton et al. 1983, Rosenfield 1981).

In order to carry out a statistically sound, locationally specific accuracy assessment of thematic maps, the analyst would ideally like to locate reference pixels within the study area (Jensen 1986). Once the relevant land cover information for each site has been collected, the analyst is equipped with unbiased reference information with which to conduct a statistically and locationally valid accuracy assessment of land use/land cover maps derived from remote sensor data. Remote sensor derived thematic maps should thus be considered point sampled data where each point possesses some spatial extent (Janssen and van der Wel 1994). Individual pixels are the most appropriate samples, but difficulties with field locational accuracy, particularly in remote regions, make cluster based sampling more appropriate (Muller et al. 1998, Congalton 1988).

It should be noted that remote sensor derived thematic maps have often been validated via comparison to the results of aerial photograph interpretation, another means of deriving thematic information from remotely sensed data. This interpretation process is not error free and thus, in order to adequately assess the accuracy of remote sensing classifications, accurate ground reference data must be collected (Congalton 1991). Actually visiting selected sites on the ground with a Global Positioning System receiver (GPS unit) helps to ensure high accuracy of ground reference data (Muller et al. 1998, Congalton 1991). Much work is yet to be done to determine the proper collection techniques and the appropriate level of effort to provide this important reference information.

Validation of land cover maps generated from remote sensor data is time consuming and expensive. The large spatial extent of modern satellite imagery, coupled with time and cost constraints make it nearly impossible to conduct a comprehensive check of each land cover patch in a given region (van Genderen and Lock 1977). Since comprehensive field checking of thematic map accuracy is impractical, a valid sampling scheme, appropriate for incorporation into an error matrix, must be adopted. The three critical elements in a sampling strategy are the sampling unit (clusters, pixels, polygons, etc.), the sampling design (simple random sampling, stratified systematic unaligned sampling, etc.), and the number of samples to collect. Most authors (e.g., Muller et al. 1998, Congalton 1988, 1991, Janssen and van der Wel 1994) agree that difficulties with field locational accuracy in locating polygon boundaries or individual pixels recommend pixel clusters as the appropriate sampling unit so long as the cluster size does not exceed 10 pixels. This sampling method also has the effect of artificially inflating the number of pixels sampled when the algorithm used to generate the final classification considers each pixel independently prior to class assignment. While the sampling unit debate may be easily resolved, the literature is replete with analyses directed at determining the appropriate size and design of accuracy assessment sampling efforts (e.g., Stehman 1992, Congalton 1988, Fitzpatrick-Lins 1981, Aronoff 1985).

The number of samples to be used in filling an error matrix is difficult to determine and is the subject of debate in the literature. Several analysts suggest computing accuracy assessment sample sizes based upon the binomial distribution or the normal approximation of the binomial distribution (Fitzpatrick-Lins 1981, Ginevan 1979). While this method is suitable for selecting the total sample number, N, to be used in situations where traditional sampling theory applies, it is not designed for selecting point samples to fill an error matrix (Stehman 1992, Congalton 1991, Hay 1979). Due to the large spatial extent of most remotely sensed satellite images, this method suggests per class sample sizes numbering in the several hundreds. van Genderen and Lock (1977) computed per class samples sizes also employing the binomial distribution. Instead of considering the whole remotely sensed image, the authors applied the relevant binomial expansion within a thematic class with an eye toward detecting and minimizing sampling error. Suggested sample sizes for guaranteeing a specified map accuracy with 95% confidence ranged from 5-60 samples per class depending upon the desired thematic accuracy. Each of the above techniques for sample size selection suffers from the fact that each of them assumes cover class independence and thus are not aimed at analyzing which cover classes are most often confused, a primary concern of thematic map validation. While work to determine adequate per class sampling sizes progresses, Congalton (1991) has suggested, as a general guideline, a sample size of 50 units per class with this number increasing to 75-100 units per class for multi-image analyses.

Specification of the sampling design to be used in the collection of reference data is also the subject of considerable debate in the literature. While most error evaluation statistical measures derived from classification error matrices assume random sampling (Congalton 1991, Rosenfield and Fitzpatrick-Lins 1986, van Genderen and Lock 1977), simple random sampling and even stratified random sampling are often difficult to implement, particularly in remote areas where logistics become problem (Janssen and van der Wel 1994, Congalton 1988, Jensen 1986). In addition, simple random sampling will tend to undersample or completely omit cover classes which represent small but important portions of the landscape unless the sample size, N, is sufficiently large (600<N<1000). Systematic sampling and stratified systematic unaligned sampling greatly overestimate population parameters and therefore should be employed with extreme caution (Congalton 1988, Jensen 1986). Common recommendations (Janssen and van der Wel 1994, Congalton 1988, 1991, Jensen 1986), suggest that some hybrid of random and systematic sampling be used. While the debate on the quantitative determination of appropriate sample size and sampling strategy to be used in the collection of accuracy assessment reference data is far from resolved, the current dogma in the literature is that logistical, financial and time constraints, particularly when working in remote regions, will play a large role in governing the selection of the sampling scheme for accuracy assessment reference data collection.

IV.C. Error Matrix Analysis to Assess Classification Accuracy

All modern methods for assessing the thematic accuracy of remote sensor derived maps commonly compare a resultant image classification to a set of georeferenced reference samples and summarize the relationship between these two information sources in the form of an error matrix (Naesset 1995, Story and Congalton 1986, Congalton et al. 1983, Hay 1979). Variously termed a(n) confusion matrix, contingency table (Story and Congalton 1986), evaluation matrix (Aronoff 1984) or misclassification matrix (Chrisman 1991), the error matrix (Fig. IV-1) is a square array of numbers set out in rows and columns expressing the number of sample units assigned to a particular category relative to the actual category as verified on the ground. Error matrices present effective ways to summarize classification error as the accuracy of each thematic class is summarized along with information on the errors of omission and commission. Columns generally summarize the reference data while the rows summarize the data generated during image processing. The main diagonal of the error matrix indicates agreement between reference data and the image classification being scrutinized. Thus in an ideal situation, all off diagonal cell values are zero, indicating that there are no classification errors (Congalton et al. 1983). Once the error matrix has been established, a number of accuracy values can be derived through simple descriptive exercises as well as a variety of statistical analytical techniques.

Reference Data

Classified Data

	X	Y	Z	Row Total
X	24	2	4	30
Y	6	45	9	60
Z	3	5	52	60
Column Total	33	52	65	150

Figure IV-1: Example of a typical error matrix used in accuracy assessment of remote sensing derived thematic maps. Diagonal cell values indicate correct classifications while off diagonal values (red) indicate misclassifications. (redrawn from Congalton and Green (1993))

IV.C.I. Descriptive Evaluation of Error Matrices

The most common way to express the accuracy of remote sensor derived maps is by a statement of the map area correctly classified relative to ground truth (Chrisman 1997, Janssen and van der Wel 1994, Congalton 1991, Jensen 1986, Story and Congalton 1986). This overall map accuracy or percent correctly classified (PCC) is calculated by dividing the sum of all cells along the major diagonal of the matrix, by the total number of samples taken (Fig. IV-2a). Since map categories frequently differ significantly in accuracy, individual category accuracies are desirable to completely assess the value of a classified image for a specific application (Story and Congalton 1986).

A widely used class level assessment of accuracy is to divide the number of correctly classified samples in category X by the number of reference data samples for category X. Referring to Fig. IV-2b this amounts to:

$$\text{\% Correct in category X} = \frac{\text{\# correctly classified (a)}}{\text{column total (g)}}$$

This calculation summarizes the probability that a pixel which represents category X on the ground will actually be classified as X in the remotely sensed image. This percentage, which measures errors of omission, has been called the producer's accuracy as it indicates the analyst's success in correctly assigning pixels to the thematic classes. Alternatively, one may divide the number of correctly classified samples in category X by the total number of samples classified as X. Referring to Figure IV-2c, this becomes:

Reference Data

Classified Data

	X	Y	Z	Row Total	Commission
X	a	b	c	d	
Y	e				
Z	f				
Column Total	g			h	
Omission					

a) Overall Accuracy (PCC):

PCC = Σ diagonal cells / total samples (h)

b) Producer's Accuracy:

PA (category X) = # correctly classified (a) / column total (g)

c) User's Accuracy:

UA (category X) = # correctly classified (a) / row total (d)

Figure IV-2: Sample error matrix showing the variety of descriptive means of summarizing thematic map classification accuracy: (a) summarizes overall accuracy or percent correctly classified (PCC); (b) illustrates the calculation of producer's accuracy for a given land cover class; (c) illustrates the calculation of user's accuracy for a given land cover class.

$$\% \text{ Correct in category X} = \frac{\text{\# correctly classified (a)}}{\text{row total (d)}}$$

This calculation summarizes the probability that a point on a map will actually represent the correct cover class as found in the field. The resulting percentage, summarizing errors of commission, has been called user's accuracy or reliability as it indicates how useful the remote sensor derived map is in describing the actual state of the landscape to the user. Both of these calculations must be considered as they convey different information that may indicate different levels of utility to the producer and a variety of users.

IV.C.II. Statistical Analytical Evaluation of Error Matrices

In addition to facilitating the aforementioned descriptive techniques for reporting thematic map accuracy, a classification error matrix is also an appropriate beginning for many analytical statistical techniques. Discrete multivariate statistics have been used to evaluate the accuracy of remote sensing derived classifications and error matrices since 1983 (Congalton et al. 1983) and are now widely accepted. These methods are appropriate because remotely sensed image data are discrete rather than continuous and are binomially or multinomially distributed. Statistics based upon the normal distribution, as implemented by Rosenfield (1986, 1981), simply do not apply. The most appropriate accuracy assessment methods employ the binomial model which distinguishes between correct and incorrect samples. Binomial probabilities can be calculated directly from the binomial probability density function or derived from the normal approximation of the binomial distribution.

It is often desirable to calculate confidence intervals for the figures calculated in the previous section. While the variety of *% correct* values summarized above are often taken as representative of the classification result, a user will be more well equipped to assess the utility of a remote sensing derived map product if confidence intervals can be calculated and hypothesis testing can be carried out. These statistics can be calculated for individual land cover categories or for the classification as a whole. Confidence intervals can be calculated for producer's, user's, and overall accuracy based upon the sample size N, the number of correct classifications k, and the significance level α. Critical values can be read directly from the relevant binomial statistical tables or calculated directly from the exact binomial distribution (Janssen and van der Wel 1994, Aronoff 1985, Ginevan 1979).

As in the case of this thesis, where the classification result should have some minimum overall accuracy, hypothesis testing based upon some predetermined level of accuracy is an appropriate step in the error matrix evaluation process. In hypothesis testing, the null (H_0) and alternative (H_1) hypotheses must be correctly formulated and the significance level (α) must be determined. According to Janssen and van der Wel (1994), if a person conducting a remote sensing classification wishes to obtain a map with some minimum level of overall accuracy, a test of the form:

H_0: Overall map accuracy < 85%

H_1: Overall map accuracy $\geq$85%

For α=0.05 with sample size N

is the most appropriate as the burden of proof lies with the analyst to minimum accuracy level; in this case, 85%. Again, the binomial distribution is used to calculate the critical values which reject H_0.

An additional purpose of accuracy assessment in this thesis is to compare the results of an identical classification performed on satellite images of differing spatial, spectral, and radiometric resolutions. The most effective way to perform this comparison is through the calculation and statistical comparison of coefficients of agreement (Ma and Redmond 1995, Foody 1992, Hudson and Ramm 1987, Rosenfield and Fitzpatrick-Lins 1986, Congalton et al. 1983). The Kappa-coefficient of agreement, as introduced by Congalton et al. (1983) has been widely used in the literature and adjusts the overall percentage correct value to account for the estimated contribution of chance agreement. Kappa typically lies on a scale from 0 to 1 and multiplication by 100 indicates how well the classification performed relative to a chance assignment of pixels to the selected land cover categories. For example, a Kappa value of 0.75 indicates that the accuracy of a land cover map is 75% better than the accuracy of a map resulting from a random classification of pixels. Calculation of Kappa involves the entire error matrix and thus includes not only information on the total percent correct but also provides insight into the errors of ommission and commission.

Foody (1992) and Ma and Redmond (1995) recently found that Kappa often overestimates chance agreement and thus may lead to erroneously low reports of classification accuracy. The authors suggest calculation of a Kappa-like statistic called the Tau coefficient (Ma and Redmond 1995) which compensates for chance agreement by assuming each pixel in an image has an equal probability of being assigned to each land cover class. This approach is appropriate for unsupervised clustering approaches like that used in this thesis research. The Tau coefficient of agreement is thus calculated from the equation:

$$T_e = \frac{P_0 - (1/N)}{1 - (1/N)}$$

where P_0 = Overall accuracy (as a decimal),

and N = number of ground reference samples.

The T_e is used to denote the Tau value for a maximum likelihood image classification based upon equal probabilities of group membership (Ma and Redmond 1995). The Tau value for classifications with unequal probabilities (T_p) is not appropriate for use here as the probability of land cover class assignment for each pixel is not known *a priori.*

Once the Tau value(s) and its variance have been calculated for a matrix or matrices, tests can be performed to determine if the coefficient is significantly greater than zero, or if two Tau coefficients derived from different remote sensor classifications are significantly different. A test of the significance level of Tau value greater than zero or of the difference between two Tau values is carried out using a Z test where the test statistic has the general formula:

$$Z = \frac{C_1 - C_2}{\sqrt{(\sigma^2_1 + \sigma^2_2)}}$$

where the C_x = accuracy coefficients from two different classifications,

and σ = variance calculated for each respective C value.

As most image classification efforts are aimed at getting a result better than that attributable to chance, finding a Tau value significantly greater than 0 is not very encouraging. However, testing the difference between two or more Tau coefficients, using the above equation, can help to answer a variety of questions regarding the effectiveness of a particular data source or classification algorithm for a particular purpose.

IV.D. Land Cover Map Accuracy Assessment Methods

Despite the considerable application of remote sensing derived mapping throughout the state of Alaska (see section I.B., Fig. I-1), quantitative accuracy assessments have been performed only by Fleming (1988), Felix and Binney (1989), Stow et al. (1989), Pacific Meridian Resources (1995), and Muller et al. (1998). Only the study by Muller et al. (1998) provided a detailed look at sampling strategy and reported accuracy assessment information facilitating a variety of judgements on the utility of resultant products by multiple end users. The methods described here summarize a comprehensive accuracy assessment effort for land cover maps of the Barrow Region, Northern Alaska in a manner which will provide a variety of potential user's with information about each map's utility for a specified purpose.

The goal of the ground reference data collection process for the accuracy assessment of the Landsat MSS and TM derived land cover maps of the Barrow

Region was to collect data that were spatially accurate, logistically feasible, and sampled in a statistically valid manner. The remote nature of the Barrow landscape presents special issues that preclude the collection of ground reference data in the ideal manner described in section IV.B. The tradeoffs made in the selection of sampling design, the sample size, and sampling unit, represent attempts to balance logistical, time, and financial constraints with the effect each decision would have on the final estimates of thematic map accuracy.

As discussed in section IV.B., individual pixels are the ideal sampling unit for maps derived from remotely sensed data (Muller et al. 1998, Congalton 1988). However the accuracy of generally accessible C/A code Global Positioning System receivers (GPS units), like the one employed in this ground reference data collection process, yields a level of uncertainty (±100m) which causes difficulties with field locational accuracy of sampling points. Consistent with the recommendations of Muller et al. (1998), a sampling unit of 3x3 blocks of pixels was selected to allow for GPS unit imprecision and minimize classification accuracy bias caused by errors in registration of reference data to the thematic maps.

While the ideal sampling design for accuracy assessment of remote sensor derived land cover maps is simple random sampling or stratified random sampling (Congalton 1991, Rosenfield and Fitzpatrick-Lins 1986, van Genderen and Lock 1977, see section IV.B.), logistical issues in remote regions have led to the development and validation of several spatially explicit sampling strategies. The cluster and transect sampling methods described by Thompson (1992) are most relevant to the research at hand. In order to make sample collection more efficient during the short Arctic growing season, a systematic, transect based sampling strategy was implemented. The strategy is similar to that employed by Muller et al. (1998) in their accuracy assessment of a Landsat MSS derived land cover map of the Kuparuk River Basin on Alaska's North Slope. Because the current mapping effort in the Barrow Region encompasses such a small geographic area, no efforts were made to stratify sampling efforts among land cover classes for this project. Instead, eight transects were identified for use in the sampling effort in a manner which attempted to represent a maximum of landscape heterogeneity and spectral reflectance over the extent of the Barrow Peninsula (Fig. IV-3). Following the arbitrary selection of one end of each transect as a zero point, sampling of 3x3 blocks was conducted every 250m along each transect. Sampling in this manner prevents the overlap of blocks of $57m^2$ MSS pixels. Sampling pixel blocks along the eight selected transects yielded a total of 164 sample sites and 1,476 pixels with all land cover types being represented in the sample set. Distribution of the sample sites among land cover types is shown in Table IV-1.

IV.D.I. Global Positioning System (GPS) Calibration

Because locational errors in ground reference data can introduce bias into estimates of classification accuracy via misregistration to the map product, positional error should be addressed when planning reference data collection (Muller et al. 1998, Janssen and van der Wel 1994). A handheld Global Positioning System receiver (GPS unit) was employed in the field location of

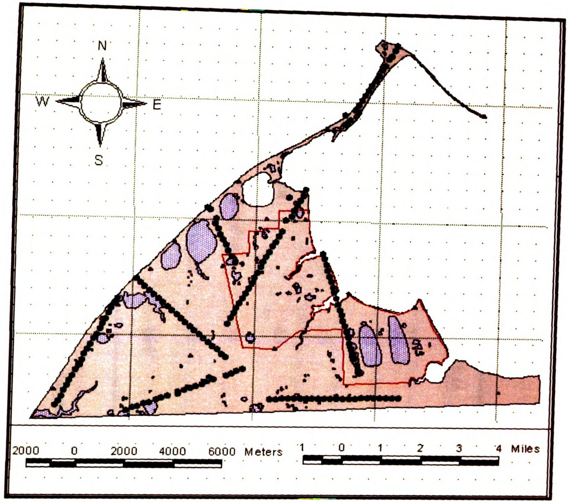

Figure IV-3: Map of the Barrow Peninsula showing the location of eight transects selected for use in cluster sampling for thematic map accuracy assessment.

	Sample Sites	Pixels
Water	14	126
Wet tundra	50	450
Moist/Wet tundra complex	15	135
Moist/Dry tundra	43	387
Moist shrub-rich tundra	11	99
Partially vegetated/ Barren	31	279
TOTAL:	164	1476

Table IV-1: Distribution of accuracy assessment sample sites and pixels among the six final land cover classes.

preselected reference data points employed in assessing the accuracy of the Landsat MSS and TM derived land cover maps of the Barrow Peninsula. Therefore, the spatial fidelity of reference data is dependent upon the positional accuracy of the selected GPS unit. The unit selected for use in this project was the Magellan 4000XL GPS unit, a C/A code (Federal Radionavigation Plan 1994) receiver providing a reported field locational accuracy within 100 meters at 2 distance root mean square (2drms = 95% confidence interval). To confirm the field locational accuracy of the selected GPS unit and investigate the possibility of applying a systematic adjustment to increase the accuracy of this unit and reduce locational error in sample site location, the Magellan 4000XL unit was tested in the field at 24 sites for which real world coordinates were known. Field test sites were selected from U.S. Coastal and Geodetic Survey (USC&GS) horizontal control points and from landscape features easily identifiable on U.S. Geological Survey (USGS) topographic maps. The raw field data, as well as summaries of horizontal error for the corrected and uncorrected GPS coordinates, can be found in the appendix to this thesis (Tables A1 and A2).

Following the field location of known coordinate points, analysis of the resultant data revealed that, for a Universal Transverse Mercator (UTM) map projection in the 1927 North American Datum (NAD27), the accuracy of our Magellan 4000XL GPS unit fell short of the reported 100m for nearly all points considered. The average distance from the known location was 186.6m. A discrepancy of this magnitude is unacceptable due to the potential for misregistration to introduce negative map accuracy bias in to the accuracy assessment process. This decrease in GPS unit accuracy at high latitudes is most likely an artifact of the algorithms used to convert the spherical location coordinates of latitude and longitude into two dimensional planar coordinates suitable for mapping. The conversion from latitude and longitude coordinates to UTM coordinates establishes a false origin for coordinate axes within a given UTM zone (Zone 4 for the Barrow Region). The algorithm which places the latitude and longitude location of a point on the earth's surface, given by the GPS satellite constellation, into an established UTM coordinate plane yields a relationship whereby accuracy of the planar coordinate location in meters decreases as distance from the false origin increases. In the Barrow Region of Alaska's North Slope, where distances from the false origin of UTM grid zone 4 are measured on the scale of several millions of meters, this relationship significantly decreases the accuracy of GPS specified field locations given in UTM coordinates.

In order to improve the investigator's ability to accurately locate the predetermined accuracy assessment sampling points in the field, a systematic adjustment was calculated using a computer-aided, iterative fitting procedure which sought to maximize the accuracy of the GPS unit relative to the known test points. Subtraction of 110m from all northing coordinates and addition of 110m to all easting coordinates of known real world locations facilitates the location of the desired ground location within 44.9m at 2drms. This reduced error consistently places the ground location being visited within the 3X3 block of pixels used for ground reference data collection. The small areal extent of the study area and wide distribution of the initial GPS accuracy test points recommend such systematic adjustments, which are analogous to differential GPS post processing used to increase accuracy of field site locations. This protocol should be used with caution in mapping larger areas and should be discarded altogether when the highly accurate Y code GPS units (currently restricted for U.S. Government use only) or differential GPS technologies are available.

IV.D.II. Data Collection and Analysis

Following systematic adjustment as described above, waypoint data (X,Y coordinate locations and unique site identifiers) for each of the 164 ground reference sample sites were entered into the GPS unit's memory. Using this waypoint information, the GPS unit was used to guide investigators to the field location of each sampling point. The primary land cover type within each sampling cluster was recorded in a data sheet (Fig. IV-4) with secondary and tertiary land cover recorded as applicable. As supplementary information, subjective notes on substrate type, site moisture, and snow cover were also recorded. The raw data from the transect based cluster sampling for thematic map accuracy assessment can be found in Table A3 in the appendix of this thesis. It should be noted that it is sometimes difficult to determine land cover type dominance by viewing a large vegetation stand and making subjective judgements. Therefore, ground reference data misclassification is an unknown source of error in the map accuracy assessment process. The simple classification scheme employed during this research, coupled with personal

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Field Data For Land Cover Map Accuracy Assessment

Vegetation Mapping Transect Data

Date of Preliminary Classification: May 1998 **Location:** Barrow Peninsula, Alaska

Observers: Noyle and Brunner

Date of Field Check: 7-9-98 **Transect #:** 3 **Survey Point #:** 3

Preliminary Classification: Moist tundra

Est. Vegetation (Walker Level C) Wet herbaceous tundra

Species Information/Percent Cover of Veg. Types:

Dominant: Arctophila fulva Secondary: Eriophorum Scheuzeri

Tertiary: Saxifraga cernua Others: —

Surface Form: unpatterned ground **Disturbance:** ATV tracks

Moisture Scalar (1=dry, 5=wet) 4 **Snow Cover Scalar (1=low, 5=high)** 4

Substrate Description: medium brown, saturated peat

General Notes and Description: standing H_2O

Date of Field Check: 7-9-98 **Transect #:** 3 **Survey Point #:** 4

Preliminary Classification: Moist tundra

Est. Vegetation (Walker Level C) Moist graminoid tundra/Dry tundra barrens

Species Information/Percent Cover of Veg. Types:

Dominant: Eriophorom rosseolum Secondary: Arctophila fulva

Tertiary: Poa arctica Others: Cochlearia officionalis.

Surface Form: HCP w/ frost scars **Disturbance:** Frost scars, human waste

Moisture Scalar (1=dry, 5=wet) 3 **Snow Cover Scalar (1=low, 5=high)** 2

Substrate Description: dark, humic soils w/ well decomposed O.M.

General Notes and Description:

Figure IV-4: Sample field data from accuracy assessment transect surveys.

knowledge of the vegetation of the region and the use of ancillary data as described in Chapter 3 (see section III.B.II.b.) should mitigate some of the uncertainty involved in ground reference data collection.

Subsequent to the collection of ground reference information, this data was compared to the Landsat MSS and TM derived land cover maps of the Barrow Peninsula via map overlay and query within a Geographic Information System. This comparison yields a binary dataset (either the land cover classification at a given point is correct or not) for each land cover type. The results of this comparison were incorporated into an error matrix, similar in format to the one shown in Fig. IV-1, for each map. The error matrix for each of the Landsat derived maps was, in turn, used to calculate overall map accuracy (PCC) for each thematic map, a confidence interval for PCC, as well as Producer's and User's accuracies for each land cover category in each map. Consistent with the recommendations of Janssen and van der Wel (1994), the calculated PCC and corresponding confidence interval were used to test the null hypotheses:

1) H_0: Overall map accuracy (PCC) of the TM derived land cover map of the Barrow Peninsula is less than 85% at the 0.95/0.05 confidence level.

2) H_0: Overall map accuracy (PCC) of the MSS derived land cover map of the Barrow Peninsula is less than 85% at the 0.95/0.05 confidence level.

In addition to facilitating calculation of the aforementioned descriptive characteristics, the error matrices were used to calculated the Kappa-like coefficient of agreement, Tau (T), as an estimate of classification accuracy for each of the Landsat MSS and TM derived land cover maps constructed. Recall that the Tau coefficient, as proposed by Foody (1992) and built upon by Ma and Redmond (1995), removes chance agreement from the estimate of classification accuracy. In the case of the accuracy assessment presented herein, the value T_e, appropriate for use with error matrices derived from images where all pixels have equal probabilities of class membership *a priori*, was calculated for each map. Finally, the T_e value for the Landsat MSS derived map was compared to that for the TM derived map by means of a Z-test to test the null hypothesis that there is no significant difference between the two Landsat derived land cover maps of the Barrow Peninsula (H_0: $T_e(MSS) = T_e(TM)$). The results of the accuracy assessment of each of the maps developed in this thesis research are presented in Chapter 5.

Chapter 5

RESULTS AND DISCUSSION OF VEGETATION MAPPING AND MAP ACCURACY ASSESSMENT

V.A. PRODUCTION OF VEGETATION MAPS

In this study, the vegetation of the Barrow Peninsula on Alaska's North Slope was mapped employing Landsat digital satellite data from both the Multispectral Scanner (MSS) and Thematic Mapper (TM) sensors. The methodologies employed have resulted in the production of two 1:63,360 scale vegetation maps of the region (included at the back of this thesis), derived from multispectral data of two different spatial resolutions. For each image, the classification, editing, and class labeling yields a land cover map of the predicted vegetation of the Barrow Peninsula based upon reflectance values in multispectral imagery. The results of each image classification indicate that the Barrow landscape is composed of the six land cover types in the proportions indicated in Table V-1. The Barrow region is a flat thaw lake plain with little topographic relief and the unsupervised classification indicates that *Dry/Moist Tundra* communities dominate the landscape, particularly in the area immediately inland from the coast south of the city of Barrow. The eastern portion of the study area, bordering Elson Lagoon, is comprised mainly of W*et Tundra* and M*oist/Wet Tundra Complex*. *Moist Shrub Rich Tundra* is most common along the

	TM		MSS	
	Total Area (km^2)	Percent of Map Area	Total Area (km^2)	Percent of Map Area
Water	225.56	46.9%	253.45	52.7%
Wet tundra	55.79	11.6	77.43	16.1
Moist/Wet tundra complex	55.31	11.5	54.35	11.3
Moist or Dry tundra	66.85	13.9	73.10	15.2
Moist shrub rich tundra	37.99	7.9	52.42	10.9
Partially Vegetated/Barren	38.47	8.0	39.44	8.2

Table V-1: Areal and percentage summaries for land cover types used in the mapping of the Barrow Peninsula.

southwest coast of the peninsula. Development and gravel placement has claimed much of the landscape from Barrow north to the point extending into the Arctic Ocean.

V.B. Land Cover Map Accuracy Assessment

The detailed accuracy assessment performed for both the TM and MSS derived maps, following preparation and output of the final thematic products, summarizes the utility of the information contained in each map. The accuracy assessment exercise also provides quantitative metadata allowing a variety of potential users to assess the potential of each map to serve a given purpose. The initial question and hypothesis related to the accuracy of Landsat derived thematic maps of Arctic tundra in the Barrow Region are reintroduced below to facilitate the discussion of results and relevant conclusions.

<u>Question:</u> Can Landsat digital satellite data from the Thematic Mapper (TM) and Multispectral Scanner (MSS) instruments be employed to accurately represent the dominant vegetation types present on the landscape in the Barrow Region?

<u>Hypothesis:</u> Both the Landsat TM and MSS sensors provide data enabling the preparation of vegetation maps which will accurately represent the general vegetation types present on the landscape in the Barrow Peninsula.

The error matrices generated for both the TM and MSS derived vegetation maps from the accuracy assessment sampling and map overlay comparison are presented in Fig. V-1. Comparison of the TM derived land cover map to ground reference data indicates that 105 of the sample clusters or 945 of the reference pixels were classified correctly. This yields an overall map accuracy value of 64.0% with a 95% confidence interval of {61.6%, 66.4%}. Overall map accuracy of the MSS derived land cover map was 54.9% with a 95% confidence interval of {52.4%, 57.4%} as only 90 sample clusters or 810 pixels were correctly classified. The producer's and user's accuracies for individual land cover classes in each map are variously distributed as indicated in Table V-2. As obtained from the binomial distribution, the range of correct classifications which rejects the null hypothesis for both the Landsat TM and MSS derived maps lies on the interval of {136, 164} correct classifications. For both the TM derived vegetation map and the MSS derived vegetation map of the Barrow Region, the data fail to reject the null hypothesis:

1) H_o: Overall map accuracy (PCC) of the TM derived land cover map of the Barrow Peninsula is less than 85% at the 0.95/0.05 confidence level.

2) H_o: Overall map accuracy (PCC) of the MSS derived land cover map of the Barrow Peninsula is less than 85% at the 0.95/0.05 confidence level.

Neither the TM derived vegetation map nor the MSS derived vegetation map attains the suggested accuracy level of 85% as proposed in Chapters I and II of this thesis.

(a) **Reference Data**

MSS Image Classification							Row Total
Water	**9**	**4**	**0**	**1**	**0**	**6**	20
Wet Tundra	**3**	**29**	**4**	**5**	**0**	**0**	41
Moist/Wet Tundra Complex	**0**	**6**	**2**	**9**	**1**	**0**	19
Moist or Dry Tundra	**1**	**8**	**7**	**22**	**5**	**2**	45
Moist Shrub Rich Tundra	**1**	**2**	**1**	**6**	**5**	**0**	15
Partially Vegetated/Barren	**0**	**1**	**1**	**0**	**0**	**23**	24
Column Total	14	50	15	43	11	31	164

(b) **Reference Data**

TM Image Classification							Row Total
Water	**12**	**4**	**0**	**2**	**0**	**2**	20
Wet Tundra	**1**	**26**	**4**	**6**	**1**	**1**	39
Moist/Wet Tundra Complex	**0**	**11**	**9**	**8**	**1**	**0**	29
Moist or Dry Tundra	**0**	**9**	**0**	**23**	**2**	**0**	34
Moist Shrub Rich Tundra	**0**	**0**	**0**	**1**	**7**	**0**	8
Partially Vegetated/Barren	**1**	**0**	**2**	**3**	**0**	**28**	34
Column Total	14	50	15	43	11	31	164

Figure V-1: Error matrices generated for Landsat MSS image classification (a) and for Landsat TM image classification (b).

	TM		MSS	
Overall Accuracy (PCC)	**64.0% {61.6, 66.4}**		**54.9% {52.4, 57.4}**	
	Producer's	**User's**	**Producer's**	**User's**
Water	85.7	60.0	64.2	45.0
Wet tundra	52.0	66.7	58.0	70.7
Moist/Wet tundra complex	60.0	31.0	13.3	10.5
Moist/Dry tundra	53.5	67.6	51.2	48.9
Moist shrub-rich tundra	63.6	87.5	45.5	33.3
Partially vegetated/ Barren	90.3	82.4	74.2	95.8

Table V-2: Summary of Overall, Producer's, and User's accuracies calculated from classification error matrices for the Landsat TM and MSS derived land cover maps of the Barrow Peninsula. Bracketed numbers indicate 95% confidence intervals.

Vegetation maps prepared for the Barrow Region from both Landsat satellite sensors have overall map accuracies of markedly less than 85%, and there are several explanations for the low accuracy of each map. The estimates of map accuracy reported herein only measure thematic accuracy and essentially ignore the other six sources of error summarized by Janssen and van der Wel (1994) and Congalton and Green (1993) (see section IV.A.). While measures were taken to minimize sources of error that were not statistically accounted for, accuracies reported in this thesis have not estimated the influences of misregistration of classified and reference data, polygon delineation error, data entry error, changes in the landscape between the time of image acquisition and time of ground reference data collection, or human inconsistencies introduced into the classification process. Low reported accuracies for the TM and MSS derived vegetation maps may thus be due to spatial errors involving misregistration of source maps and reference data during the geometric correction or map overlay process. For example, closer inspection of the misclassifications of the *Water* class as *Partially Vegetated or Barren Surfaces* (Fig. V-1) in both the TM and MSS derived maps reveals that the errors occur for beach gravel sampling points that are directly adjacent to ocean water. In addition, errors in the keyboard entry of reference data land cover type codes, or other sources of human error may have introduced pessimistic bias into the reported map accuracy values. Recommendation of ways to reduce, eliminate, or mathematically account for these sources of error is hindered by the relatively recent initiation of research concerning how such error propagates through image processing and GIS lineages (Lunetta et al. 1991, Goodchild and Gopal 1989).

A more compelling explanation of the low reported map accuracy values involves a comparison of the date of image acquisition to the data of field data collection. A period of twelve years had elapsed between the date of image acquisition and initiation of this research. The concept of land cover change through time is one that currently is receiving much attention in the literature (e.g., Erickson 1995, Gopal and Woodcock 1996, Lambin 1997). The passage of more than a decade between image acquisition and initiation of ground truth and reference data collection efforts is consistent with reported time intervals necessary for change detection using Landsat MSS imagery (Schwabe 1991, Pickup, et al. 1993). Presumably this temporal change effect also applies to TM imagery with its increase in spatial, spectral, and radiometric resolutions. While the selection of the two digital images obtained in 1986 facilitates a direct comparison of image information content, land cover change subsequent to image acquisition may be obscuring a clear view of the present state of the landscape and introducing considerable pessimistic bias into reported map accuracy values for both data sources. Selection of satellite data obtained in the same year as field data or within one or two years of reference data collection would be ideal and would serve to reduce or eliminate this source of map classification error.

An examination of the distribution of classification errors within each error matrix also provides insight into the low reported accuracy for each remote sensor derived map. The largest proportion of misclassifications in each image map represent confusion between *Wet Tundra* and *Moist/Wet Tundra Complex* and between *Moist/Wet Tundra Complex* and *Moist or Dry Tundra* land cover classes (23 of 59 misclassifications in the TM derived map, 26 of 74 misclassifications in the MSS derived map). The complex mosaic of patterned ground represented in polygonized tundra often produces well-defined changes in vegetation and site moisture over distances measured on the scale of a few meters. This heterogeneity within the *Moist/Wet Tundra Complex* land cover class is often not detectable given the ground resolution of each satellite sensor. Variations in polygon size, producing conspicuous differences in proportions of moist and wet tundra present over the spatially aggregated extent of a pixel, complicate accurate identification of the *Moist/Wet Tundra Complex* land cover type on the Barrow tundra. Such confusion occasionally places this vegetation into either the *Wet Tundra* or the *Moist or Dry Tundra* classes depending upon the proportions of wet and moist tundra present in the complex. While such errors are understandable from a logical standpoint, the result is still a measurably negative impact on derived map accuracies.

Misclassifications of *Moist/Wet Tundra Complex* might be significantly reduced through the incorporation of ancillary data layers summarizing landform or soils data into the unsupervised clustering and class labeling stages. Additionally, increased accuracy levels may be achieved by identifying such complex vegetation types from conventional aerial photography and writing the resultant polygons to the final digital classification file. Also, this problem of "mixed pixels", resulting from the spatially controlled aggregation of a heterogeneous area on the ground, is common in a variety of remote sensing applications and may reduced with the evolution or implementation of new satellite technologies aimed at significantly improving the spatial resolution of satellite sensors. SPOT Image data provides multispectral information at a spatial scale of 10m and 15m for panchromatic and multispectral sensing respectively. Stowe et al. (1989) have not had great success accurately mapping tundra vegetation but ancillary data or novel classification algorithms may further recommend the use of this high spatial resolution imagery for tundra mapping in the near future. In addition, the problem of mixed pixels promises to be significantly reduced with the declassification of a large archive of military satellite imagery providing data at 1m ground resolution or better. It may also prove beneficial to develop alternative systems of classification which produce a suitable division of tundra vegetation into discrete classes while avoiding the complication that arises in accurately delineating vegetation/landform complexes. This final option is further discussed below.

This consideration of the factors influencing map accuracy would be incomplete without mention of the fact that the Barrow Peninsula vegetation maps are being affected by the nature of tundra hydrology within and between growing seasons. The Walker (1983) tundra vegetation classification scheme relies heavily on site moisture status for class assignment. Land cover class assignment is thus not directly contingent upon the presence or absence of a specific vegetation type, but rather relies on the correlation between site moisture and vegetation during the classification process. Hydrology is dynamic over tundra landscapes both througout the growing season and between growing seasons. Interannual variability in precipitation and depth of thaw, in addition to within year precipitation and drying events, create an ever changing hydrology with a general pattern determining presence or absence of broad vegetation communities.

The task thus becomes one of generating a consistent classification from a dynamic attribute. As in the case of controlling for time series changes in the state of the landscape, the best way to eliminate such error due to site moisture dynamics is to conduct ground reference surveys on or near the date of image acquisition. The paucity of cloud free days makes it nearly impossible to know *a priori* the specific instance when a cloud free Landsat scene for the coast of Alaska's North Slope might be obtained. However, the SPOT Image Corporation now operates a French multispectral satellite spectrally similar to the Landsat MSS, with 15m ground resolution, and allows a user to custom order scenes prior to acquisition thus introducing some user control of the proximity in time of image and reference data acquisition. In addition, the revision of the chosen classification scheme to depend on more constant plant community traits may serve to increase map accuracy. Recently, Walker et al. (1998) and Muller et al. (1998) developed a revised classification scheme for mapping northern Alaskan Arctic Tundra (Table V-3). While still including a site moisture term in the naming convention, the latest iteration of the classification scheme relies on soil pH, substrate color, amount of standing dead graminoid vegetation, and other factors

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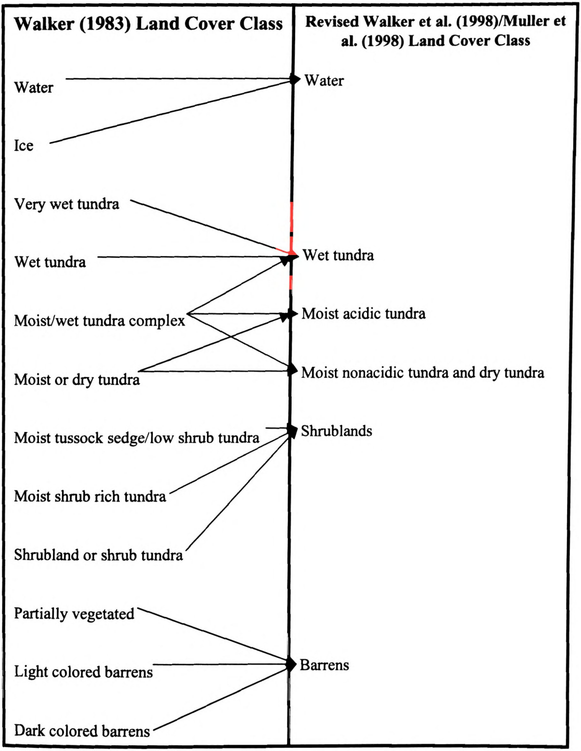

Table V-3: Table summarizing the original Walker (1983) tundra vegetation classification in relation to the revised Walker et al. (1998)/Muller et al. (1998) classification scheme. Arrows indicate correspondence between land cover classes in each system.

including the presence or absence of a defined set of Braun-Blanquet vegetation associations. Mapping efforts employing the new classification scheme have achieved overall derived map accuracies in excess of 90% (Muller et al 1998).

V.C. A Comparison of Image Information Content

Subsequent to the descriptive assessment of the Landsat TM and MSS derived land cover maps of the Barrow Region, AK, the Tau (T_e) (Ma and Redmond 1995) coefficient of agreement was calculated for each thematic map. Recall from Chapter 4 (see section IV.C.II.) that coefficients of agreement report a thematic map accuracy which accounts for instances of chance agreement in class assignment. By removing chance agreement from estimates of map classification accuracy, the calculation of T_e values facilitates the direct comparison of two or more classifications to test for significant differences. Calculated T_e values and a direct statistical comparison of the values for the thematic maps prepared for this thesis are discussed below following the reintroduction of the relevant research question and hypothesis.

Question: Are land cover maps, of the Arctic tundra near Barrow, AK, derived from Landsat TM data, with its increased spatial, spectral, and radiometric resolution, able to provide information at a higher level of accuracy relative to maps derived in an identical manner from Landsat MSS data?

Hypothesis: Maps produced from Landsat TM data will provide information on land cover in the Barrow Region that is more accurate than maps of the same area, derived in the same manner using Landsat MSS data.

The Tau (T_e) values calculated for the TM and MSS derived land cover maps of the Barrow Region, subsequent to error matrix generation and calculation of descriptive percent correct values, indicate that the maps are 56.8% and 45.9% accurate respectively, once chance agreement is accounted for. Another way of looking at this statistic is to say that the TM derived land cover map is 56.8% better than if the pixels were randomly assigned to land cover classes and the MSS derived map is 45.9% better than a random pixel assignment. Once chance agreement was accounted for in each classification, the two T_e values were compared by means of a Z test to test for significant differences between the coefficients derived from each map error matrix.

H_0: There is no significant difference between the TM and MSS derived land cover maps of the Barrow Region, Northern Alaska at the 95% confidence interval (T_e(TM) = T_e(MSS)).

The results of this test indicate that the null hypothesis is rejected; the TM derived land cover map of the Barrow Region is significantly more accurate than the MSS derived map at the 95% confidence interval.

The results of this comparison of derived map accuracy for TM and MSS derived land cover maps is consistent with expectations based upon the rationale put forth in Chapter 1 (see section I.D.IV.). With a substantial improvement in spatial resolution, the TM sensor yields a finer grain size over the landscape and facilitates the reduction of the problem of mixed pixels which can often result in the misclassification of pixels which contain two or more discrete land cover types. In addition, a greater number of spectral bands, a substantial improvement in the quantization of radiance values from 6 bit encoding for MSS data to 8 bit encoding for TM data, and an increased data rate in the TM sensor all contribute to the increase in information available in the TM imagery relative to the MSS imagery. Furthermore, the placement of the near infrared band on the TM sensor avoids the problem associated with rapid vegetation reflectance transitions that is encountered in Band 3 of MSS imagery. The TM sensor thus provides a means to distinguish vegetation types that is unavailable in MSS data due to the structure of the sensor. The results obtained in this thesis are consistent with the results of similar investigations reported by Solomonson (1984) and by Jensen (1986). According to these two concurring authors, the increase in accuracy of TM derived maps relative to MSS derived maps prepared for the same area, in the same manner, is based on the TM sensor's ability to provide twice as many separable classes over a given area as the MSS, to numerically provide 2 more independent vectors or principle components in the data, and to demonstrate through classical information theory that roughly twice as much information exists in the TM data.

V.D. Conclusions and Future Directions

V.D.I. Implications of This Study

The results of the thematic map accuracy assessment indicate that the Landsat TM and MSS derived maps presented in this thesis are not suitable for applications where location specific data on the land cover of the Barrow Peninsula, AK are required. While the point specific testing of the two maps indicates low levels of accuracy, the maps do provide an excellent general description of the distribution of discrete vegetation types over the Barrow landscape. The Landsat derived land cover maps prepared during this investigation will prove useful to a variety of applications in which site-specific data is not required.

The maps presented here represent a contribution to the state of knowledge regarding the unique coastal or "littoral" (Cantlon 1961) tundra of Alaska's North Slope which has traditionally been mapped at coarser resolutions (Morrissey and Ennis 1981, Walker and Lillie 1997). In addition, the results of this thesis stand to contribute to the ongoing Circumpolar Arctic Vegetation Mapping (CAVM) effort (Walker and Lillie 1997) which seeks to provide a circum-Arctic vegetation map through an international collaboration. Studies of the patterns of disturbance associated with human development, wildlife migration preferences, and native subsistence patterns can all be enhanced through the incorporation of the land cover maps and digital databases prepared throughout the course of this research. In addition, the field data collected during the 1998 field season provides a snapshot of the state of the Barrow landscape which may prove useful in local educational programs and current and future studies of vegetation pattern and process on the Arctic tundra near Barrow, AK.

Perhaps most importantly, the vegetation maps presented herein provide useful information critical to current Global Change Modeling efforts. Current GCM's model vegetation response and feedbacks to the climate cycle based upon Spetzman's (1959) map of Alaskan vegetation. Based upon the potential natural vegetation of the state, this resource for Global Change modelers presents data for Alaska's North Slope in a context which has little to do with the actual state of the landscape considering the pressures from anthropogenic disturbance that have been brought to bear on the landscape since the original map was prepared. Vegetation of the Arctic Regions has become one of the most important and dynamic inputs into current GCM's. The Landsat derived vegetation maps prepared for the Barrow Region will soon be combined with the results of a variety of vegetation mapping efforts on the North Slope of Alaska to provide critical information regarding distribution of general vegetation type, vegetation stature, surface albedo, and a variety of other variables important for the accurate modeling of vegetation response and feedbacks to the global climate cycle.

Finally, the mapping effort performed during this research project has utilized a standard image processing method that promises to remain applicable with the evolution of advanced digital remote sensing technologies. The Landsat derived maps of the Barrow Region can thus serve as a beginning for a variety of regional scale studies including time series change analysis and the effects of scale on ecological studies of tundra vegetation, among others. In addition, this research has followed and contributed to a very important trend in the fields of remote sensing and Geographic Information Systems (GIS): The products prepared during this investigation are accompanied by a comprehensive, quantitative, statistically valid summary of the reliability and utility of the information contained within the resultant products. This information will provide a variety of user groups with the information necessary to determine each map's suitability for a given purpose.

V.D.II. Future Directions

The results presented in this thesis are part of an ongoing research effort to characterize the distribution of vegetation over the Barrow Peninsula in northern Alaska. This study will continue and will first attempt to significantly improve the accuracy of the Landsat derived thematic maps. Efforts will focus on the incorporation of novel sources of ancillary data into the classification process, the utilization of alternative classification algorithms, and the formulation or incorporation of alternative schemes of vegetation classification for use in tundra vegetation mapping. In addition, following editing and final additions to the digital databases prepared during this research, all products will be forwarded to the North Slope Borough, the National Snow and Ice Data Center, and the Institute for Arctic and Alpine Research for incorporation into existing databases.

In addition, larger scale maps (approximately 1:25,000 scale) for the entire peninsula will be prepared from conventional aerial photography. The Barrow Environmental Observatory (BEO) is an area of special concern to officials in the North Slope Borough and to scientists currently conducting research in the area. This area will be intensively studied and mapped using large-scale aerial photography (1:12,000 scale or greater) to provide detailed, highly accurate maps of the vegetation and landforms of this important biological resource.

The goal of future research will be to integrate and combine the results of these basic vegetation mapping efforts into a time series investigation of land use and land cover change through time in the Barrow Region. The project will attempt to integrate and find linkages between biotic change on the Barrow tundra and economic and social impacts which have occurred through time in the region. In addition, members of the Arctic Ecology Laboratory plan to test the hypothesis that moderate surface disturbance of coastal Alaskan tundra will accelerate the rate at which the vegetation changes in response to climatic amelioration (Fig. V-2). Focusing on a 100km transect acting as a temperature gradient from Barrow to Atquasuk, AK, the proposed study will draw on the state of knowledge of tundra plant ecology, data from the International Tundra Experiment (ITEX) operating at Barrow and Atqasuk, AK (Hollister 1998), and data from the recently established Arctic Transitions in the Land Atmosphere System (ATLAS) program. For a conceptual diagram of the proposed future research program, refer to Fig. V-3. The ultimate goal of future research efforts is the production of a fully predictive, GIS-based model of Alaskan coastal tundra responses to disturbance and climatic change through a study of time series data available for the region. Using vegetation mapping as a portion of the initial data gathering stage, the Arctic Ecology Laboratory will strive toward a reasonable prediction of vegetation change through time at the species level (Hollister 1998) and on the regional scale, to provide information to land use planners, scientists, and educators on the potential impacts of anthropogenic disturbance and climate change on the tundra at Barrow, Alaska.

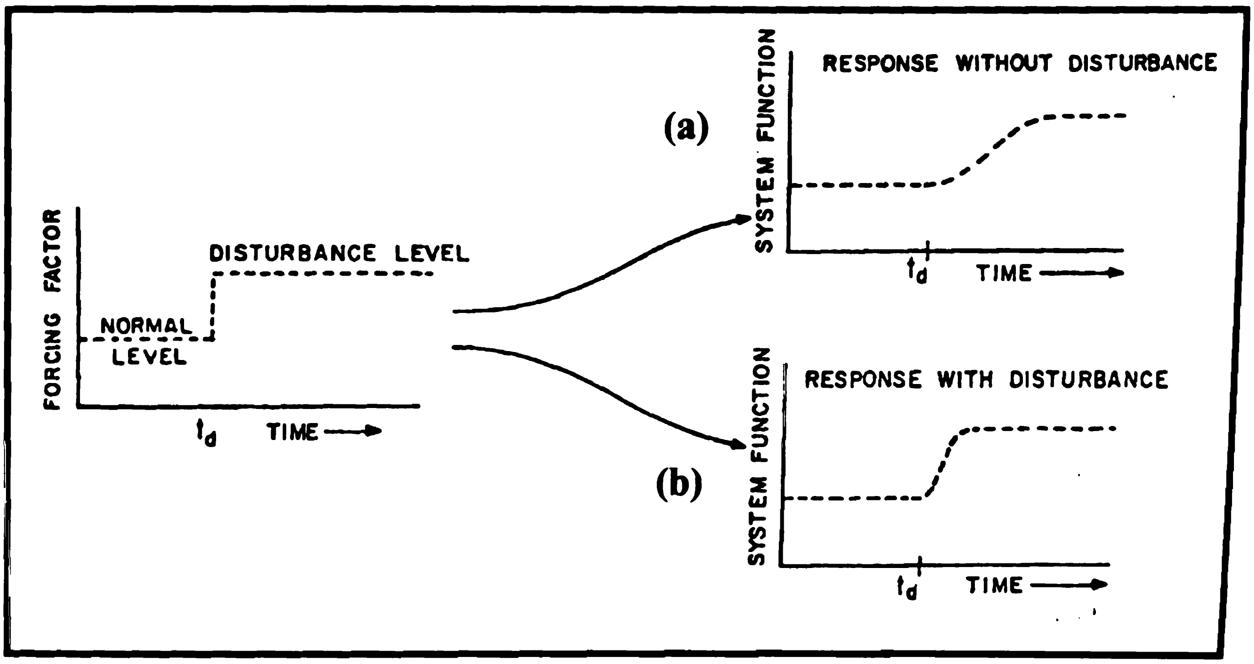

Figure V-2: Schematic illustrating the proposed hypothesis of future investigations. Vegetation response to climatic amelioration in the absence of forcing factors is rather gradual (a). In the presence of disturbance, the response time of vegetation change in response to climatic amelioration may be shortened due to a variety of factors (b).

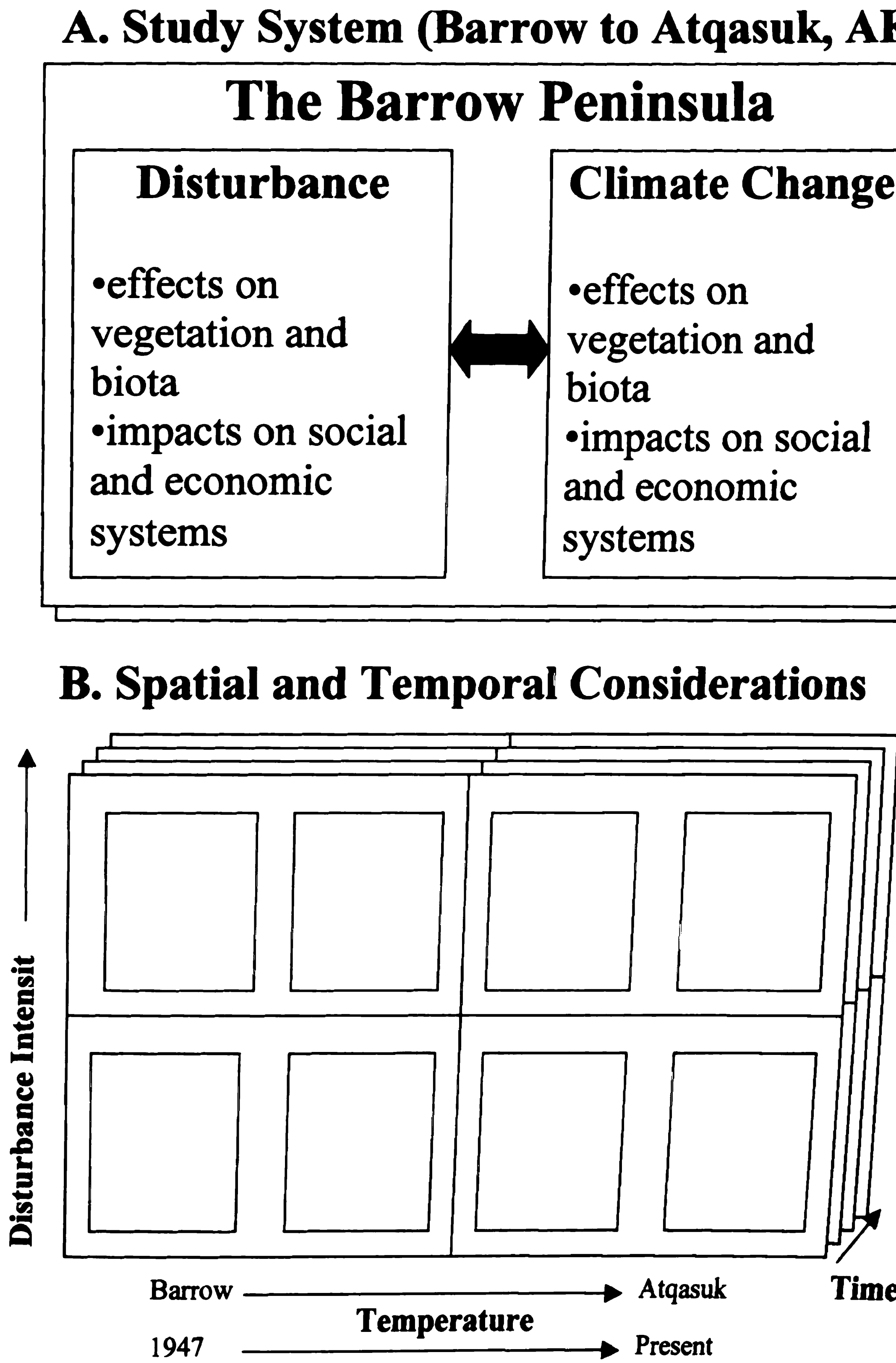

Figure V-3: (a) Conceptual diagram of proposed integrated assessment of the effects of disturbance and climate change on the Barrow Tundra. (b) Expanded view of the research to illustrate the spatial and temporal considerations important to the project (adapted from Hollister (1998)).

APPENDIX

No.	Description of Location	Known Northing	Known Easting	GPS 1 Northing	GPS 1 Easting	GPS 2 Northing	GPS 2 Easting
1	DF W Line Road Intersection	7915450	584725	7915621	584606	7915638	584596

No.	Description of Location	Known Northing	Known Easting	GPS 1 Northing	GPS 1 Easting	GPS 2 Northing	GPS 2 Easting
1	DEW Line Road Intersection	7915450	584725	7915621	584606	7915638	584596
2	Voth Creek Bridge	7912075	583100	7912181	582965	7912182	582954
3	Gravel Mine Road	7909775	579300	7909861	579154	7909870	579162
4	USC&GS Pt. Barrow S.W.	7915050	585470	7915199	585330	7915214	585340
5	ARCSS Grid Point #11	7914100	586700	7914206	586546	7914218	586541
6	ARCSS Grid Point #41	7913800	586400	7913918	586261	7913925	586267
7	ARCSS Grid Point #85	7913400	586400	7913536	586252	7913532	586255
8	ARCSS Grid Point #61	7913600	586200	7913727	586081	7913712	586083
9	ARCSS Grid Point #37	7913800	586000	7913936	585877	7913938	585882
10	ARCSS Grid Point #81	7913400	586000	7913806	585866	7913507	585867
11	ARCSS Grid Point #1	7914100	585700	7914222	585589	7914220	585577
12	ARCSS Grid Point #111	7913100	585700	7913227	585577	7913220	585582
13	Barrow Lagoon Bridge	7911650	579650	7911759	579523	7911772	579529
14	South Lake	7906625	580075	7906788	579880	7906796	579844
16	Brant Point	7916262.5	587025	7916369	586856	7916349	586862
17	Slough Point	7913725	587425	7913765	587315	7913767	587315
18	Old Airstrip Terminus	7917225	585050	7917349	584985	7917345	584980
19	ARCSS Grid Point #66	7913600	586700	7913713	586561	7913708	586559
20	ARCSS Grid Point #56	7913600	585700	7913716	585588	7913716	585585
21	ARCSS Grid Point #6	7914000	586200	7914132	586059	7914152	586050
22	ARCSS Grid Point #116	7913100	586200	7913213	586080	7913228	586052
24	Unknown Lake	7910200	584887.5	7910262	584711	7910278	584692
25	North Salt Lagoon Bridge	7916637.5	585725	7916753	585603	7916745	585600
26	ARCSS Grid Point #121	7913100	586700	7913211	586579	7913212	586573

Table A1: Raw data used in assessing the utility of C/A code GPS units for identification of known field locations. All distances are measured in meters from the false origin of UTM grid zone 4, 1927 North American Datum (NAD27).

Horizontal Error Summaries for GPS Units

		Uncorrected	Corrected
GPS 1			
	Average Northing Error	128.958m	31.833m
	Average Easting Error	132.854m	26.604m
GPS 2			
	Average Northing Error	119.541m	21.958m
	Average Easting Error	136.895m	30.229m
Average Distance from known point			
	GPS 1	189.450m	48.421m
	GPS 2	183.837m	41.439m
	Average	186.644m	44.930m

Table A2: Summary of horizontal errors for uncorrected and corrected GPS unit coordinates of known field locations. Average distance to known point was improved approximately 140m by the application of a systematic 110m adjustment to the measured Northing and Easting coordinates.

Transect	No.	Easting	Northing	Land Cover Type	General Notes and Description
1	1	[illegible]	[illegible]	[illegible]	[illegible]

Transect	No.	Easting	Northing	Land Cover Type	General Notes and Description
1	1	590600	7922400	Ocean Water	Transect point in ocean may indicate coastal erosion
1	2	590500	7922200	Barrens	Well mixed sand and gravel on beach; heavy ATV traffic.
1	3	590375	7921975	Barrens	Well mixed sand and gravel on beach; heavy ATV traffic; <2% veg. cover.
1	4	590250	7921825	Partially Vegetated	~35% veg. cover=Dupontia fisheri, Salix phlebophylla, Festuca rubra; standing H2O.
1	5	590125	7921550	Partially Vegetated	~35% veg. cover=Dupontia fisheri, Salix phlebophylla, Festuca rubra; standing H2O.
1	6	590000	7921350	Barrens	Well mixed sand and gravel on beach; heavy ATV traffic.
1	7	589875	7921125	Barrens	Well mixed sand and gravel on beach; heavy ATV traffic.
1	8	589750	7920900	Barrens	Well mixed sand and gravel on beach; heavy ATV traffic.
1	9	589600	7920700	Barrens	Well mixed sand and gravel on beach; heavy ATV traffic.
1	10	589475	7920475	Barrens	Well mixed sand and gravel on beach; heavy ATV traffic.
1	11	589350	7920275	Barrens	Well mixed sand and gravel on beach; heavy ATV traffic.
1	12	589225	7920050	Barrens	Well mixed sand and gravel on beach; heavy ATV traffic.

Table A3: Raw data on vegetation type as collected for the 8 cluster based transects to facilitate assessment of thematic map accuracy.

Transect	No.	Easting	Northing	Land Cover Type	General Notes and Description
1	13	589100	7919850	Barrens	Well mixed sand and gravel on beach; heavy ATV traffic.
1	14	588975	7919625	Barrens	Well mixed sand and gravel on beach; heavy ATV traffic.
1	15	588550	7919425	Barrens	Well mixed sand and gravel on beach; heavy ATV traffic.
1	16	588725	7919200	Barrens	Well mixed sand and gravel on beach; heavy ATV traffic.
1	17	588600	7919000	Partially Vegetated	Festuca rubra, Stellaria humifusa; gravel in places but mostly reddish brown muck.
2	1	587025	7916263	Ocean Water	Transect point in ocean may indicate coastal erosion
2	2	586925	7916025	Moist sedge, dwarf shrub/wet graminoid tundra complex	Low center polygons; Carex aquatilis, Dupontia fisheri, Eriophorum russeolum.
2	3	586800	7915825	Wet graminoid tundra	Unpatterned ground; Carex aquatilis, Eriophorum russeolum, Dupontia fisheri.
2	4	586675	7915600	Inland fresh water	~10% Arctophila fulva in lake margins
2	5	586550	7915375	Wet graminoid tundra	Unpatterned ground; Dupontia fisheri, Carex aquatilis ssp. stans, Arctophila fulva.
2	6	586450	7915150	Wet sedge tundra	Large low center polygons; Carex aquatilis, Eriophorum angustifolium, E. scheuchzeri.
2	7	586325	7915950	Wet sedge tundra	Unpatterned ground; Carex aquatilis ssp. stans, Dupontia fisheri

Table A3: Raw data on vegetation type as collected for the 8 cluster based transects to facilitate assessment of thematic map accuracy.

Transect	No.	Easting	Northing	Land Cover Type	General Notes and Description
2	8	586200	7914975	Moist sedge/wet graminoid tundra complex	Large flat center polygons; Carex aquatilis, Eriophorum russeolum, E. angustifolium.
2	9	586075	7914500	Moist sedge/wet graminoid tundra complex	Low center polygons; Carex aquatilis ssp. stans, Arctophila fulva, Ranunculus palasii
2	10	585950	7914275	Moist sedge, dwarf shrub tundra	Large flat center polygons; Carex aquatilis, Luzula confusa, Eriophorum russeolum.
2	11	585825	7914050	Moist graminoid, dwarf shrub tundra	Raised beach ridge; Dupontia fisheri, Salix rotundifolia, Carex aquatilis ssp. stans.
2	12	585725	7913850	Wet sedge tundra	Unpatterned ground; Eriophorum angustifolium, Dupontia fisheri.
2	13	585600	7913625	Moist sedge/wet graminoid tundra complex	Low center polygons; Eriophorum angustifolium, Dupontia fisheri.
2	14	585475	7913400	Moist sedge/wet graminoid tundra complex	Low center polygons; Eriophorum angustifolium, Dupontia fisheri, Sphagnum sp.
2	15	585350	7913175	Wet sedge tundra	Unpatterned ground; Eriophorum angustifolium, Petisites frigidus, Sphagnum sp.
2	16	585250	7912963	Moist sedge/wet graminoid tundra complex	Low center polygons; Carex aquatilis ssp. stans, Poa arctica, Eriophorum angustifolium.
2	17	585125	7912725	Wet graminoid tundra	Low center polygons; Carex aquatilis ssp. stans, Arctophila fulva, Ranunculus palasii.
2	18	585000	7912525	Wet graminoid tundra	Unpatterned ground; Carex aquatilis ssp. stans, Dupontia fisheri, Arctophila fulva.
2	19	584900	7912300	Wet graminoid tundra	Low center polygons; Carex aquatilis ssp. stans, Dupontia fisheri, Arctophila fulva.

Table A3: Raw data on vegetation type as collected for the 8 cluster based transects to facilitate assessment of thematic map accuracy.

Transect	No.	Easting	Northing	Land Cover Type	General Notes and Description
2	20	584775	7912075	Moist sedge/wet graminoid tundra complex	Large low center polygons; Carex aquatilis ssp. stans, Salix rotundifolia, Sphagnum sp.
2	21	584650	7911863	Moist graminoid tundra	Unpatterned ground; Dupontia fisheri, Carex aquatilis ssp. stans.
2	22	584525	7911650	Moist graminoid/dry forb tundra	High center polygons; Luzula confusa, Dupontia fisheri, Potentilla hyparctica.
2	23	584400	7911425	Moist graminoid/dry forb tundra	High center polygons; Carex aquatilis ssp. stans, Luzula confusa, Eriophorum angustifolium.
2	24	584275	7911200	Wet sedge tundra	Unpatterned ground; Carex aquatilis ssp. stans, Dupontia fisheri, Eriophorum angustifolium.
2	25	584175	7910988	Wet graminoid tundra	Unpatterned ground; Hierochloe pauciflora, Eriophorum triste, Carex aquatilis ssp. stans.
2	26	584050	7910775	Wet sedge tundra	Unpatterned ground; Carex aquatilis ssp. stans, Ranunculus palasii, Sphagnum sp.
2	27	583925	7910550	Wet sedge tundra	Highly disturbed northern margin, Footprint Lake; Carex aquatilis, Eriophorum scheuchzeri, E. angustifolium.
3	1	583025	7915475	Barrens	Well mixed sand and gravel on beach; Heavy ATV traffic
3	2	583125	7915400	Urbanized area	NARL Facility, many buildings and heavily travelled gravel roads.
3	3	583400	7915025	Wet graminoid tundra	Arctophila fulva, Eriophorum scheuchzeri, Saxifraga cernua; unpatterned ground
3	4	583350	7914800	Moist graminoid tundra/ Dry Barren Complex	High Center Polygons (Frost scars); Poa arctica, Cochlearia officianalis, E. angustifolium.

Table A3: Raw data on vegetation type as collected for the 8 cluster based transects to facilitate assessment of thematic map accuracy.

Transect	No.	Easting	Northing	Land Cover Type	General Notes and Description
3	5	583475	7914575	Moist graminoid tundra/ Dry Barren Complex	High Center Polygons (Frost scars); Carex aquatilis ssp. stans, Arctophila fulva, Eriophoum scheuchzeri,
3	6	583575	7914350	Dry graminoid, dwarf shrub tundra	High Center Polygons; Carex aquatilis ssp. stans, Poa arctica, Salix rotundifolia.
3	7	583700	7914125	Wet graminoid tundra	Unpatterned ground; Eriophorum angusifolium, Dupontia fisheri, E. scheuchzeri
3	8	583800	7913900	Wet sedge tundra	Unpatterned ground; Carex aquatilis ssp. stans, Calliergon sp., Eriophorum angustifolium.
3	9	583913	7913675	Moist graminoid tundra	Unpatterned ground; Carex aquatilis ssp. stans, Salix rotundifolia.
3	10	584050	7913400	Inland fresh water	~10% Arctophila fulva in lake margins
3	11	584175	7913150	Moist graminoid, dwarf shrub tundra	Unpatterned ground; Carex aquatilis ssp. stans, Sphagnum sp., Salix rotundifolia.
4	1	589388	7908425	Moist graminoid tundra	Poorly dev. flat center polygons; Dupontia fisheri, Carex aquatilis ssp. stans, Salix pulchra.
4	2	589350	7908575	Inland fresh water	
4	3	589275	7908825	Wet graminoid tundra	Unpatterned ground; Carex aquatilis ssp. stans, Eriophorum russeolum, Salix rotundifolia.
4	4	589175	7909050	Inland fresh water	
4	5	589125	7909288	Inland fresh water	

Table A3: Raw data on vegetation type as collected for the 8 cluster based transects to facilitate assessment of thematic map accuracy.

Transect	No.	Easting	Northing	Land Cover Type	General Notes and Description

Transect	No.	Easting	Northing	Land Cover Type	General Notes and Description
4	6	589050	7909525	Inland fresh water	
4	7	588975	7909750	Inland fresh water	
4	8	588900	7910000	Moist sedge/wet graminoid tundra complex	Low center polygons; Carex aquatilis ssp. stans, Eriophorum russeolum, Dupontia fisheri.
4	9	588825	7910250	Wet graminoid tundra	Arctophila pond complex; Arctophila fulva, Eriophorum angustifolium, E. russeolum.
4	10	588750	7910488	Moist graminoid/Wet sedge tundra complex	Low center polygons; Carex aquatilis ssp. stans, Eriophorum angustifolium, E. russeolum.
4	11	588675	7910713	Moist graminoid tundra	Poorly dev. flat center polygons; Eriophorum angustifolium, E. russeolum, Petisites frigidus.
4	12	588600	7910963	Moist graminoid/Dry graminoid tundra complex	High center polygons; Carex aquatilis ssp. stans, Luzula confusa, Eriophorum russeolum.
4	13	588525	7911175	Moist graminoid/Dry graminoid tundra complex	High center polygons; Luzula confusa, Eriophorum russeolum, Dupontia fisheri.
4	14	588450	7911438	Moist graminoid tundra	Eroding coastal bluff; Luzula confusa, Carex aquatilis ssp. stans, Eriophorum angustifolium.
4	15	588375	7911675	Ocean Water (Slough)	
4	16	588300	7911913	Ocean Water (Slough)	
4	17	588225	7912150	Moist graminoid/Dry lichen tundra complex	High center polygons; Carex aquatilis ssp. stans, White crustose lichens, Luzula confusa.

Table A3: Raw data on vegetation type as collected for the 8 cluster based transects to facilitate assessment of thematic map accuracy.

Transect	No.	Easting	Northing	Land Cover Type	General Notes and Description

Transect	No.	Easting	Northing	Land Cover Type	General Notes and Description
4	18	588150	7912388	Moist sedge/wet graminoid tundra complex	Low center polygons; Carex aquatilis ssp. Stans, Eriophorum russeolum, Ranunculus palasii.
4	19	588075	7912625	Moist graminoid/Dry graminoid tundra complex	Poorly dev. high center polygons; Eriophorum triste, Arctagrostis latifolia, E. russeolum.
4	20	588000	7912863	Moist graminoid/Dry graminoid tundra complex	High center polygons; Carex aquatilis ssp. stans, Luzula confusa, Salix pulchra.
4	21	587925	7913100	Wet graminoid tundra	Unpatterned ground; Carex subspathacea, C. aquatilis ssp.stans, Dupontia fisheri, Eriophorum russeolum.
4	22	587850	7913350	Eroding coastal bluff-see notes	Profound disturbance yields mixing of substrate, exposure of ice wedges, and only parial vegetation.
4	23	587775	7913588	Ocean Water	Transect point in ocean may indicate coastal erosion.
5	1	579425	7911600	Urbanized area	Point within Barrow; Large buidings with tin roofs, gravel roads.
5	2	579325	7911375	Urbanized area	Point within Barrow; Large buidings with tin roofs, gravel roads.
5	3	579200	7911175	Urbanized area	Point within Barrow; Large buidings with tin roofs, gravel roads.
5	4	579100	7910950	Urbanized area	Point within Barrow; Large buidings with tin roofs, gravel roads.
5	5	578963	7910725	Moist graminoid tundra	Disturbed area near homes; Arctophila fulva, Arctagrostis latifolia, Dupontia fisheri.
5	6	578850	7910500	Moist sedge/Wet graminoid tundra complex	Poorly dev. low center polygons and artificial mounds; Carex aquatilis ssp. stans, Dupontia fisheri, Poa arctica.

Table A3: Raw data on vegetation type as collected for the 8 cluster based transects to facilitate assessment of thematic map accuracy.

Transect	No.	Easting	Northing	Land Cover Type	General Notes and Description
5	7	578750	7910275	Wet graminoid/Dry barren tundra complex	High center polygons; Carex aquatilis ssp. stans, Arctophila fulva, Dupontia fisheri (troughs).
5	8	578625	7910050	Moist graminoid/Dry graminoid tundra complex	High center polygons; Eriophorum russeolum, Dupontia fisheri, Poa malacantha.
5	9	578500	7909850	Barrens	Barrow gravel mine.
5	10	578375	7909625	Barrens	Barrow gravel mine.
5	11	578275	7909400	Moist graminoid tundra	Poorly dev. low center polygons; Carex aquatilis ssp. stans, Dupontia fisheri, Eriophorum angustifolium.
5	12	578150	7909175	Moist graminoid/Dry dwarf shrub tundra complex	High center polygons; Carex aquatilis ssp. stans, Salix pulchra, Luzula arctica.
5	13	578038	7908950	Wet graminoid tundra	Arctophila pond complex; Arctophila fulva, Carex aquatilis ssp. stans, Eriophorum russeolum.
5	14	577925	7908725	Wet graminoid tundra	Poorly dev. low center polygons; Carex aquatilis ssp. stans, Eriophorum angustifolium, Sphagnum sp.
5	15	577800	7908525	Moist graminoid/Wet sedge tundra complex	Low center polygons; Carex aquatilis ssp. stans, Eriophorum russeolum, Luzula confusa.
5	16	577675	7908275	Barrens	Gravel Road adjacent to wet sedge tundra.
5	17	577550	7908075	Moist graminoid/Dry graminoid tundra complex	High center polygons; Carex aquatilis ssp. Stans, Luzula confusa, Salix pulchra.
5	18	577450	7907850	Moist graminoid/Dry moss tundra complex	High center polygons; Dicranum elongatum, Carex aquatilis ssp. stans, Dupontia fisheri.

Table A3: Raw data on vegetation type as collected for the 8 cluster based transects to facilitate assessment of thematic map accuracy.

Transect	No.	Easting	Northing	Land Cover Type	General Notes and Description

Transect	No.	Easting	Northing	Land Cover Type	General Notes and Description
5	19	577350	7907625	Moist sedge/Dry graminoid tundra complex	High center polygons; Carex aquatilis ssp. stans, Luzula arctica, Eriophorum russeolum.
5	20	577225	7907400	Moist graminoid tundra	Unpatterned ground; Eriophorum angustifolium, Carex aquatilis ssp. stans, Salix rotundifolia.
5	21	577100	7907188	Dry dwarf shrub tundra	North facing slope; Salix pulchra, Arctagrostis latifolia, Carex aquatilis ssp. stans.
5	22	577000	7907000	Dry dwarf shrub tundra	North facing slope; Salix pulchra, Carex aquatilis ssp. stans, Dicranum sp.
6	1	584613	7908588	Wet graminoid tundra	Unpatterned ground; Eriophorum scheuchzeri, Arctophila fulva, Dupontia fisheri.
6	2	584375	7908500	Wet graminoid tundra	Unpatterned ground; Eriophorum scheuchzeri, Arctophila fulva, Dupontia fisheri.
6	3	584150	7908400	Wet graminoid tundra	Unpatterned ground; Eriophorum scheuchzeri, Arctophila fulva, Dupontia fisheri.
6	4	583925	7908325	Moist graminoid, dwarf shrub tundra	Flat center polygons; Carex aquatilis ssp. stans, Poa arctica, Salix rotundifolia.
6	5	583263	7908225	Moist sedge/Dry graminoid tundra complex	High center polygons; Eriophorum russeolum, Luzula arctica, Carex aquatilis ssp. stans, Dupontia fisheri.
6	6	583450	7908138	Wet sedge tundra	Poorly dev. low center polygons; Carex aquatilis ssp. stans, Eriophorum russeolum.
6	7	583200	7908050	Wet sedge tundra	Poorly dev. low center polygons; Carex aquatilis ssp. stans, Eriophorum angustifolium.
6	8	582975	7907950	Wet sedge tundra	Unpatterned ground; Carex aquatilis ssp. stans, Eriophorum russeolum, Ranunculus palasii.

Table A3: Raw data on vegetation type as collected for the 8 cluster based transects to facilitate assessment of thematic map accuracy.

Transect	No.	Easting	Northing	Land Cover Type	General Notes and Description

Transect	No.	Easting	Northing	Land Cover Type	General Notes and Description
6	9	582725	7907825	Wet graminoid tundra/pond complex	Low center polygon pond complex; Carex aquatilis ssp. stans, Eriophorum angustifolium, Ranunculus palasii.
6	10	582500	7907775	Moist sedge/Wet graminoid tundra complex	Low center polygons; Carex aquatilis ssp. stans, Eriophorum russeolum, Salix pulchra.
6	11	582275	7907675	Moist sedge/Wet graminoid tundra complex	Low center polygons; Carex aquatilis ssp. stans, Eriophorum scheuchzeri, Salix pulchra.
6	12	582025	7907600	Moist graminoid tundra	Flat center polygons; Carex aquatilis ssp. stans, Dupontia fisheri, Eriophorum russeolum.
6	13	581988	7907525	Moist graminoid tundra	Unpatterned ground; Carex aquatilis ssp. stans, Eriophorum russeolum, Petasites frigidus.
6	14	581575	7907425	Wet graminoid tundra	Unpatterned ground; Eriophorum angustifolium, Eriophorum russeolum, Carex aquatilis ssp. stans.
6	15	581325	7907325	Moist graminoid/Wet sedge tundra complex	Low center polygons; Carex aquatilis ssp. stans, Eriophorum russeolum, Melandrium apetalum.
6	16	581100	7907250	Moist graminoid, dwarf shrub tundra	Flat center polygons; Eriophorum triste, Carex aquatilis ssp. stans, Salix rotundifolia.
6	17	580838	7907150	Inland fresh water	
6	18	580625	7907075	Moist graminoid/Dry dwarf shrub tundra complex	High center polygons; Eriophorum russeolum, Salix pulchra, Carex aquatilis ssp.stans.
6	19	580375	7906975	Moist graminoid tundra	Unpatterned ground; Dupontia fisheri, Carex aquatilis ssp. stans, Eriophorum angustifolium.
6	20	580150	7906900	Moist graminoid/Dry dwarf shrub tundra complex	High center polygons; Carex aquatilis ssp. stans, Eriophorum scheuchzeri, Salix pulchra.

Table A3: Raw data on vegetation type as collected for the 8 cluster based transects to facilitate assessment of thematic map accuracy.

Transect	No.	Easting	Northing	Land Cover Type	General Notes and Description

Transect	No.	Easting	Northing	Land Cover Type	General Notes and Description
6	21	579900	7906800	Wet sedge tundra	Unpatterned ground; Carex aquatilis ssp. stans, Arctophila fulva, Eriophorum angustifolium.
7	1	585750	7907313	Moist sedge/Wet graminoid tundra complex	Poorly dev. high center polygons; Eriophorum scheuchzeri, Dupontia fisheri, Alopecurus alpinus.
7	2	586000	7907313	Moist graminoid tundra	Unpatterned ground; Eriophorum scheuchzeri, Alopecurus alpinus, Dupontia fisheri,Salix spp.
7	3	586250	7907325	Dry graminoid, barrens tundra	High center polygons; Luzula confusa, Salix rotundifolia, S. pulchra, light colored crustose lichens.
7	4	586500	7907325	Moist sedge tundra	Poorly dev. flat center polygons; Carex aquatilis, Heavy cover of several unknown mosses, Salix rotundifolia.
7	5	586750	7907325	Wet graminoid tundra	Unpatterned ground; Carex aquatilis ssp. stans, Dupontia fisheri, Eriphorum triste.
7	6	587000	7907325	Wet graminoid tundra (pond complex)	Pond complex; Arctophila fulva, Carex aquatilis ssp. stans, Eriophorum russeolum.
7	7	587250	7907325	Moist sedge tundra	Unpatterned ground; Carex aquatilis ssp. stans, Dupontia fisheri, Sphagnum sp.
7	8	587500	7907338	Wet graminoid tundra	Unpatterned ground; Carex aquatilis ssp. stans, Eriophorum russeolum, Dupontia fisheri.
7	9	587750	7907338	Wet graminoid tundra	Unpatterned ground; Dupontia fisheri, Eriophorum russeolum, E. angustifolium.
7	10	588000	7907338	Wet graminoid tundra	Unpatterned ground; Eriophorum angustifolium, Dupontia fisheri, E. russeolum.
7	11	588250	7907338	Wet graminoid tundra (pond complex)	Arctophila pond complex; Arctophila fulva, Ranunculus palasii.

Table A3: Raw data on vegetation type as collected for the 8 cluster based transects to facilitate assessment of thematic map accuracy.

Transect	No.	Easting	Northing	Land Cover Type	General Notes and Description

Transect	No.	Easting	Northing	Land Cover Type	General Notes and Description
7	12	588500	7907350	Wet graminoid tundra (pond complex)	Pond complex; Carex aquatilis ssp. stans, Eriophorum russeolum, Sphagnum sp.
7	13	588750	7907350	Moist graminoid/Wet sedge tundra complex	Low center polygons; Carex aquatilis ssp. stans, Eriophorum russeolum, Salix pulchra.
7	14	589000	7907350	Moist graminoid/Wet sedge tundra complex	Low center polygons; Carex aquatilis ssp. stans, Dupontia fisheri, Eriophorum russeolum.
7	15	589250	7907350	Wet graminoid tundra	Unpatterned ground; Carex aquatilis ssp. stans, Eriophorum russeolum, Hierochloe pauciflora.
7	16	589500	7907363	Wet graminoid tundra	Unpatterned ground near stream margin; Dupontia fisheri, Carex aquatilis, Eriophorum angustifolium.
7	17	589750	7907363	Moist graminoid/Dry lichen tundra complex	High center polygons; Carex ramenskii, Alectoria nigricans, Luzula arctica.
7	18	590000	7907363	Moist graminoid/Dry lichen tundra complex	High center polygons; Carex aquatilis ssp. stans, Alectoria nigricans, Luzula arctica.
7	19	590250	7907363	Dry dwarf shrub tundra	Poorly dev. high center polygons; Salix pulchra, Luzula arctica, L. confusa.
7	20	590500	7907375	Moist graminoid/Dry moss tundra complex	Poorly dev. high center polygons; Carex aquatilis ssp. stans, Polytrichum spp., Luzula confusa.
7	21	590750	7907375	Moist graminoid/Dry lichen tundra complex	High center polygons; Dupontia fisheri (troughs), Several white crustose lichens, Luzula arctica.
7	22	591000	7907375	Dry forb tundra	Stream margin; Petasites frigidus, Salix pulchra, Alopecurus alpinus.
8	1	580175	7912425	Urbanized area	Point within Barrow; Large buidings with tin roofs, gravel roads.

Table A3: Raw data on vegetation type as collected for the 8 cluster based transects to facilitate assessment of thematic map accuracy.

Transect	No.	Easting	Northing	Land Cover Type	General Notes and Description
8	2	580375	7912275	Urbanized area	Point within Barrow; Large buidings with tin roofs, gravel roads.
8	3	580550	7912100	Urbanized area	Point within Barrow; Large buidings with tin roofs, gravel roads.
8	4	580725	7911925	Moist sedge, dwarf shrub tundra	Unpatterned ground; Carex aquatilis ssp. stans, Salix rotundifolia, Arctagrostis latifolia.
8	5	580925	7911775	Inland fresh water	~10% Arctophila fulva in lake margins.
8	6	581125	7911600	Inland fresh water	~10% Arctophila fulva in lake margins.
8	7	581300	7911425	Dry graminoid, dwarf shrub tundra	Hummocks; Arctagrostis latifolia, Salix phlebophylla, Petisites frigidus.
8	8	581500	7911250	Moist sedge tundra	Disjunct flat center polygons; Carex aquatilis ssp. stans, Salix pulchra, high cover value for unknown mosses.
8	9	581675	7911075	Moist sedge/Dry graminoid, crustose lichen tundra complex	High center polygons; Carex aquatilis, Luzula arctica, Eriophorum russeolum, crustose lichens.
8	10	581875	7910925	Moist sedge/Dry graminoid, crustose lichen tundra complex	High center polygons; Carex aquatilis, Luzula arctica, Eriophorum russeolum, crustose lichens.
8	11	582050	7910750	Moist sedge, dwarf shrub tundra	Unpatterned ground; Carex aquatilis ssp. stans, Eriophorum angustifolium, Petisites frigidus.
8	12	582225	7910600	Wet graminoid tundra	Low center polygons; Carex aquatilis ssp. stans, Arctophila fulva, Ranunculus palasii.
8	13	582425	7910425	Wet graminoid tundra	Low center polygons; Carex aquatilis ssp. stans, Dupontia fisheri, Arctophila fulva.

Table A3: Raw data on vegetation type as collected for the 8 cluster based transects to facilitate assessment of thematic map accuracy.

Transect	No.	Easting	Northing	Land Cover Type	General Notes and Description
8	14	582600	7910250	Wet graminoid tundra	Unpatterned ground; Carex aquatilis ssp. stans, Eriophorum angustifolium, Dupontia fisheri.
8	15	582800	7910075	Wet sedge tundra	Unpatterned ground; Carex aquatilis ssp. stans, Eriophorum russeolum, Arctophila fulva.
8	16	582975	7909925	Moist sedge/Wet graminoid tundra complex	Wet meadow with owl mounds; Dupontia fisheri, Carex aquatilis ssp. stans, Eriophorum russeolum.
8	17	583175	7909750	Moist sedge, dwarf shrub tundra	Hummocks; Carex aquatilis ssp. Stans, Salix rotundifolia.
8	18	583350	7909575	Moist graminoid/Dry dwarf shrub tundra complex	High center polygons; Eriophorum russeolum, Luzula confusa, Salix pulchra.
8	19	583550	7909425	Dry dwarf shrub, crustose lichen tundra	High center polygons; Salix pulchra, Luzula confusa, Arctagrostis latifolia; White crustose lichens.
8	20	583725	7909250	Wet graminoid tundra	Unpatterned ground; Eriophorum scheuchzeri, E. angustifolium, Alopecurus alpinus.
8	21	583900	7909088	Dry graminoid, dwarf shrub tundra	Footprint Lake margin; Poa arctica, Salix rotundifolia, Carex aquatilis ssp. stans.

Table A3: Raw data on vegetation type as collected for the 8 cluster based transects to facilitate assessment of thematic map accuracy.

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