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Detection and Classification of Muskox Habitat on Banks Island, Northwest Territories, Canada, Using Landsat Thematic Mapper Data

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ABSTRACT. The feasibility of using Landsat Thematic Mapper data for mapping muskox summer habitat was tested on northern Banks Island, Northwest Territories. Digital image enhancement and classification techniques were examined to determine if summer foraging habitats could be detected and mapped using Thematic Mapper imagery. Interpretations of the satellite data were verified in the field during the summers of 1988 and 1989. The most important summer foraging habitats for muskoxen included the wet sedge meadow, graminoid tundra and graminoid/dwarf shrub tundra cover types. These lowland habitats were generally distinguishable on enhanced colour images and were easily differentiated from upland areas. The most suitable colour composite for differentiating muskox summer habitats was the near-infrared (band 4), shortwave infrared (band 5) and red (band 3) spectral bands displayed in red, green and blue respectively. Upland cover types, including dwarf shrub tundra, hummocky tundra and dwarf shrub/lichen barrens, were more difficult to differentiate because of spectral variability resulting from differences in plant cover and site characteristics. The classified image had an overall accuracy of 88%. The summer habitats of particular importance to muskoxen had classification accuracies of 84-89%. Detection of important foraging habitats on Thematic Mapper imagery is attributable to the spectral distinctiveness of wet graminoid communities and the high spectral sensitivity and spatial resolution of the infrared sensors, which allow detection of differences in surface moisture and vegetation physiognomy.

Key words: muskox habitat, remote sensing, arctic Canada, digital classification, Landsat Thematic Mapper data, Banks Island, habitat mapping, *Ovibos moschatus*, periglacial environments

RÉSUMÉ. L'île Banks située dans les Territoires du Nord-Ouest a servi de site pour l'étude de faisabilité concernant l'utilisation des données obtenues avec l'appareil de cartographie thématique Landsat pour circonscrire l'habitat estival du boeuf musqué. On a utilisé l'accentuation de l'image numérique ainsi que des techniques de classification pour déterminer si les aires de pâturage pouvaient être détectées et cartographiées à l'aide des images de cartographie thématique. Au cours des étés de 1988 et de 1989, on a procédé sur le terrain à des vérifications de l'interprétation des données obtenues par satellite. Les aires de pâturage du boeuf musqué les plus importantes comprenaient la prairie à laîches humide, la toundra de graminées et les types de couvert de toundra de graminées/buissons nains. On pouvait généralement distinguer ces habitats de terres basses sur les images accentuées en couleur, et ils se démarquaient nettement des zones situées dans les terres hautes. La meilleure palette de couleurs permettant de distinguer l'habitat estival du boeuf musqué se situait dans la bande infrarouge proche (bande 4), la bande infrarouge à ondes courtes (bande 5) et la bande rouge (bande 3) du spectre, affichées respectivement en rouge, en vert et en bleu. Les types de couvert des terres hautes, y compris la toundra de buissons nains, la toundra à creux et bosses et les landes à buissons nains/lichens, se sont révélés plus difficiles à différencier, en raison des variations spectrales dues au couvert végétal et aux caractéristiques du site faisant varier le spectre. L'image classifiée était dans l'ensemble précise à 88 p. cent. La classification de l'habitat estival de grande importance pour le boeuf musqué avait une précision allant de 84 à 89 p. cent. On attribue la détection des aires de pâturage importantes sur les images de cartographie thématique, à la particularité spectrale des communautés de graminées humides ainsi qu'à la sensibilité spectrale et à la résolution spatiale des capteurs infrarouges, ce qui a permis de distinguer les différences dans l'humidité de la surface et dans la physionomie végétale.

Mots clés: habitat du boeuf musqué, télédétection, Canada arctique, classification numérique, données obtenues à l'aide de l'appareil de cartographie thématique Landsat, île Banks, cartographie de l'habitat, *Ovibos moschatus*, environnements périglaciaires

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INTRODUCTION

Recent advances in remote sensing technologies present new opportunities and challenges for researchers working in remote areas. However, few studies have examined the advantages and limitations of using satellite data for mapping wildlife habitats of the Canadian Arctic. Vegetation and terrain mapping using Landsat Multispectral Scanner (MSS) data have been conducted in northern Canada (Harvie *et al.*, 1982; Petersen, 1987; Thompson *et al.*, 1980) and in Alaska (reviewed by Shasby and Carneggie, 1986). Landsat Thematic Mapper (TM) data, with improved spatial, spectral and radiometric properties, have been used in boreal and arctic regions of Canada to map wetland habitats (Dickson *et al.*, 1989; Wakelyn, 1990) and in northern Norway to map reindeer (*Rangifer tarandus*) ranges (Tommervik and Lauknes, 1987). TM data have not been tested thoroughly in arctic regions.

This project investigated the feasibility of using Landsat TM data as the primary basis for a muskox (*Ovibos moschatus*) habitat inventory on Banks Island, Northwest Territories. The objectives were to: 1) determine if the summer foraging habitats of muskoxen could be detected by visual interpretation of Landsat TM imagery; 2) classify and map muskox summer habitats and other arctic tundra cover types using digital analysis of TM data; 3) assess the accuracy of the classification; and 4) determine the advantages and limitations of inventorying muskox habitats of the arctic tundra using Landsat data. This project was completed under the Northwest Territories Technology Enhancement Program, a cooperative program between the Canada Centre for Remote Sensing and the Department of Renewable Resources, Government of the Northwest Territories.

The muskoxen of Banks Island are of interest to wildlife management agencies because of rapid population growth. Comparable surveys suggest that the population has increased from approximately 18 300 animals in 1979-80 (Vincent and Gunn, 1981) to 34 200 animals in 1989 (B. McLean, pers. comm. 1989). Management concerns relate to the increasing population densities and their possible negative effects on food supply, habitat condition and incidence of disease (Blake *et al.*, 1989; Gunn *et al.*, 1989; McLean *et al.*, 1986).

The summer food habits and feeding ecology of muskoxen have been described for a wide geographic area, including Alaska (O'Brien, 1988; Robus, 1984), Greenland (Ferns, 1977; Thing, 1984; Thing *et al.*, 1987), the Union of Soviet Socialist

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Republics (Rapota, 1984) and several localities within the Canadian Arctic (Parker, 1978; Parker and Ross, 1976; Tener, 1965; Thomas and Edmonds, 1984; Wilkinson *et al.*, 1976). Geographic variations in diet have been noted, but most studies agree that the predominant forage plants are graminoids, especially hydrophytic sedges (*Carex* spp. and *Eriophorum* spp.), and willows (*Salix* spp.). Willows are more prevalent in the summer diet in Greenland and Alaska than in the Canadian Arctic, where graminoids are predominant (Thing *et al.*, 1987). Parker (1978) reported that the most important graminoids for muskoxen on the Queen Elizabeth Islands are *Carex aquatilis* var. *stans*, *Eriophorum triste* and *E. scheuchzeri*. Thomas and Edmonds (1984) determined that use of feeding sites on eastern Melville Island is related to the abundance of *Carex aquatilis* var. *stans*. This sedge is also an important component in the foraging areas and diets of muskoxen on Banks Island (Wilkinson *et al.*, 1976) and the Taimyr Peninsula, U.S.S.R. (Rapota, 1984). The close relationship that exists between the summer distribution of muskoxen and the presence of well-vegetated lowland and riparian habitats is well documented (Henry *et al.*, 1986; O'Brien, 1988; Parker and Ross, 1976; Thing *et al.*, 1987; Thomas *et al.*, 1981).

Remote sensing by satellite involves measuring and recording the levels of electromagnetic radiation reflected from the earth's surface (Sabins, 1978). The principal sensors used in the Landsat series of satellites are the MSS and TM sensors, which are capable of detecting minimum areas of approximately 57 m × 79 m and 30 m × 30 m respectively (Richards, 1986). Reflectance values from each minimum area ("pixel"), recorded in different parts of the electromagnetic spectrum, have brightness values in the range 0-63 for the MSS sensor and 0-255 for the TM sensor. Bands 1-4 represent the blue, green, red and near-infrared portions of the electromagnetic spectrum respectively. Bands 5 and 7 represent different regions of the shortwave infrared portion of the spectrum. Band 6 is a thermal infrared band. The reflectance values recorded by the sensors for each pixel represent an average measure of reflectance obtained from the composite of surficial features (e.g., vegetation, bare soil, rock and water).

Landsat TM data are strongly influenced by vegetation type, pattern and abundance (Kenk *et al.*, 1988). Vegetation in the Arctic is dominated by low herbaceous perennials, prostrate shrubs, graminoids, bryophytes and lichens (Billings and Mooney, 1968; Bliss *et al.*, 1973; Edlund and Alt, 1989). In the Canadian Arctic Archipelago, the polar desert (<5% vascular plant cover) and polar semi-desert (5-20% vascular plant cover) landscapes predominate (Bliss and Svoboda, 1984). In areas where plant cover is sparse, background reflectance from soil or bare rock often dominates the reflectance from vegetation (Frank, 1988). This can potentially reduce the usefulness of Landsat imagery when attempting to recognize and inventory vegetation communities of importance to arctic wildlife.

STUDY AREA

This study was carried out in north-central Banks Island (Fig. 1). The study area (1835 km^2) is bisected by the Thomsen River, which flows in a general south to north direction. Elevations west of the Thomsen River range from 30 to 225 m above sea level (asl). The topography is characterized by rounded, irregularly shaped uplands with undulating plains, small lakes, wet sedge meadows and narrow drainages in the intervening lowlands. Rolling uplands are drained by the Muskox River and its numerous tributaries and by smaller streams such as Able and Baker creeks, which empty into the Thomsen River.

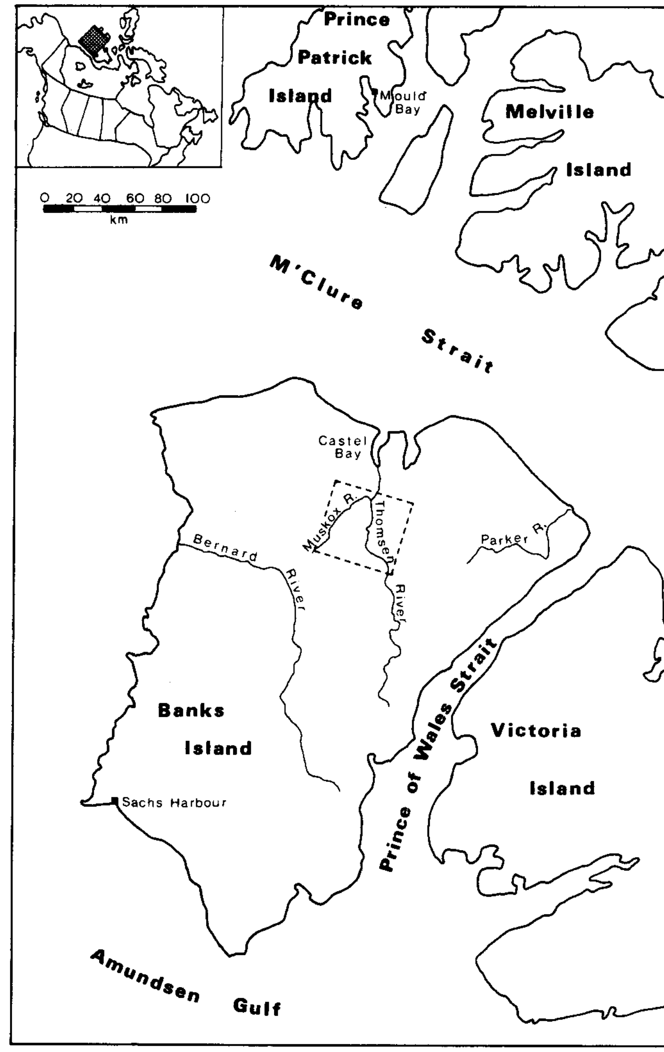

FIG. 1. Location of study area on northern Banks Island, Northwest Territories, Canada.

East of the Thomsen River, the topography is more rugged and elevations are more variable, ranging from 30 m asl along the Thomsen River valley to over 365 m asl at the eastern limit of the study area. These highlands form the western edge of the Parker River Plateau, an elevated plateau of Devonian sandstone with deeply dissected valleys and gorges (Zoltai *et al.*, 1980). A general overview of the geology, physiography and glacial history of northern Banks Island is provided by Zoltai *et al.* (1980). The flora of northern Banks Island has been described by Porsild (1955), Steere and Scotter (1979), Wilkinson *et al.* (1976) and Zoltai *et al.* (1980).

METHODS

Image Processing

Landsat TM data for northern Banks Island, recorded on 5 August 1986, were acquired as computer compatible tapes and a colour transparency (scale, 1:1 000 000). The transparency was used to identify a relatively cloud-free and snow-free study area. Panchromatic aerial photographs (approximate scale, 1:100 000) of northern Banks Island, taken in 1961, were also examined to provide information on topographic features.

Digital analyses of Landsat data were performed on an ARIES III system (Applied Resource Image Exploitation System, DIPIX) at the Northwest Territories Centre for Remote Sensing in Yellowknife. Digital image enhancements (including histogram equalizations, linear and power stretches, and logarithmic and principal components transformations) were produced and various band combinations were used to increase the visual interpretability of the raw data. Digital image classifications were created using both unsupervised and supervised techniques. An unsupervised classification defines the "natural groupings" of the multispectral data based on their reflectance values. Unsupervised classification techniques assign each pixel to a spectral class by a statistical algorithm that groups pixels having similar reflectance values. The algorithm used for all classifications (both unsupervised and supervised) was the "maximum likelihood classifier," using bands 1-5 and 7.

Supervised classification procedures assign pixels to specific classes by comparing the reflectance value of each pixel with the spectral signatures of known training areas (i.e., areas having known land cover types). The number of pixels used to generate spectral signatures for the known cover types (described below) ranged from 970 to 4597. The separability of spectral signatures was measured statistically by calculating the autocorrelation distance (ACD) between each pair of signatures, where an ACD value >2.0 indicates $<10\%$ correlation between spectral signatures (Dipix Systems Limited, 1987). Detailed descriptions of ARIES functions and the fundamentals of digital image analysis and classification are provided by Schowengerdt (1983) and Short (1982).

An accuracy assessment of the supervised classification was performed following Story and Congalton (1986). Accuracy was determined by sampling 196 areas (representing seven cover types) distributed throughout the study area and is expressed as the percentage of the image that has been classified correctly when compared with reference data ("ground truth"). Sampling units varied in size according to cover type and generally comprised >20 pixels. It was not possible to assess accuracy on a pixel-by-pixel basis because of difficulties in determining precise locations of pixels on the ground.

Field Studies

Field work was carried out from 30 July to 10 August 1988 and from 9 to 25 July 1989 to obtain information on land cover types. The colour enhancement and unsupervised classification were used to identify homogeneous areas for field sampling. The following information was recorded for each cover type by walking linear transects across representative areas: landform (ridgetop, plateau, terrace, slope, lowland, wetland); topography (level, undulating, hummocky, slope aspect, degree of slope); microtopographic features (earth hummocks, striping, ice-wedge polygons, sorted and non-sorted circles, frost fissures); substrate (bedrock, boulders, sand, gravel, till, clay/silt, peat); surface moisture (hydric, hygric, mesic, xeric); and living (green) vegetation. Vegetation descriptions included the dominant growth form (dwarf shrubs, forbs, grasses/sedges, mosses, lichens), species composition, visual estimates of total plant cover ($<10\%$, 25%, 50%, 75%, $>90\%$) and average height (cm). (Nomenclature for vascular plants follows that of Porsild and Cody [1980], and the terminology of periglacial features follows French [1976]). Colour photographs from ground level and from the air were taken at many sites to secure a permanent photographic record for future reference. The field data were used to "train" the computer to recognize specific cover types, based on their spectral signatures, during the supervised classification procedures.

RESULTS

Cover Types

Seven terrestrial cover types differing in topography, vegetation and surface moisture (Table 1) were defined for the Banks Island study area. Two additional cover types (water bodies and ice and snow cover) were also included because they are important sources of moisture during the growing season. The following descriptions of the cover types are listed in order of generally increasing elevation and decreasing surface moisture availability.

Water Bodies: Water bodies include the open water of lakes, rivers, streams and tundra ponds.

Wet Sedge Meadow: Wet sedge meadows occur on level, hydric lowlands (Fig. 2) and support a nearly continuous cover of sedges, especially *Carex aquatilis* var. *stans*, and other hydrophytic species growing in shallow (<10 cm) water (e.g., *Eriophorum scheuchzeri*, *Dupontia fisheri*, *Pedicularis*

TABLE 1. Ecological moisture regime classes[1] of the Banks Island study area

Moisture class	Description	Primary water source	Topographic position
Xeric	Water removed very rapidly in relation to supply; soil is moist for brief periods following precipitation.	Precipitation.	Elevated, wind-blown sites such as the upper slopes and summits of hills, ridges, plateaus and bedrock outcrops.
Mesic	Water removed somewhat slowly in relation to supply; soil remains moist for a significant but sometimes short period of the year.	Precipitation (and limited seepage).	Moderately sloping terrain, including the middle and upper parts of slopes and raised surfaces in lowlands.
Hygric	Water removed slowly enough to keep the soil moist to wet for most of the growing season.	Seepage from snowbeds and ice lenses.	Gently sloping terrain and lowlands particularly those located downslope from persistent snowbeds.
Hydric	Water removed so slowly that the water table is at or above the soil surface all year.	Permanent water table; water held at surface due to underlying permafrost.	Margins of tundra lakes and ponds; low-centred, ice-wedge polygons; level depressional areas downslope from snowbeds.

[1]Adapted from Walmsley *et al.* (1980).

FIG. 2. Wet sedge meadow vegetation growing on a level hydric lowland.

sudetica, *Saxifraga hirculus* var. *propinqua*, *Senecio congestus*, *Caltha palustris* var. *arctica* and mosses). The substrate is typically water-saturated peat, and meltwaters from upslope snowpacks collect on the surface in depressional areas at the base of slopes. Wet sedge meadows also occur in the shallow water of low-centred polygons (Fig. 3) and bordering tundra lakes and ponds (Fig. 2). The depressional area of a polygon typically features either a central area of open water ringed by emergent plant growth, especially sedges (*Carex aquatilis* var. *stans*) and *Arctophila fulva*, or a nearly continuous cover of sedges and mosses growing in water-saturated peat. These polygons are generally restricted to the valley bottoms of the Thomsen and Muskox rivers.

Graminoid Tundra: Graminoid tundra occupies mesic to hygric sites in lowlands and on gentle slopes (Fig. 4) and is characterized by a continuous cover of graminoid species, particularly *Eriophorum triste*, but also *Carex* spp., *Dupontia fisheri*, *Arctagrostis latifolia* ssp. *latifolia* and *Alopecurus alpinus*. The peaty substrates of this cover type also support mosses, dwarf willows (*Salix* spp.) and a variety of herbs (e.g., *Melandrium apetalum* ssp. *arcticum*, *Cerastium regelii*, *Petasites frigidus*, *Pedicularis sudetica*, *Ranunculus nivalis* and *Saxifraga hirculus* var. *propinqua*). Plant growth is most luxuriant along watercourses and on gentle slopes located downslope from snowbeds (Fig. 5). During winter, windblown snow accumulates on south- and east-facing slopes in deep drifts, which often persist until late July or early August. Meltwaters from these drifts are an important source of moisture for graminoid tundra plants. The plant associations that develop downslope from persistent drifts are often termed snowpatch fens (Tarnocai and Zoltai, 1988). They are generally associated with gentle slopes where runoff moves downslope as a broad flowing sheet rather than in well-defined channels (*cf.* Graminoid/Dwarf Shrub Tundra).

Graminoid/Dwarf Shrub Tundra: This diverse and variable cover type is intermediate between graminoid tundra and dwarf shrub tundra in terms of topographic position, moisture regime and vegetation. The vegetation (75-100% cover) is typically a mosaic of graminoids and dwarf shrubs, with graminoids (*Eriophorum triste*, *Arctagrostis latifolia* ssp. *latifolia* and *Alopecurus alpinus*) and mosses dominant in moist depressional areas, and a mixture of herbs and dwarf shrubs (particularly *Dryas integrifolia* and *Salix* spp.) on the drier substrates of elevated sites. Sites having good representation of both graminoids and dwarf shrubs include well-drained, alluvial terraces along the Thomsen and Muskox rivers; areas of high-centred ice-wedge polygons; shallow depressional areas in uplands; the intergradation zone between graminoid tundra and dwarf shrub tundra; and

FIG. 3. Wet sedge meadow vegetation growing in the central depressions of low-centred polygons.

FIG. 4. The graminoid tundra cover type occurs on mesic to hygric sites along watercourses and provides important summer foraging habitat for muskoxen.

FIG. 5. Gentle slopes below snowbeds support lush growths of graminoid tundra vegetation and are heavily used by muskoxen in July and August.

moderate-to-steep slopes below snowbeds where meltwaters and precipitation move downslope in narrow runnels with intervening areas of higher ground.

Dwarf Shrub Tundra: Dwarf shrub tundra is characteristic of moist, well-drained sites, including the middle and upper parts of slopes (Fig. 6) and raised surfaces (e.g., solifluction lobes and terraces) in lowlands. The substrate is variable, ranging from fine-textured clays to coarse sands and stony till, but typically lacks peat development. Small, non-sorted polygons are characteristic of the surface micro-relief, and cryoturbated surfaces are often present. Vegetation is diverse and is dominated by dwarf shrubs (*Salix arctica*, *Dryas integrifolia* and, less frequently, *Cassiope tetragona* ssp. *tetragona*), lichens and a variety of herbs (*Pedicularis arctica*, *P. capitata*, *Parrya arctica*, *Arnica alpina* ssp. *angustifolia*, *Potentilla vahliana*, *Polygonum viviparum*, *Cerastium* spp., *Papaver radicatum* and *Draba* spp.). Graminoids are a minor and localized component of this cover type, often occurring near bird perches and lemming burrows, and include species tolerant of dry to moist conditions (e.g., *Alopecurus alpinus*, *Festuca brachyphylla*, *Poa* spp. and *Carex rupestris*). Plant cover varies in response to differences in micro-relief and changes in moisture availability, but is generally between 50 and 75%.

Hummocky Tundra: Hummocky tundra is characterized by the presence of earth hummocks, a non-sorted, polygonal expression of patterned ground often covering extensive areas. Individual hummocks are roughly hemispherical in shape, measure up to 45 cm in diameter and are separated from adjacent hummocks by narrow furrows and cracks, producing a very uneven surface (Fig. 7) with a micro-relief of 10-35 cm. Hummocky tundra occurs predominantly on moderate to steep slopes in relatively stone-free soils. The moisture regime of hummocky tundra is complex: the tops of hummocks tend to be dry, while the furrows channel meltwater downslope and tend to be wetter. Vegetation cover is usually discontinuous (approximately 50%) and is characterized by dwarf shrubs (*Dryas integrifolia*, *Salix arctica* and *Cassiope tetragona* ssp. *tetragona*), herbs (*Oxyria digyna*, *Oxytropis arctica*, *O. glutinosa*, *Cardamine digitata* and *Pedicularis arctica*) and lichens, with mosses occurring in the furrows. On sheltered, south-facing slopes adjacent to snowbeds, hummocky tundra is frequently very lush. Under these conditions, a variety of flowering plants often form a continuous ground cover (e.g., *Polemonium boreale*, *Arnica alpina* ssp. *angustifolia*, *Saxifraga cernua*, *S. nivalis*, *Papaver radicatum*, *Castilleja elegans*, *Pedicularis arctica*, *Cerastium* spp., *Petasites frigidus* and *Erigeron eriocephalus*).

Dwarf Shrub/Lichen Barrens: This cover type occurs predominantly on upper slopes and on the tops of hills, ridges, plateaus and other elevated, wind-blown sites where winter snow cover is light and moisture availability is low. Surficial deposits are coarse-textured, frequently stony and very rapidly drained (Fig. 8). The primary source of moisture is summer precipitation. Microtopographic relief occurs on many uplands in the form of non-sorted stripes, frost fissures and fissure polygon terrain. Individual polygons generally range from 25 to 45 m in diameter. Vegetation is discontinuous, typically 25-50% cover, and is dominated by mat and cushion plants (e.g., *Oxytropis arctobia*, *Saxifraga oppositifolia* and *Silene acaulis* ssp. *acaulis*), prostrate shrubs (*Dryas integrifolia* and *Salix arctica*), lichens (particularly *Thamnolia* spp.), and xeric sedges (*Carex rupestris*). Forbs are sparsely distributed and include *Saxifraga tricuspidata*, *Astragalus* spp., *Draba* spp., *Pedicularis arctica*, *Potentilla vahliana*, *Taraxacum* spp., *Erigeron compositus* and *Papaver radicatum*.

FIG. 7. Hummocky tundra is characterized by the presence of earth hummocks and occurs predominantly on moderate to steep slopes.

FIG. 6. Dwarf shrub tundra vegetation is characteristic of moist, well-drained slopes. The dominant dwarf shrubs are *Dryas integrifolia* (shown here in bloom) and *Salix arctica*.

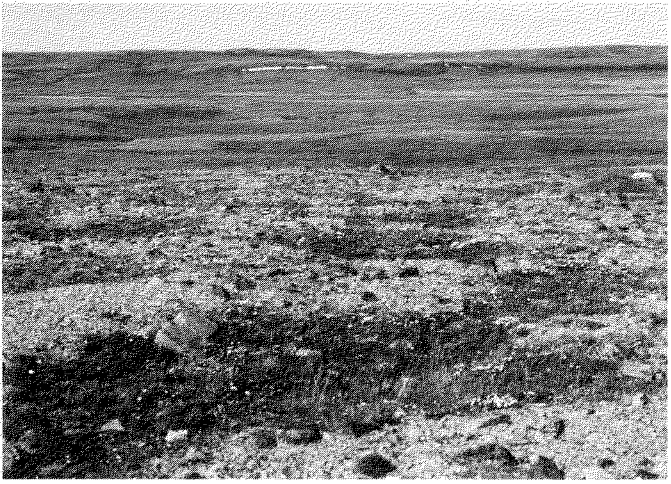

FIG. 8. The dwarf shrub/lichen barrens cover type (foreground) is characteristic of coarse-textured substrates on ridgetops and other elevated sites.

Sparsely Vegetated Ground: Sparsely vegetated ground (<10% vascular plant cover) represents a diversity of landforms, topographic positions, substrates and moisture gradients. In lowlands, fluvial processes associated with the Thomsen and Muskox rivers produce cutbanks, mudflats, and sand and gravel bars largely devoid of vegetation (Fig. 9). In upland areas, sparsely vegetated habitats occur on exposed outcrops of frost-shattered bedrock (Fig. 10) and on the surrounding debris-mantled slopes and cryoplanation surfaces. These topographic expressions are most conspicuous east of the Thomsen River, where consolidated outcrops of sandstone, siltstone and shale of the Parker River Plateau are a prominent feature of the landscape (Zoltai *et al.*, 1980). Sparsely vegetated ground also appears on coarse-textured substrates on the tops of wind-blown hills and ridges. Localized slope failures, characterized by the sudden downslope movement of the active layer and its vegetation cover, also account for the presence of bare substrates on sloping terrain.

Ice and Snow: This cover type includes ice-covered water bodies and snow-covered terrestrial features.

Visual Interpretation of TM Image

The most suitable colour composite for visually interpreting the land cover types was the near-infrared (band 4), shortwave infrared (band 5) and red (band 3) bands displayed in red, green and blue respectively. Image quality was improved by using a power contrast stretch of band 4 and linear contrast stretches of bands 5 and 3. These radiometric enhancements were superior to the histogram equalizations and logarithmic and principal components transformations.

Bands 4 and 5 were particularly useful for recognizing areas of lush vegetation growing on hygric and hydric sites. These areas include the wet sedge meadow, graminoid tundra and graminoid/dwarf shrub tundra cover types. They were easily differentiated from upland cover types, but the graminoid-dominated communities could not always be separated from each other (Fig. 11). Spectral overlap between wet sedge meadow and graminoid tundra and between graminoid tundra and graminoid/dwarf shrub tundra reflects the ecological continuums that exist between contiguous cover types. On the ground, sharp boundaries between ecologically similar habitat types rarely occur. Instead, one cover type generally

FIG. 9. Receding water levels of the Muskox River in mid-summer expose sand and gravel bars that are largely devoid of vegetation.

FIG. 10. Exposed outcrops of frost-shattered bedrock are a prominent feature of the landscape east of the Thomsen River.

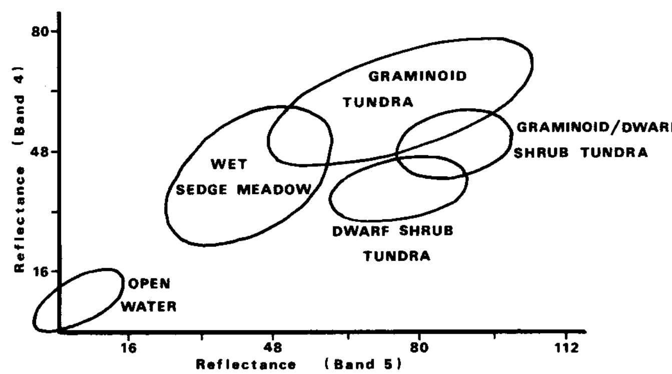

FIG. 11. Representation of training areas for several cover types in two-dimensional spectral space, using TM bands 4 and 5. The ellipses define 95% confidence limits. A reflectance value of zero indicates no reflectance; increasing values indicate increasing levels of reflectance.

grades into adjacent ones in response to gradual environmental changes along topographic and moisture gradients.

The upland cover types (dwarf shrub tundra, hummocky tundra and dwarf shrub/lichen barrens) were not always separable. They exhibited wide variation in colour and tone as a result of differences in the type and amount of exposed substrate, extent of plant cover, degree and orientation of slope and the presence of microtopographic features. For example, terrain with earth hummocks, frost fissures or other surface irregularities that create shadows had lower reflectance than similar terrain without these features.

Most types of sparsely vegetated ground were readily discernible, particularly highly reflective, light-coloured substrates such as dry sand and gravel deposits, frost-shattered bedrock and eroded cliff faces (as well as ice and snow cover). Dark-coloured substrates (e.g., mudflats) were sometimes confused with hummocky tundra and other upland cover types, especially those under shadow on northern exposures.

Unsupervised Classification

The unsupervised classification was useful for identifying spectrally homogeneous areas and selecting sampling areas, but it was of limited value as a representation of a cover type map. Problems centred on producing a classification that exhibited both a reasonable number of classes (16 or fewer) and good separation of the cover types of interest. Classifications with a reasonable number of classes assigned pixels representing the cover types of interest (i.e., those with continuous plant cover) to a single class. The remaining classes represented various open water classes and predominantly unvegetated terrestrial surfaces. Classifications that differentiated highly vegetated areas resulted in so many classes (>48) that visual interpretability was poor and cover type patterns were obscured.

Supervised Classification

The supervised classification had an overall accuracy of 88% (Table 2). Accuracy for individual classes ranged from 72 to 100%, and only two of seven classes had accuracies <80%. The cover types of greatest importance to muskoxen (wet sedge meadow, graminoid tundra and graminoid/dwarf shrub tundra) had classification accuracies of 84-89%. Misclassified areas were generally placed in an ecologically similar cover type rather than in a dissimilar one (Table 3).

Narrow drainages (<2 pixels wide, or approximately 60 m), which often provide foraging areas for muskoxen and serve as useful reference features, were difficult to classify because of the spectral variability of edge pixels. Edge pixels comprised a mixture of water and other cover types in varying proportions. Supervised classification procedures placed most of these pixels in an "unclassified" category. As a result, the drainages were difficult to discern on the classified image, so they were mapped separately.

Discrimination between the dwarf shrub tundra and hummocky tundra cover types was difficult because of the variability in reflectance caused by differences in slope, substrate, extent of vegetation cover and other modifying parameters. Confusion between these cover types was circumvented by merging them into a single category (i.e., dwarf shrub tundra). This did not reduce the usefulness of the classification because neither cover type is important to muskoxen as summer foraging habitat due to a lack of graminoid species. The principal difference between these cover types is the microtopographic relief (i.e., earth hummocks) associated with hummocky tundra.

The cover types that represent good foraging habitat for muskoxen (wet sedge meadow, graminoid tundra and graminoid/dwarf shrub tundra) occupy 24.8% of the study area (Table 3). These cover types are not uniformly distributed but are concentrated in an area between the Thomsen and Muskox rivers. Although this subarea represents only 18% of the total study area, it supports 27% of the total wet sedge meadow cover type and 31% of the total graminoid tundra cover type. The three graminoid-dominated cover types occupy 33% of this subarea, an area that supports high densities of muskoxen (McLean *et al.*, 1986; McLean and Fraser, unpubl. ms.).

DISCUSSION

The ability to detect the important cover types for muskoxen using Landsat TM data is attributable to the spectral distinctiveness of wet graminoid communities. Wetland areas support a lush growth of sedges, grasses and mosses, which are physiognomically and spectrally distinct from the discontinuous cover of dwarf shrubs, forbs and lichens in upland areas. Upland and lowland sites are readily distinguished on colour composite images by visual interpretation. The high spectral and radiometric resolution of the TM sensors allows detection of differences in vegetation physiognomy and soil moisture (Lillesand and Kiefer, 1987). Throughout the Arctic, graminoid communities are restricted to places where there is abundant soil moisture during the growing season (Edlund and Alt, 1989). Thus, TM data may have widespread application for inventorying muskox habitats.

A reconnaissance-level overview of a large geographic area can be attained quickly by examining colour composite images (one Landsat scene measures 185 × 185 km, or 34 225 km^2). Broad overviews of vegetation and other biophysical attributes are often useful when assessing general suitabilities of areas for wildlife and when selecting study sites for more intensive research. Use of Landsat data also provides flexibility because computer-generated colour plots of any part of an image can be produced easily at whatever scales are

TABLE 2. Error matrix for supervised classification of the Banks Island study area

	Reference data (# of areas sampled)								
	WAT[3]	WSM	GRT	GST	DST	DLB	SVG	Row totals	User's accuracy[1] (% correct)
Classification data: WAT	22	1						23	96
WSM		25						25	100
GRT		2	21	1				24	87
GST			4	22	3			29	76
DST				2	23	6		31	74
DLB					2	18	1	21	86
SVG					1	1	41	43	95
Column totals:	22	28	25	25	29	25	42	196	
Producer's accuracy[2]: (% correct)	100	89	84	88	79	72	98		

Overall accuracy = $\frac{\text{sum of number of correctly classified areas}}{\text{total number of areas}} = \frac{172}{196} = 88\%$

[1] User's accuracy indicates the probability that an area on the ground will be classified correctly.
[2] Producer's accuracy indicates the probability that a unit from a classified map actually represents that category on the ground.
[3] WAT = water bodies; WSM = wet sedge meadow; GRT = graminoid tundra; GST = graminoid/dwarf shrub tundra; DST = dwarf shrub tundra; DLB = dwarf shrub/lichen barrens; SVG = sparsely vegetated ground.
[4] Ice and snow cover on the 1986 image could not be verified during 1988 and 1989 field sampling.

TABLE 3. Summary of supervised classification of the Banks Island study area using Landsat TM data from 5 August 1986

Cover type	Area (ha)	% of total
Water bodies	7 243	4.0
Wet sedge meadow	3 297	1.8
Graminoid tundra	8 186	4.5
Graminoid/dwarf shrub tundra	34 020	18.5
Dwarf shrub tundra	62 000	33.8
Dwarf shrub/lichen barrens	27 580	15.0
Sparsely vegetated ground	29 211	15.9
Ice and snow	814	0.4
Unclassified[1]	11 109	6.1
Total	183 460	100.0

[1]The unclassified category included pixels representing clouds, highly reflective surfaces such as ice, snow and dry sand, and edge pixels between water bodies and terrestrial cover types.

desired. Wildlife survey data marked directly on these products would permit direct comparison of wildlife distribution and abundance in relation to cover types. Survey areas could also be stratified beforehand on the basis of the distribution of particular cover types and survey effort could be allocated accordingly (Falconer, 1979).

The primary advantages of producing a supervised classification are the abilities to simplify the visual complexity of images by "translating" the spectral information into meaningful land cover types for presentation on habitat maps and to quantify the availability of particular habitat types. Wildlife habitat inventories typically involve determining the availability and spatial distributions of certain cover types within a geographic area. Digital analysis enables the total areas of cover types to be calculated in just a few minutes, and an accuracy assessment gives map users and producers an indication of how good the classification is (Story and Congalton, 1986). Planimetric methods of calculating areas, on the other hand, are very time consuming and labour intensive and may produce results with variable precision.

The usefulness of TM data for mapping and inventorying habitats of other arctic wildlife has not been tested thoroughly, but some general observations can be made on the basis of this study. Vegetation types having discontinuous cover may be difficult to detect because background reflectance from soil or exposed rock often dominates the reflectances from the vegetation. This limitation has also been noted for alpine tundra (Frank, 1988). Additional information concerning topographic and other environmental parameters is often needed in combination with TM data to map these areas successfully (Frank, 1988; Frank and Thorn, 1985). Thus, in the Arctic, Landsat data alone are probably insufficient for discriminating upland vegetation types having discontinuous plant cover.

Remote sensing studies of arctic areas may be hampered by a lack of imagery. Landsat data are not recorded for the Queen Elizabeth Islands. In other areas, the probability of acquiring a good quality image during the period of photosynthetic activity is low due to the combined effects of a short growing season (generally <60 days), the high incidence of cloud cover during the snow-free season (Edlund and Alt, 1989) and the orbital frequencies of the Landsat satellites (16 or 18 days). Given these limitations, several years may be required before a usable image of a particular geographic area is available.

Ideally, it is preferable to collect ground data during the same growing season in which the satellite image was recorded. In the Arctic this is seldom possible. Field studies in remote northern regions, where access is difficult and expenses are high, are by necessity planned well in advance. It is impractical to schedule field studies on the condition that "same year" imagery can be acquired. Instead, field work is generally planned after a suitable image of a particular area is obtained. Images from arctic areas have useful application for many years because arctic tundra conditions are slow to change. Unlike boreal habitats, where recurring forest fires abruptly modify successional communities, succession in arctic ecosystems is very gradual. Furthermore, arctic landscapes are not disrupted by extensive land-use activities that cause widespread changes in ground-cover patterns (e.g., forestry or agriculture). The long-term usefulness of satellite images of arctic regions may offset the high costs associated with the acquisition and field verification of satellite data.

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