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Mapping Muskox Habitat in the Canadian High Arctic with SPOT Satellite Data

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ABSTRACT. SPOT satellite data were used to detect and map muskox habitat on Devon Island, N.W.T. Muskox habitat in the Canadian High Arctic is restricted to small islands of productive sedge meadow isolated within a matrix of sparsely vegetated polar desert. On Devon Island, muskox herds move among small lowlands on the northeast coast adjacent to Jones Sound in response to the seasonal availability of sedge-dominated habitat. Comparisons between the enhanced satellite images and species composition, plant cover, and standing crop on these lowlands showed that sedge meadows were spectrally distinct from the dwarf shrub/heath and cushion plant/lichen-moss cover types on beach ridges and rock outcrops, indicating that spectral data can be used to identify critical forage habitat for muskoxen in the High Arctic. The hummocky sedge/moss meadow and the less productive frost boil sedge/moss meadow types could be separated from each other on the enhanced imagery. The satellite data were simplified using a supervised classification to document the type and areal cover of muskox habitat along the northeast coast of Devon Island. The spatially isolated hummocky sedge/moss and frost boil sedge/moss meadows occupied only 3% (16.73 km^2) and 6% (32.84 km^2) respectively of a total land area of 549.38 km^2.

Key words: muskox habitat, SPOT satellite data, sedge meadows, Devon Island, Truelove Lowland

RÉSUMÉ. Des données du satellite Spot ont été utilisées pour détecter et cartographier l'habitat du boeuf musqué dans l'île Devon (Territoires du Nord-Ouest). L'habitat du boeuf musqué dans l'Extrême-Arctique canadien est restreint à de petites îles de prairies à laîches isolées sur un fond de désert polaire à la végétation clairsemée. Sur l'île Devon, les troupeaux de boeufs musqués se déplacent sur un territoire limité de terres basses sur la côte nord-est adjacente à Jones Sound, en réponse à la disponibilité saisonnière de l'habitat où dominent les laîches. Des comparaisons entre les images satellites accentuées et la composition des espèces, le couvert végétal ainsi que les plantes sur pied dans ces terres basses, ont révélé que les prairies à laîches avaient un spectre distinct des types de couvert à buissons nains/bruyère et de plantes coussinées/lichens-mousses sur les rides de plage et les affleurements rocheux, ce qui montre que les données spectrales peuvent servir à identifier un habitat de pâturage critique pour le boeuf musqué dans l'Extrême-Arctique. Sur l'image accentuée, on a pu distinguer le genre prairie à laîches/prairie de mousse avec creux et bosses, des types moins productifs, prairie à laîches/prairie de mousse avec boursouflements. Les données satellites ont été simplifiées à l'aide d'une classification dirigée pour documenter le genre et la superficie de l'habitat du boeuf musqué le long de la côte nord-est de l'île Devon. Les prairies à laîches/prairies de mousse avec creux et bosses et les prairies à laîches/prairies de mousse avec boursouflements, prairies spatialement isolées n'occupaient respectivement que 3 p. cent (16,73 km^2) et 6 p. cent (32,84 km^2) sur une superficie terrestre totale de 549,38 km^2.

Mots clés: habitat du boeuf musqué, données fournies par le satellite Spot, prairies à laîches, île Devon, basses terres Truelove

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INTRODUCTION

Important forage habitat for muskoxen (*Ovibos moschatus* Zimmerman) in the Canadian High Arctic is found in small islands or "oases" of sedge-dominated vegetation within the polar desert (Thing, 1984; Thomas *et al.*, 1981). In the Queen Elizabeth Islands, these oases occupy only ca. 1% of the total land area (Bliss, 1977) but may support all of the muskox populations. Critical sedge meadow habitat in arctic oases is susceptible to disturbance and undoubtedly will respond to predicted climate warming. However, identifying and monitoring this habitat over the vast area of the Canadian High Arctic is not feasible without remotely sensed data. Spectral data from the earth's surface collected by orbiting satellites could provide the means for identifying and mapping critical muskox habitat and monitoring its response to environmental change on both a spatial and temporal basis.

Previous research using satellites to study wildlife habitat has focussed on Landsat Multispectral (MSS) and Thematic Mapper (TM) data. For example, Landsat MSS and TM data were used to identify habitat for elk (Isaacson and Leckenby, 1981), whitetail deer (Ormsby and Lunetta, 1987), kestrels (Lyon, 1983), and prairie ducks (Gilmer *et al.*, 1978). In the North American tundra, muskox, caribou, goose, and shorebird habitats have been mapped over large areas (Acevedo *et al.*, 1982; Cooperrider *et al.*, 1986; Dickson, 1988; Ferguson, 1988; George *et al.*, 1977; Thompson *et al.*, 1980; Wickware *et al.*, 1980). However, the coarse spatial resolution of Landsat MSS data (ground cells 56 m × 79 m across a swath width of 185 km) is unsuitable for mapping the small areas of muskox habitat in the Canadian High Arctic. Landsat TM data offer improved spatial resolution (ground cells 30 m × 30 m), but these data are not routinely collected for the Queen Elizabeth Islands. A High Resolution Visible (HRV) sensor system was developed by the Centre National d'Etudes Spatiales (CNES) in France and launched in 1986 aboard the Système Pour l'Observation de la Terre (SPOT). SPOT sensors record spectral data from ground cells 20 m × 20 m in multispectral mode across a total swath width of 117 km, thus potentially offering improved information content. Repeat coverage of 4 (off-nadir viewing) to 26 days (direct vertical viewing) at arctic latitudes provides an excellent monitoring capability.

This paper examines the spectral data collected by SPOT as a tool for identifying and mapping critical muskox habitat in the Canadian High Arctic. The study was conducted on Devon Island in the Queen Elizabeth Islands, where muskox herds move among small lowlands on the northeast coast in response to the seasonal availability of sedge-dominated habitat. Two specific questions were asked: 1) Could the spectral data gathered by SPOT be used to detect and map muskox habitat on Devon Island? 2) Could the spectral data be used to identify and analyze the critical sedge meadow habitat on the lowlands?

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STUDY AREA

Devon Island is the fifth-largest island in the Canadian Arctic Islands. Small lowlands between Firkin Point and Cape Newman-Smith (140 km^2), Truelove Inlet (58 km^2), Cape Skogn (13 km^2), Cape Sparbo-Hardy (86 km^2), and near Sverdrup Glacier (26 km^2) on the northeast coast of Devon Island (Hubert, 1977) (Fig. 1) have formed on shallow marine platforms that emerged as a result of post-glacial isostatic uplift (Barr, 1971). Small lakes on some of the lowlands are remnants of former lagoons cut off from Jones Sound during uplift. Beach ridges and rock outcrops partition poorly drained lacustrine deposits on the lowlands into sedge meadows of varying sizes. Permafrost is continuous at this latitude (75°33′N) and on Truelove Lowland is reached at depths from 25 to 45 cm in sedge meadows and 50 to 100 cm below beach deposits in late July (Bliss, 1977). Temperatures during the short growing season are cool (3-5°C in July and August). Precipitation averages only 160-180 mm over the year, most of which falls as snow.

A dense sward of hydrophytic sedges, grasses, and mosses forms the meadow vegetation. Dwarf shrubs, heaths, cushion plants, and lichens dominate dry substrates on gravelly beach deposits and granite outcrops on both the lowlands and throughout the upland polar desert. A muskox population with numbers fluctuating between 200 and 300 animals has occupied the northeast coast of Devon Island for several hundred years (Hubert, 1977). Local herds move seasonally among the lowlands in response to the availability of the sedge meadow habitat. Lowlands between Cape Hardy and the Sverdrup Glacier are heavily used in June and July. Sedge meadows on Truelove Lowland are heavily utilized in winter and again in early spring for calving (Hubert, 1977). Polar bear, arctic wolf, arctic fox, arctic hare, short-tailed weasel, lemming, and 35 species of birds (mostly waterfowl) also use the Devon Island lowlands (Bliss, 1977).

METHODS AND MATERIALS

Ground Measurements

An extensive data base on the biophysical environment of Truelove Lowland was available from International Biological Program (IBP) studies carried out on Devon Island between 1970 and 1974 (Bliss, 1977). These data and a detailed map of the plant communities (scale 1:5000) prepared by Muc (Muc and Bliss, 1977) formed the framework for the collection of the ground measurements in this study.

Because the vegetation measurements for the IBP studies were collected more than 15 years ago, the lowland was resampled in July 1988 and July 1989 along two 6 km transect lines running from the west coast of the lowland east to the base of the escarpment (Fig. 2). Measurements were collected only within meadow, beach ridge, and rock outcrop plant communities along randomly located 100 m segments of each transect line within these communities. In all, 20 sedge meadows, 27 beach ridges, and 10 granite rock outcrops were sampled. The ground cover type touching a 100 m tape at 50 cm intercept points was recorded and used to estimate percent cover of vascular plants, lichens, mosses, litter, and bare ground. Above-ground biomass of vascular plants in forty 50 cm × 50 cm plots randomly located within meadow, beach ridge, and granite outcrop communities between Fish Lake and the Beschel Lakes (Fig. 2) were harvested during the first week of August 1989, air-dried for one month, and weighed to estimate standing crop. The boundaries of the plant communities mapped by Muc were checked in the field to record any changes that might have occurred since 1974.

Each of the lowlands was visited by helicopter to determine if the plant communities described for Truelove Lowland were also characteristic of the other lowlands along the northeast coast of Devon Island. Of particular interest were the location of sedge meadow habitat on the lowlands and the current

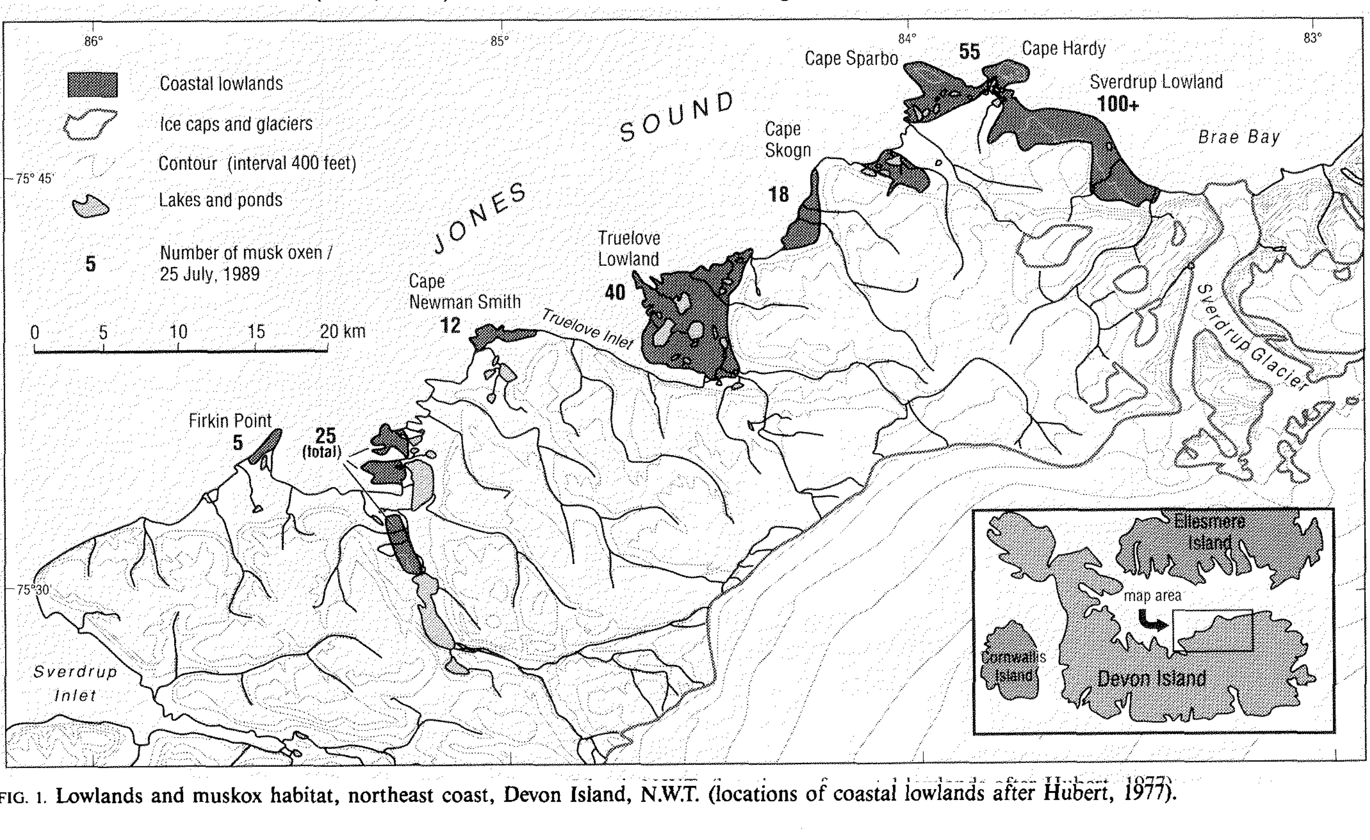

FIG. 1. Lowlands and muskox habitat, northeast coast, Devon Island, N.W.T. (locations of coastal lowlands after Hubert, 1977).

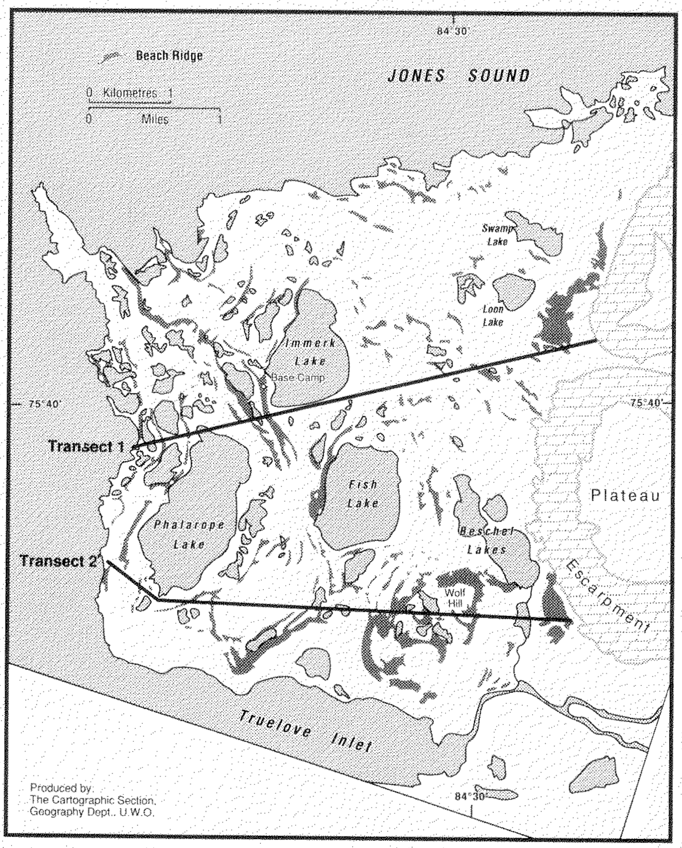

FIG. 2. Truelove Lowland, Devon Island. The locations of the sampling transects (Transect 1 and Transect 2) are shown.

use of these meadows by muskoxen. The number of muskoxen using each lowland was estimated during helicopter counts in July 1989.

Satellite Measurements

Digital data for a cloud-free SPOT overpass on 24 July 1989 over eastern Devon Island were analyzed on a PCI EASI/PACE image analysis work station located in the Department of Geography, University of Western Ontario, London, Ontario, Canada. SPOT HRV sensors detect and record reflectance information from the earth's surface in three wavelengths — green (band 1), red (band 2), and reflective (or photographic) infrared (band 3) — within cells (or "pixels") representing 20 m × 20 m on the ground. The spectral data were corrected to the vegetation map, enhanced using a histogram equalization procedure, and displayed as a false colour infrared image on the computer monitor for interpretation and comparison with the ground measurements.

Band-ratioing techniques were applied to the data to enhance the spectral information on the vegetation. Band ratios can provide an index to the amount of vegetation present in an area (Mather, 1987). Chlorophylls and other pigments within green plants absorb most of the light energy in the red wavelength, while near-infrared wavelengths are reflected. Unvegetated soils and rocks reflect both red and near-infrared radiation; water absorbs near-infrared radiation. Thus, the differences between spectral data for vegetated and for non-vegetated surfaces will be enhanced with a ratio of the near-infrared to red wavelengths. (Curran [1980], Perry and Lautenschlager [1984], and Tucker [1979] provide detailed information on the use of band ratios to analyze vegetation amount.) Ratios between radiance values in the near-infrared wavelength and the red wavelength were calculated for each pixel using an arithmetic function in EASI/PACE. The ratios were displayed as grey levels on the computer monitor, printed as a theme map, and compared to both the false colour infrared image and the vegetation map.

The spectral data for the three SPOT wavelengths were reduced for mapping using automated classification procedures available with the digital analysis software. "Unsupervised" classification assumes no *a priori* knowledge of the cover types in the area of interest. Clustering algorithms within the digital analysis software assign each pixel to a class that defines natural spectral groupings. The analyst must then decide what cover type each spectral class represents. In "supervised" classification, training sites are selected by the analyst to represent cover types, the identity and location of which have been determined from ground sampling, aerial photographs, or vegetation maps (Mather, 1987). Because both a detailed vegetation map and recent ground measurements were available for part of the study area on Devon Island, a supervised classification was used. A maximum likeihood classifier was "trained" by the identification of known cover types on Truelove Lowland. Six training sites, distributed as evenly as possible over the lowland, were used for each of the following cover types: hummocky sedge/moss meadow; frost boil sedge/moss meadow; cushion plant-moss/lichen on beach ridges; dwarf shrub/heath on granite rock outcrops; moss/herb on dolomite rock outcrops; clear water, silty water, and shallow water; and ice. Each training site selected contained at least 40 pixels from the largest and most homogeneous parts of the cover type. The spectral data within these training sites were then used to classify all of the spectral data for the lowland into cover type classes.

The classification results were displayed on the computer monitor. Each class was assigned a different colour. The areal extent of each class on Truelove Lowland (percent of area and square kilometres) was calculated. The classification was printed as a transparent overlay to the same scale as the vegetation map. The success of the classification was assessed based on direct visual comparisons between the vegetation map and the overlay and between the areal extent of each cover type on the lowland as documented in Bliss (1977:6) and calculated during the classification.

Because problems were encountered in accurately classifying some of the cover types, the spectral data for each wavelength were examined to identify the spectral patterns associated with the dominant cover types and to assess the degree of between-class separability possible. The pixel digital values from each of the training sites for each cover type were extracted, summarized (mean and standard deviation), graphed, and compared using an analysis of variance procedure available on Statview (TM) for the Macintosh computer.

The spectral data for the entire study area between Sverdrup Inlet and Sverdrup Glacier were displayed, classified, and evaluated using the methods described above.

RESULTS

Description of the Plant Communities

Five plant communities on meadows (hummocky sedge/moss and frost boil sedge/moss), beach ridges (cushion plant/moss and cushion plant/lichen), and rock outcrops (dwarf shrub/heath) were sampled and analyzed on Truelove Lowland for comparison with the satellite data. A sixth community, the moss/herb community characteristic of the polar desert surrounding Truelove Lowland, was not sampled in this study and data extracted from Bliss *et al.* (1977) are presented here. No major changes in the distribution of the plant communities, as mapped during the IPB studies, were observed.

Meadows: Sedge meadows occupy the poorly drained lacustrine deposits of infilled lakes and ponds on all of the lowlands. Muskoxen using the Devon Island lowlands appear to be grazing preferentially on graminoid species associated with the sedge meadow vegetation, particularly within the productive hummocky sedge/moss meadow plant community (Hubert, 1977:483). The hummocky sedge/moss meadow plant community occupies 20% of Truelove Lowland (Muc, 1977). This community is dominated by sedge (*Carex aquatilis* ssp. *stans* Drej.) and cottongrass (*Eriophorum angustifolium* Honck.), with lesser cover of arctic grass (*Arctagrostis latifolia* [R.Br.] Griseb.) and dwarf willow (*Salix arctica* Pall.). Mosses (e.g., *Cinclidium arcticum* [B.S.G.] Schimp. and *Drepanocladus revolvens* [Sw.] Warnst.) form the characteristic hummocks of this community. Green vascular plant and moss cover ranged between 70 and 90% in 1988 and 1989 and standing crop was 48 g·m^{-2} (± 12 S.D.) (Table 1).

The frost boil sedge/moss meadow plant community occupies 18% of Truelove Lowland on older lacustrine surfaces (Muc, 1977) and provides important muskox habitat on the Cape Newman-Smith, Sparbo-Hardy, and Sverdrup Glacier lowlands, as well. Cover of sedge (*Carex membranacea* Hook.), cottongrass (*Eriophorum triste* [Th. Fr.] Hadac and Love), dwarf willow, arctic grass, and mosses (e.g., *D. revolvens* and *Campylium arcticum* [Williams] Mitt.) was high (72% in 1989, 65% green vascular plants), although bare soil has been exposed through cryoturbation processes. Standing crop averaged 41 g·m^{-2} (± 3 S.D.) (Table 1).

Three other meadow communities were mapped during the IBP studies — wet sedge meadow, hummocky graminoid meadow, and graminoid/moss meadow — but as these communities have limited coverage on the Devon Island lowlands, they were not sampled in this study.

Beach Ridges: The cushion plant/moss and cushion plant/lichen plant communities occupy the slopes and crests of beach ridges that dissect the meadows on most of the lowlands (Fig. 2). Beach deposits are predominantly coarse sands and gravels from weathered dolomites. The cushion plant/moss community occupies 13% of Truelove Lowland on the lower slopes of the beach deposits (Svoboda, 1977). Dwarf willow, heather (*Cassiope tetragona* [L.] D. Don.), avens (*Dryas integrifolia* M. Vahl.), saxifrage (*Saxifraga oppositifolia* L.), and sedge (*Carex rupestris* All.) contributed most of the green plant cover. Although vascular plant cover in this community was only 35% in 1988 and 1989, standing crop (91 g·m^{-2}, ± 8 S.D.) was higher than in the meadow communities because of the dominance of woody plants (Table 1).

The cushion plant/lichen community on beach ridge crests covers 6% of Truelove Lowland. Only 18% of the plant cover was from vascular plants (avens, saxifrage, sedge, and dwarf willow) (Table 1). Lichens (e.g., *Alectoria pubescens* [L.] R.H. Howe and *Umbilicaria arctica* [Ach.] Nyl.), mosses (e.g., *Encaplypta rhaptocarpa* Schwaegr. and *Distichium capillaceum* [Hedw.] B.S.G.), and stones dominated ridge surfaces. Standing crop was low (46 g·m^{-2} ± 5 S.D.) compared to the cushion plant/moss community. Beach ridge vegetation appears to provide only minor foraging habitat for muskoxen on the Devon Island lowlands, unlike other muskox ranges where willow and other cushion plants are used extensively (Tener, 1965); however, these plant communities may be locally important in winter when sedge meadows are under deep snow (Hubert, 1977).

Granite Rock Outcrops: Rock outcrops on Truelove Lowland are predominantly granite and occupy 14% of the lowland (Bliss, 1977). Granite outcrops are also found on the other lowlands, particularly those to the southwest of Truelove Lowland. Heather dominated the dwarf shrub/heath plant community with avens, saxifrage, dwarf willow, and sedge (*C. misandra* R.Br.) of lesser importance. Vascular plant cover and standing crop on rock outcrops averaged 38% and 65 g·m^{-2} respectively in 1988 and 1989 (Table 1). It is unlikely that rock outcrops provide an important food source for muskoxen on the Devon Island lowlands, but these communities are used for shelter during winter storms and for foraging when the sedge meadows are covered by deep or crusted snow (Hubert, 1977).

Dolomite Rock Outcrops: The polar desert on the plateau above the coastal lowlands is characterized by sedimentary (primarily dolomite) rocks and a sparse coverage of plants within the moss/herb community. Mosses and lichens, with a few plants of saxifrage (*S. oppositifolia, S. cernua* L., *S. caespitosa* L.) and arctic poppy (*Papaver radicatum* L.), have a total plant cover of <10% and standing crop of 15 g·m^{-2} (Table 1). These outcrops do not provide important foraging habitat for muskoxen on this part of Devon Island.

More detailed descriptions of the plant communities on Truelove Lowland are available in Muc and Bliss (1977), Muc (1977), Svoboda (1977), and Bliss *et al.* (1977).

TABLE 1. Summary of plant communities, Truelove Lowland, Devon Island, N.W.T., 1988 and 1989

Plant community	Mean vascular plant cover (%)	Mean vascular standing crop (g·m^{-2})
Meadows		
Hummocky sedge/moss	80	48
Frost boil sedge/moss	65	41
Beach ridges		
Cushion plant/moss	35	91
Cushion plant/lichen	18	46
Rock outcrops		
Dwarf shrub/heath	38	65
Moss/herb[1]	6	15

[1]Data from Bliss *et al.* (1977).

Muskox Distribution on the Devon Island Lowlands

The distribution and size of local muskox herds on the northeastern coast of Devon Island in mid-July 1989 are shown on Figure 1. At this time, most of the muskoxen were grazing sedge meadows on the Sparbo-Hardy and Sverdrup Glacier lowlands, although all of the lowlands along the coast were being used (C. Somr, pers. comm. 1989). Small numbers of muskoxen were also observed in the Truelove River Valley and well into the large river valley between Firkin Point and Cape Newman-Smith. Hubert (1977) counted muskoxen in the same area between 1970 and 1973. Although his summer counts were hampered by poor flying conditions, his data show similar patterns to the 1989 surveys, with larger numbers of muskoxen observed on the Sparbo-Hardy and Sverdrup Glacier lowlands than on the other lowlands.

Evaluation of the Satellite Data

Enhanced Images: The satellite data for Truelove Lowland, displayed as an enhanced false colour image on the computer monitor, are shown on Figure 3. Because of differences in spatial resolution between the spectral data collected from a satellite orbiting at an altitude of 832 km above the earth and that collected from an airplane at a flight altitude of 750 m, it was not possible to detect all of the units shown on the vegetation map using the SPOT sensors. Nevertheless, a surprising amount of detail was provided.

On false colour infrared images, vigorous green vegetation with a leaf cover that masks the underlying substrate appears pink to red because of high reflectance in the near-infrared portion of the light spectrum. On the display monitor, the dense vegetation within the sedge meadows on Truelove Lowland appeared red, with the more productive hummocky sedge/moss meadows clearly visible as very bright red patches (very light grey on Fig. 3), such as at 1 near the Beschel Lakes. Frost boil sedge/moss meadows (see at 2 on Fig. 3), with less cover of green vascular plants than the hummocky sedge/moss meadows, occupied the remainder of the low-lying areas on Truelove Lowland and appeared dull red on the display monitor (light grey on Fig. 3).

Plant communities on beach ridges and rock outcrops with less than 50% green cover were not actually detectable against the underlying gravel and rock substrates, although various tones associated with these features were, in part, caused from differences in plant cover (such as between the cushion plant/moss and cushion plant/lichen beach ridge communities) that masked the underlying substrates. Dry light-coloured gravel and rock reflect much of the visible and near-infrared radiation received. Beach ridges on Devon Island are long, narrow (often only 5 m wide), gravelly landforms, and from the satellite viewpoint they were identifiable as gently curving and often branching, light to medium brown (very light grey on Fig. 3) features that partitioned the meadows (for example, at 3). The dolomite pavement on Rocky Point (at 4) and dolomite rocks on the escarpment and plateau above Truelove Lowland (at 5) were also light to medium brown. Dark grey granite outcrops are prevalent on the north coast of Truelove Lowland adjacent to Jones Sound (at 6) and were a medium grey-green on the false colour images (mid to dark grey on Fig. 3).

Near-infrared radiation is strongly absorbed by water, and clear water appears black on false colour infrared images. Unvegetated clear lakes and ponds on the lowland were clearly visible (black on Fig. 3). On 24 July 1989, ice (white to light blue on the false colour images, white and light grey on Fig. 3) still covered much of Immerk, Phalarope, and Fish lakes and had not yet cleared from Jones Sound, although Truelove Inlet was ice free.

Band Ratioing: The results of ratioing individual pixel values in the red and near-infrared wavelengths are shown on Figure 4. Water has been displayed as white (higher reflectance in the red wavelength and mean ratio values of <0.5) and unvegetated to sparsely vegetated beach ridges and rock outcrops and moderately vegetated frost boil sedge/moss meadows as grey (similar reflectance in near-infrared and red wavelengths and mean ratio values between 0.9 and 1.0). The hummocky sedge/moss meadows as mapped by Muc (Muc and Bliss, 1977) corresponded very closely with the black areas on Figure 4. Plants cover most to all of the ground surface in these meadows, resulting in a high reflectance in the near-infrared wavelength and a low

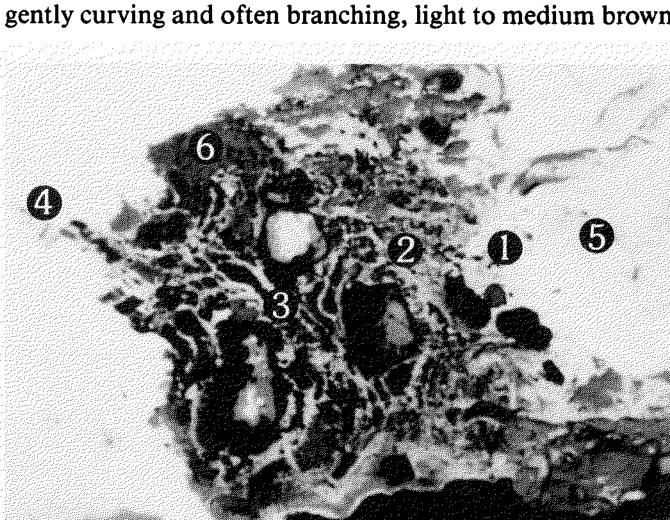

FIG. 3. Computer enhancement SPOT satellite data (bands 1, 2, and 3), Truelove Lowland, 24 July 1989, original scale 1:47 244 (1, hummocky sedge/moss meadow; 2, frost boil sedge/moss meadow; 3, beach ridge; 4, dolomite pavement; 5, dolomite rock outcrop; 6, granite rock outcrop).

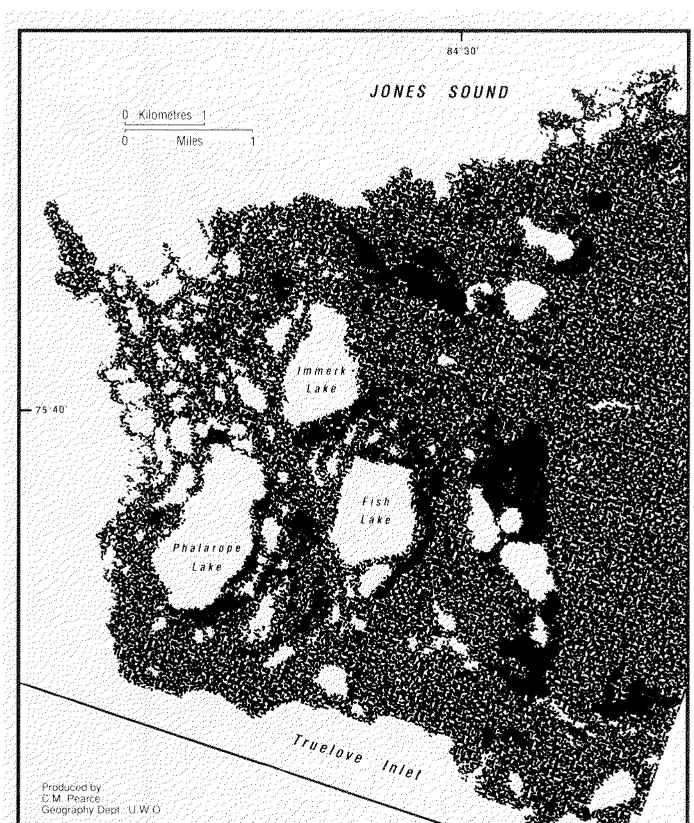

FIG. 4. Band ratios, near-infrared/red, Truelove Lowland, 24 July 1989, original scale 1:47 244 (black areas — hummocky sedge/moss meadows; grey areas — sparsely to moderately vegetated cushion plant/moss, cushion plant/lichen, dwarf shrub/heath, moss/herb, and frost boil sedge/moss meadow communities; white areas — water).

reflectance in the red wavelength (mean ratio values between 1.1 and 1.5).

Automated Classification: The supervised classification of Truelove Lowland and part of the Truelove River Valley and upland plateau resulted in 8 cover classes (Table 2): 2 classes for the sedge meadows (classes 1 and 2), 2 classes for dolomite surfaces (classes 4 and 7), 1 class for granite surfaces (class 5), and 3 classes for water and ice (classes 3, 6, and 8) (2.76% of the area could not be classified, but almost all of the unclassified satellite data were associated with disintegrating ice on Jones Sound). Classes 3, 6, and 8 and the unclassified data (water and ice) and classes 4 and 7 (dolomite rocks on the upland plateau and beach ridges on Truelove Lowland) were combined to simplify the mapping into only 5 cover type classes: class 1, hummocky sedge/moss meadow; class 2, frost boil sedge/moss meadow; class 3, freshwater lakes and ponds; class 4, dolomite outcrops and beach ridges; and class 5, granite outcrops (Fig. 5).

A comparison between the classified image and the vegetation map showed that most of the sedge meadows were identified (Table 3). Some of the hummocky sedge/moss meadows and most of the frost boil sedge/moss meadows were classified correctly. The hummocky sedge/moss meadows were confused with the frost boil type. Plots of the pixel digital numbers (Fig. 6) and analysis of variance showed considerable spectral overlap in the near-infrared wavelength between these two cover types, which resulted in misclassification at some locations.

TABLE 2. Results of the supervised classification, Truelove Lowland, Devon Island, N.W.T.

Class description	No. pixels[1]	% of image[1]
Class 1, hummocky sedge/moss meadow	6 839	2.61
Class 2, frost boil sedge/moss meadow	30 464	11.62
Class 3, ice	78 259	29.85
Class 4, dolomite rock outcrop	32 429	12.37
Class 5, granite rock outcrop	29 274	11.17
Class 6, clear water	19 643	7.49
Class 7, beach ridges and dolomite rock outcrop	38 406	14.65
Class 8, shallow water and ice	19 602	7.48
Unclassified (ice)	7 228	2.76
Total	262 144	100.00

[1]For land and water area shown on Figure 3 (512 lines × 512 pixels or 10.2 km × 10.2 km).

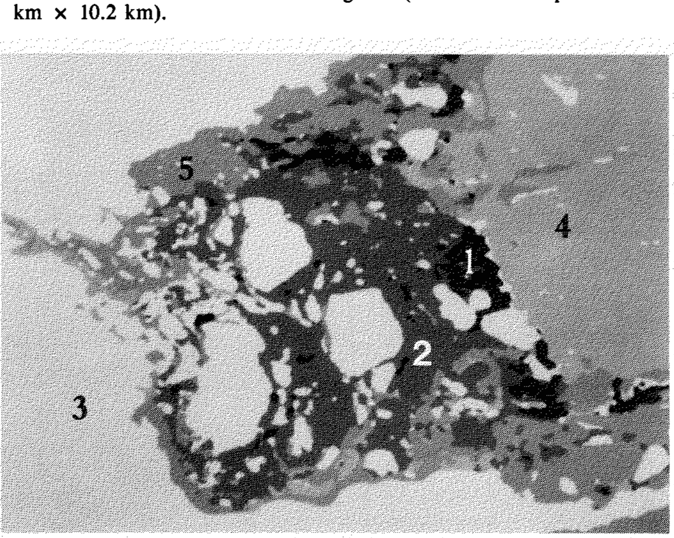

FIG. 5. Supervised classification of SPOT data for Truelove Lowland, 24 July 1989, original scale 1:47 244 (1 — Class 1, hummocky sedge/moss meadow; 2 — Class 2, frost boil sedge/moss meadow; 3 — Class 3, water and ice; 4 — Class 4, beach ridges and dolomite rock outcrops; 5 — Class 5, granite rock outcrops).

TABLE 3. Areal extent of plant communities and water, Truelove Lowland, Devon Island, N.W.T.

	% of lowland	
	IBP[1]	SPOT
Sedge meadows	39.0	36.0
Hummocky sedge/moss	20.6	6.6
Frost boil sedge/moss	18.4	29.4
Beach ridges	18.9	18.5
Cushion plant/moss	13.3	*
Cushion plant/lichen	5.6	*
Granite rock outcrops		
Dwarf shrub/heath	13.6	24.1
Lakes and ponds	21.7	21.5

[1]Data from Bliss (1977:6).
*Could not be separated in the satellite data.

Granite outcrops occupied by the dwarf shrub/heath plant community were also classified accurately and were completely separated from beach ridges on the lowland and the dolomite rocks on the upland plateau. (Although Bliss [1977:6] reports granite outcrops occupying only 13.6% of Truelove Lowland, the outcrops in the Truelove River Valley were not included in the measurements.) The limestone pavement and larger beach ridges on the lowland, occupied by the cushion plant/moss and cushion plant/lichen communities, were also classified very well. Small beach ridges were confused with sedge meadows and granite outcrops. The plots of the pixel digital numbers (Fig. 6) showed some spectral overlap between beach ridges and granite outcrops in the green and red wavelengths and between beach ridges and sedge meadows in the near-infrared wavelength. Water in lakes and ponds on the lowland was classified very accurately and varied by only 0.2% from the areal coverage documented in Bliss (1977:6).

The statistics for the training sites used on Truelove Lowland applied to the entire study area produced a very good classification of muskox habitat along the northeast coast of Devon Island. The classification showed small areas of the hummocky sedge/moss meadow cover type within frost boil sedge/moss meadows on all of the lowlands, particularly on Skogn Lowland near the escarpment, but nowhere did the sedge meadows cover as much area as on Truelove Lowland. Granite outcrops covered most of the lowlands between Firkin Point and Cape Newman-Smith and on Skogn Lowland; beach ridges were prominent on Firkin Point, on a lowland just to the east of Cape Newman-Smith, and on the Sparbo-Hardy Lowlands. In all, the critical sedge meadow habitat occupied only 9% (49.57 km^2) of the total land area shown on Figure 1 (Table 4). (This figure is very close to the 51 km^2 of sedge meadow calculated from air photos over the same area during the IBP studies [Hubert, 1977:485]). Of these sedge meadows, hummocky sedge/moss meadows occupied 3% of the land area, and frost boil sedge/moss meadows 6%. Freshwater lakes and ponds (5.6% of the land area), beach ridges and other dolomite surfaces (66%), and granite rock outcrops (19.4%) covered the remaining land surface.

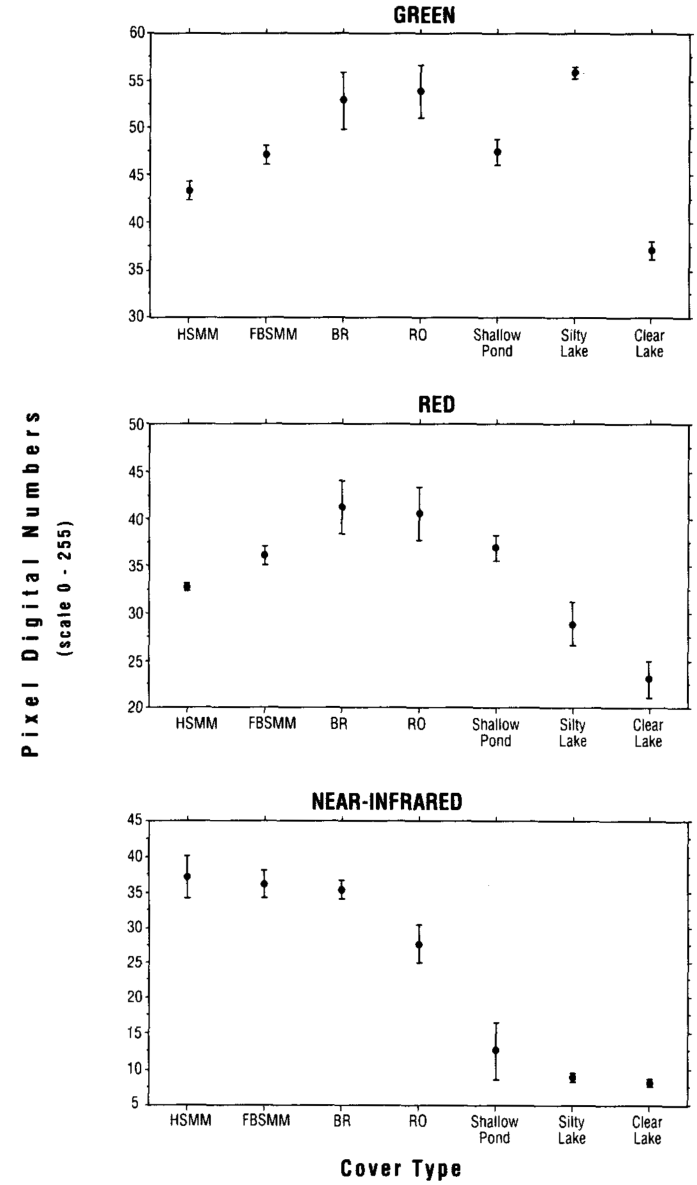

FIG. 6. Radiance data (as pixel digital numbers, mean ± 1 S.D.) for cover types on Truelove Lowland, 24 July 1989 (HSMM — hummocky sedge/moss meadow; FBSMM — frost boil sedge/moss meadow; BR — cushion plant-lichen/moss on beach ridges; RO — dwarf shrub/heath and moss/herb on granite and dolomite rock outcrops; ice not shown).

DISCUSSION AND CONCLUSIONS

Sedge meadows provide critical habitat for muskoxen on Devon Island (Hubert, 1977), Ellesmere Island (Henry *et al.*, 1986), Banks Island (Ferguson, 1988), and in other High Arctic areas (Thing, 1984; Thomas *et al.*, 1981). SPOT satellite data were manipulated to produce high quality images that could be used to detect and analyze this habitat on lowland oases along the northeast coast of Devon Island. Enhancements of the spectral data emphasized subtle differences within vegetated surfaces. Sedge meadows were completely separable from beach ridges and rock outcrops, and many of the productive hummocky sedge/moss meadows favoured by muskoxen on the Devon Island lowlands could be identified. It is probable that visual interpretation of enhanced satellite data could accurately identify and analyze the sedge meadow habitat throughout the Canadian High Arctic.

Although Cihlar *et al.* (1978) and Harvie *et al.* (1982) recommend visual interpretation of enlarged, digitally enhanced satellite imagery for analyzing arctic vegetation, there has been little use of this technique to identify and map habitat for grazing animals in the Canadian High Arctic. In Alaska, Cooperrider *et al.* (1986) identified the sedge meadow habitat along rivers and streams and in low areas using visual analysis of Landsat MSS data. Enhanced Landsat TM data were used to identify muskox habitat in the Low Arctic on Banks Island (Ferguson, 1988). Eight habitat types were identified on the imagery based on differences in vegetation, topography, substrate, and moisture regime. Wet sedge meadows and wet tussock tundra, important as summer habitat for muskoxen on Banks Island, were also located on the imagery.

Although both the hummocky and frost boil sedge/moss meadows provide critical habitat for muskoxen on Devon Island, the more productive hummocky type is utilized most heavily on the lowlands (Hubert, 1977:483) and should be mapped and monitored for change. Band ratioing identified the location of the hummocky sedge/moss meadow habitat along the northeast coast of Devon Island. Band ratioing is easy to apply using a digital image analysis system, and large areas can be ratioed in a very short time to provide a "quick look" for this habitat type. Again, there has been little use of this technique to analyze wildlife habitat in the Canadian High Arctic. However, in the Low Arctic, Tarnocai and Kristof (1976) applied a red/infrared ratio of Landsat MSS data to map vegetated and unvegetated terrestrial surfaces and water in the outer Mackenzie Delta area. Sedge-dominated vegetation was separated from unvegetated or sparsely vegetated mudflats and water. Lyon and George (1979) successfully used ratios of Landsat MSS data to discriminate among tundra vegetation types in Alaska.

A supervised classification of the SPOT data for Truelove Lowland and part of the northeast coast of Devon Island resulted in five distinct cover classes: hummocky sedge/moss meadows, frost boil sedge/moss meadows, dolomite rock outcrops and beach ridges, granite rock outcrops, and freshwater lakes and ponds. Once the cover types were classified, it was then a simple task to document the kind and amount of muskox habitat available in this part of the Canadian High Arctic. The study area between Sverdrup Inlet and Sverdrup Glacier enclosed a land area of *ca.* 550 km^2. Only 9% (or 50 km^2) of this area is occupied by the critical sedge meadow habitat.

Automated classification techniques have been used more frequently than visual analysis of satellite data to map wildlife

TABLE 4. Results of the supervised classification, northeast coast, Devon Island, N.W.T.

Cover type	% of land area	Km^2
Class 1, hummocky sedge/moss meadow	3.0	16.73
Class 2, frost boil sedge/moss meadow	6.0	32.84
Class 3, freshwater lakes and ponds	5.6	30.71
Class 4, dolomite outcrops and beach ridges	66.0	362.65
Class 5, granite outcrops	19.4	106.45
Total land area (Sverdrup Inlet to Sverdrup Glacier)		549.38

habitat in arctic areas. Both unsupervised and supervised classification, using Landsat TM data, were used to produce habitat maps for muskoxen on Banks Island (Ferguson, 1988). An unsupervised classification of Landsat MSS data resulted in 13 habitat classes for reindeer in Alaska, although problems were encountered in the consistent delineation of plant communities over large areas (George *et al.*, 1977). Snow goose (*Chen caerulescens*) habitat at Cape Henrietta Maria, Hudson Bay, was mapped using both unsupervised and supervised classification of MSS data (Wickware *et al.*, 1980). Eight habitat classes were identified, but 21% of the pixels could not be classified and problems were encountered in misclassification of some surfaces.

It must be stressed that care should be taken in using classified satellite data without ground confirmation. Classification algorithms assume that similar spectral patterns describe similar features. However, the spectral complexity associated with tundra surfaces is difficult to simplify into a few classes. For example, the spectral response from vegetated surfaces results from a variable mixture of green and brown leaves with different orientations, woody stems and branches, flowers, shadows, rocks, and bare earth. This mixture can vary depending on species composition, phenological stage of the individual plants, plant vigour, and substrate conditions. Although a supervised classification would appear to be ideal when detailed ground measurements such as those for Truelove Lowland are already available, the analyst must ensure that each training site is homogeneous and composed of enough "pure" pixels to accurately represent a particular cover type (Mather, 1987). The training sites must also be distributed throughout the area being examined to ensure that all of the spatial variability has been included. If ground information is not available, it must be collected. These criteria may be difficult to meet in arctic areas where field work is constrained by accessibility, timing, and tight budgets.

This research has shown that satellite platforms such as SPOT can provide a reliable and relatively inexpensive tool to detect and map spatially isolated muskox habitat throughout the vast regions of the Canadian High Arctic. Analyzing the satellite data on a digital analysis work station offers flexibility in that numerous enhancements can be applied to the data to improve identification of surface features and to emphasize subtle details. In addition, the data can be simplified by a variety of classification and band-ratioing algorithms, merged with other ground measurements to augment the spectral information and improve interpretation, and matched to data collected during subsequent satellite overpasses to detect changes in surface reflectance over time.

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