

Topographic Data and Satellite Spectral Response in Subarctic High-Relief Terrain Analysis

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ABSTRACT. Satellite images and digital elevation models were analyzed to interpret and quantify vegetation communities and active geomorphic surfaces in a mountainous area in southwest Yukon, Canada. High levels of discrimination were determined for the digital satellite and terrain data when compared to field studies and aerial photo interpretation of basic biophysical units, specific vegetation cover types and geomorphic process categories. The agreement between field identification of a site and discriminant analysis of that site using the digital data as discriminating variables ranged from 60 to 85% and contained improvements of up to 20% when topographic data such as slope angle and incidence value or aspect were added to spectral discriminant functions. Active geomorphic surfaces were grouped successfully into process categories such as landslides, debris flows, solifluction and talus sorting. Visual interpretation of the changes in the landscape detected using Landsat Thematic Mapper imagery from 1985 and SPOT HRV MLA imagery in 1989 were attributed to 1) running water in the alluvial deposits and organic terrain, 2) different water levels in the river, delta and floodplain, and 3) a general trend of class change from wet to dry throughout the study area. This latter change may be a result of imaging the same class (e.g., alpine tundra) under more senescent (i.e., brown) conditions and may be explained with reference to a warming/drying trend in the intervening years.

Key words: satellite imagery, digital elevation models, change detection

RÉSUMÉ. On a procédé à l'analyse d'images satellites et de modèles numériques d'élévation pour interpréter et quantifier des communautés végétales et des surfaces géomorphiques actives dans une région montagneuse du sud-ouest du Yukon, au Canada. On a déterminé des niveaux de discrimination élevés pour les données numériques obtenues par satellite et sur le terrain, en les comparant à des études sur le terrain et à l'interprétation de photos aériennes d'unités biophysiques fondamentales, de types particuliers de couvert végétal et de catégories de processus géomorphiques. L'accord entre l'identification d'un site sur le terrain et l'analyse discriminante de ce site grâce à l'emploi de données numériques comme variables permettant la discrimination, allait de 60 à 85 p. cent et s'améliorait de jusqu'à 20 p. cent lorsque des données topographiques telles que l'angle de la pente et la valeur ou l'aspect de l'incidence étaient ajoutées aux fonctions discriminantes du spectre. On a réussi à regrouper les surfaces géomorphiques actives en catégories de processus comme les glissements de terrain, les coulées de débris, la solifluction et le granoclassement de gravité. L'interprétation visuelle des changements dans le paysage détectés grâce aux images obtenues en 1985 avec l'appareil de cartographie thématique Landsat et à celles obtenues en 1989 à l'aide de l'appareil à haute résolution dans le visible MLA Spot, a montré qu'ils étaient dus à 1) l'eau courante dans les dépôts d'alluvions et le terrain organique, 2) des niveaux d'eau différents dans la rivière, le delta et la plaine inondable et 3), une tendance générale de changement de classification d'humide à sec dans toute la zone d'étude. Ce dernier changement pourrait résulter du fait que les images de la même classe (p. ex., la toundra alpine) ont été prises alors que ces plantes subissaient une sénescence (c.-à-d. qu'elles étaient plus brunes), et il pourrait s'expliquer par une tendance au réchauffement/dessèchement au cours des années qui s'écoulèrent entre les prises d'images.

Mots clés: images satellites, modèles d'élévation numériques, détection des changements

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INTRODUCTION

Satellite remote sensing is the science of choice for many diagnostic and prognostic studies of the physical environment (LeDrew, 1989). In mountain areas, digital elevation models (DEMs) are essential for the successful analysis of satellite imagery. DEMs provide topographic information in computer-compatible formats (Pike, 1988; Dikau, 1989) that can be used to describe more completely the distribution of terrain components contributing to spectral response. DEMs also can be used to guide field work (Walsh, 1987) and stratify image analysis problems (Hutchinson, 1982) and are necessary to normalize and correct satellite-observed radiance or reflectance (Civco, 1989; Woodham, 1989; Robinove, 1982) to true physical values in planimetric form. When analyzed within a geomorphological system (e.g., Evans, 1972), digital elevation models can be of profound interest as a source of terrain information independent of the satellite data. With their current availability for virtually any location on earth as products of stereo-processing satellite images (Swann *et al.*, 1988; Guban and Dowman, 1988), it may be that elevation models will be selected for use in certain applications concurrently with the original spectral response; certainly, their use will become more widespread.

The objectives of this study were to determine the role of satellite imagery and digital elevation models as tools to monitor and analyze surface resources of mountain environments in southwest Yukon and to investigate the changes in surface cover for the period 1985-89 in the Slims River valley area of Kluane National Park. Such changes may be a result of chronic or entropy-accumulating (Haigh, 1988) catastrophic or gradation processes, such as debris flows (Harris and Gustafson, 1987), biotic or cultural modification of vegetation cover (Raynolds and Felix, 1989) and boundaries, or paraglacial adjustment (Johnson, 1984). They may reflect short-term climatic, base-level or human-induced local changes or may be a process response to longer term environmental thresholds (Schumm, 1979, 1988). An inventory and spatial analysis of change is a key requirement in understanding such processes. The results of such studies can provide input to geographic information systems that will be valuable for future detection and monitoring of change and for understanding the evolution of landscape systems.

Satellite spectral response patterns are recorded reflectance or energy levels that are highly related to vegetation, soils and background material; DEMs are important sources of information on surface geometry and orientation. The basis for this research is the hypothesis that using the satellite

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imagery with geometric data from the elevation model — an integrated spectral/topographic data set — would result in significantly better analyses than using either data set alone. Further, it was felt that the results of the digital analysis would be compatible with results obtained through conventional aerial photo-interpretation methods of analysis (Christian and Stewart, 1968; Geological Society Working Party, 1982; Hansen, 1984). Using image analysis techniques, a multispectral, multitemporal digital data set of spectral and topographic variables was compiled for a portion of Kluane National Park for use in a range of monitoring and mapping projects aimed at vegetation communities and surficial materials. In addition, “active geomorphic surfaces,” such as debris flows, alluvial fanheads and talus-dominated slopes, were separated and interpreted.

STUDY AREA AND DATA COLLECTION

The study area is approximately 75 km² in size and is located in southwest Yukon (Fig. 1a,b) in Kluane National Park, centred on Sheep Mountain in the Slims River valley area. This environment has been studied extensively as part of a summary biophysical inventory (Lopoukhine, 1983) and was selected for use in several remote sensing experiments because of the great diversity of terrain conditions (Franklin, 1989). The suitability of satellite remote sensing imagery for monitoring and analyzing surface resources in this type of terrain is clear and well documented (e.g., Hutchinson, 1982; Jankowski, 1987; Walsh, 1987; Jones *et al.*, 1988; Frank, 1988), but the difficulties in image analysis caused by topographic influences on satellite spectral responses can be severe (Civco, 1989; Woodham, 1989). These range from altered spectral response for the same class on different slopes and

aspects (Moulton, 1989) to confusion in the classifier caused by decision surfaces that increase in complexity as new topographic descriptions are considered (Franklin and Wilson, 1991).

The vegetation ranges from a boreal cover of mature virgin white spruce forest to a mixed cover containing poplar, aspen and several varieties of willow. A montane tundra and alpine meadow cover exist at higher elevations. Three main geomorphic zones can be recognized in the area, including the alluvial or piedmont areas at low elevations, the Sheep/Bullion Plateau and the sediment source areas (mapped as undifferentiated alpine and subalpine zones by Lopoukhine, 1983). The soils are largely undeveloped, and bedrock exposures dominate the high slopes. The area contains low-grade metamorphic Paleozoic rocks, some late Triassic sedimentary rocks and volcanics. The ablation zone of the Kaskawulsh glacier is located a few kilometres south of Sheep Mountain.

Landsat Thematic Mapper (TM) and SPOT High Resolution Visible (HRV) Multiple Linear Array (MLA) satellite imagery were acquired on computer-compatible tape for 31 July 1985 and 29 July 1989 respectively for the study site. These images have no visible radiometric degradation and are cloud free. The images were registered to the Universal

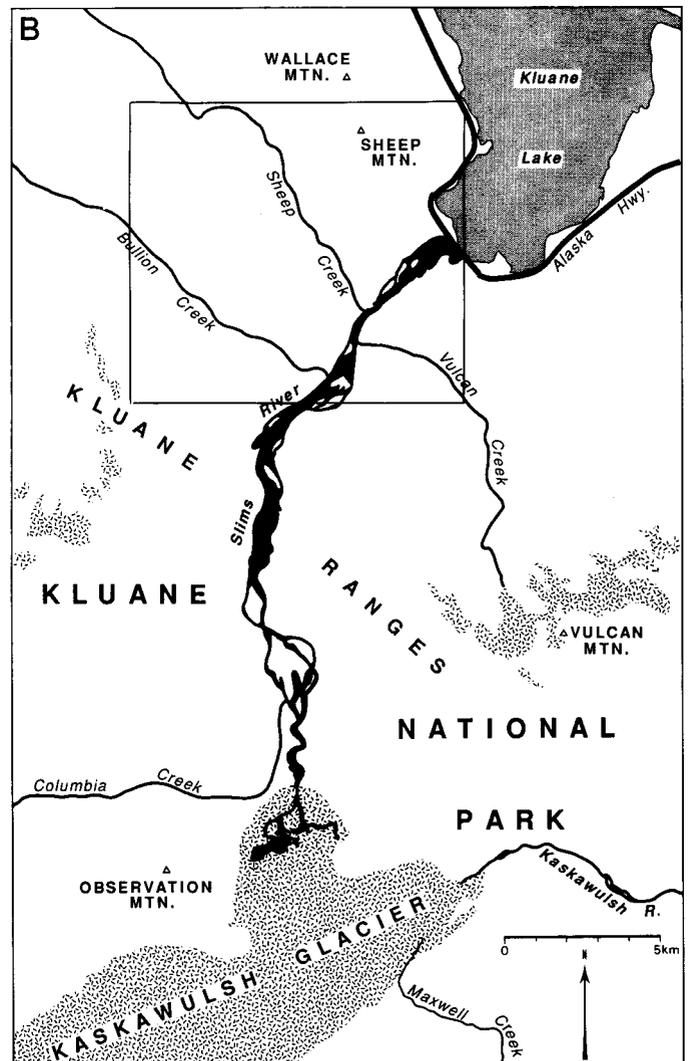
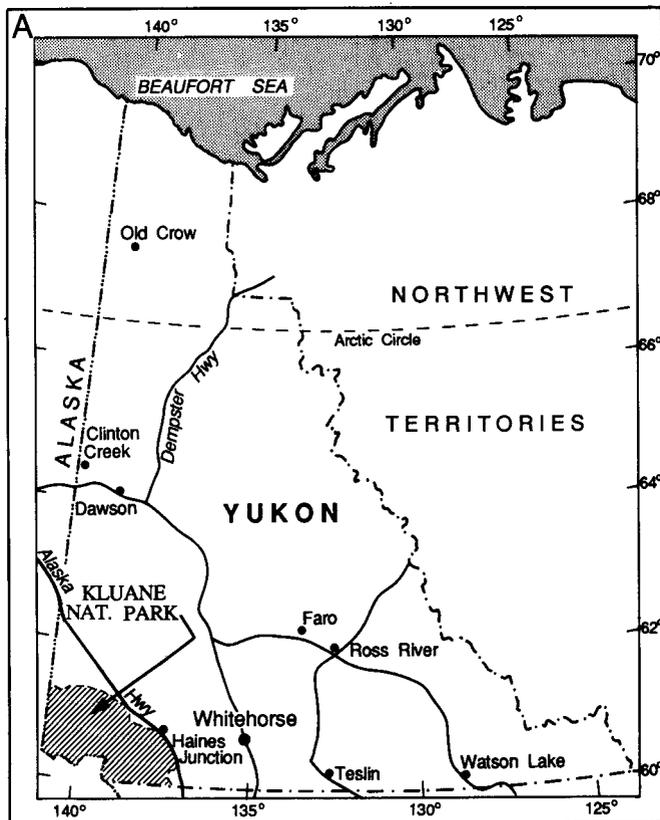


FIG. 1. A) The study area in southwestern Yukon Territory is contained within Kluane National Park. B) Detailed map of the study area.

Transverse Mercator (UTM) Grid with less than 0.5 pixel root-mean-square (RMS) error. The Landsat image was resampled from the original 30 m pixel size to a 20 m grid resolution using cubic convolution. A digital elevation model was generated by digitizing existing topographic maps at scale 1:50 000 with contour intervals of 50 m and interpolating a 20 m grid using the Surface II Graphics System (Davis, 1987). The model was registered to the satellite imagery using 20 ground control points with less than 0.5 pixel RMS location error. Geomorphometric software described by Franklin (1987) was used to compute terrain slope angle, aspect and incidence value for each 20 m pixel in the elevation grid.

METHODS

The principal technique used in the digital analysis of the satellite imagery and the elevation model was supervised computer classification (see Jensen, 1986; Mather, 1987; Townshend, 1981). This technique is one of the most powerful procedures available for organizing digital image data for information extraction. Many classificatory procedures are available in commercial image analysis systems. Since it is known that the statistical methodology used can influence the results significantly (Tom and Miller, 1984), the selection of technique should be based on a consideration of the characteristics of the data and the anticipated results. For example, several classificatory techniques assume Gaussian distribution of input data. Often, this assumption is not valid for digital elevation model variables, which should be analyzed using non-parametric statistics. Therefore, the techniques used in this study were a linear discriminant function and a maximum likelihood classifier (Franklin and Wilson, 1991); however, only one set of results will be discussed here.

The classifications were derived from the existing biophysical survey reports and from extensive aerial photo interpretation and field work by an interdisciplinary field team during the summers of 1986, 1987 and 1989. The classes are listed and described in Table 1. The discriminant analysis was done on data from field sites that were randomly sampled. A list of random UTM coordinates was generated; these locations were visited in the field and described according to percentage of vegetation cover in 10% increments by species, surficial deposit and soil exposure, topographic characteristics and dominant geomorphic process. An attempt was made to visit a minimum of 30 sites in each vegetation class in Table 1. For the geomorphic categories, only a few (68) pixels could be grouped unambiguously

TABLE 1: Sheep Mountain landscape classes

Class	Active geomorphic surfaces	Vegetation communities	Colour, Figures 2-5
1	non-active alluvial fan	coniferous forest	dark green
2	recently active alluvial fan	deciduous shrub	light green
3	active alluvial fan disposition	mixed forest	red
4	landslide deposits	organic terrain	pink
5	solifluction slopes	alpine tundra	dark purple
6	talus on east aspect	alpine meadow	yellow
7	talus on south aspect	alpine barrens	light purple
8	talus on west aspect	gravel/alluvium	grey
9	debris flow fan	water	blue
10	debris flow chute (canyon)	olian deposits	white
11	N/A	montane grassland	brown

into classes. The discrimination constitutes a test of the power of the variables in representing the classes (i.e., how well do these data predict the classes in known areas?). The maximum likelihood classification was done on the entire study area and used a straightforward supervised image analysis strategy that calls for "training area" selection by the image analysts (see Jensen, 1986; Mather, 1987; Townshend, 1981). Training areas included the field sites for each class.

Finally, an independent sample was taken to test the maximum likelihood classification accuracy. This sample was collected in the same way as the data for the discriminant analysis. The analysis of these independent pixels constitutes a test of the spatial integrity of the digital data set (i.e., how well do these training data predict the classes in unknown areas?). The final step in the analysis was to produce maps of the classes that could be compared to aerial photo interpretations and available biophysical survey maps. Since maps with certain planimetric accuracy were not required for this study, image maps were generated from 35 mm slides of the colour monitor.

The discriminant analysis results are discussed in this paper, and the maximum likelihood classification maps are presented to complement this discussion, but the maximum likelihood classifications are described in detail by Franklin and Wilson (1991).

RESULTS

Sheep Mountain Vegetation Communities

The discriminant analysis of vegetation communities on Sheep Mountain is summarized in Table 2 as the percentage of agreement between the field identification of a site and the predicted class membership based on combinations of the discriminating variables. A total of 793 pixels was sampled and grouped according to percentage of vegetation cover by species. The first part of the table contains the results of the discrimination using the percentage of cover variables (94%) and the percentage of cover plus topographic variables (97%). These results suggest that the field identification of a site based on the vegetation and topographic observations in the field is sufficient to distinguish the vegetation communities of interest in this area. The remainder of the table contains

TABLE 2. Discriminant analysis of Sheep Mountain vegetation communities based on 793 randomly sampled field sites

	Percentage classified into class											
	1	2	3	4	5	6	7	8	9	10	11	Mean
FIELD DATA												
Veg. cover	100	100	75	89	100	100	70	100	100	100	100	94
Veg./topo	100	100	75	100	100	100	90	100	100	100	100	97
SPOT IMAGE DATA												
MLA alone	92	13	42	99	45	74	60	71	81	40	44	60
MLA & elev.	92	54	83	100	66	80	81	73	81	34	78	75
MLA & inc.	89	38	50	100	40	73	79	75	83	23	37	63
MLA & slope	92	17	44	99	54	73	60	74	81	34	43	61
MLA & DEM*	89	61	67	100	71	80	80	81	81	23	74	80
TM IMAGE DATA												
TM alone	93	64	47	94	66	78	80	100	75	83	74	77
TM & elev.	96	63	97	90	73	81	79	100	75	83	78	83
TM & inc.	97	64	81	91	59	88	80	100	75	83	68	81
TM & slope	97	56	75	91	55	84	79	100	75	83	70	79
TM & DEM*	98	63	92	95	74	92	88	100	75	83	77	85

*DEM = elevation, slope angle, incidence value.

results of various combinations of discriminating variables. The maximum likelihood classification contains the spatial complement of these discriminant results for the Landsat Thematic Mapper spectral alone and spectral/topographic classification in Figures 2 and 3 respectively. A perspective diagram of the best classification results for the SPOT HRV imagery is shown in Figure 4.

The discrimination of the spectral variables on the vegetation communities yielded an overall classification accuracy for the 1985 TM image of 77%; the corresponding accuracy for the 1989 SPOT image was 60%. These results improve with the addition of variables extracted from the DEM. For example, elevation added to the spectral variables increased accuracies to an average of 83 and 75% for the Landsat and SPOT data sets respectively. The best overall results were achieved when all three topographic variables — elevation, slope angle and incidence value — were added to the dis-

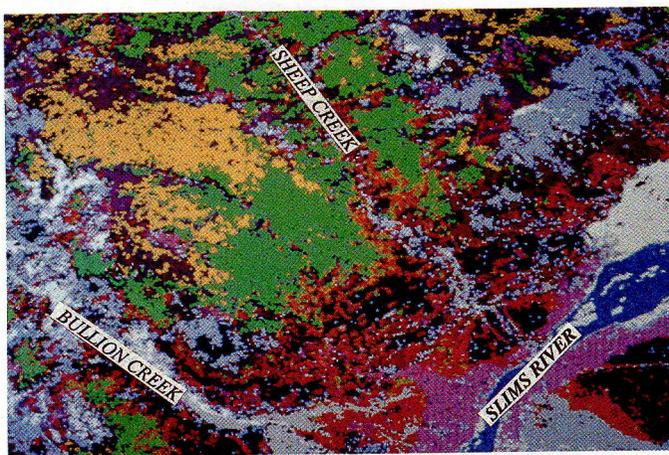


FIG. 2. A maximum likelihood classification map of the Sheep Mountain vegetation communities was obtained using Landsat Thematic Mapper data alone for a portion of the Kluane National Park study area. Width of the area shown is approximately 7.5 km. North is to the top of the map. The class colours correspond with those listed in Table 1. The overall accuracy of this map was determined to be 77% when compared to field observations of classes at 793 randomly sampled sites.

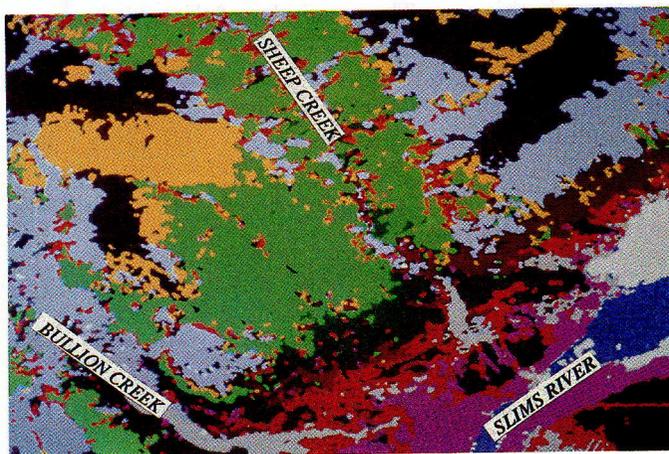


FIG. 3. A second maximum likelihood classification map of the Sheep Mountain vegetation communities was obtained using Landsat Thematic Mapper data plus the DEM variables of elevation, slope angle and incidence value for a portion of the Kluane National Park study area. The area shown is the same as that contained in Figure 2. The overall accuracy of this map was determined to be 85% when compared to field observations of classes at 793 randomly sampled sites.

criminant functions. These results were 85% correct for the Landsat data and 80% correct for the SPOT data. The poorest classes in both analyses were classes 2 (deciduous shrub) and 5 (alpine tundra). These results are considered to be adequate for the level of detail required in the mapping (e.g., Robinove, 1981) and for an analysis of change between the two image dates. However, complete analysis of the errors in these classes has been reported by Franklin and Wilson (1991).

The analysis of change between the two dates was conducted visually on the false colour composites and on the classified images (Fig. 5). In Figure 5a the major changes that result from different water levels in the Slims River are readily apparent. Some of the other changes require interpretation. For example, there appears to be a net loss of class 1 (spruce forest) from 1985 to 1989 on the three alluvial fans. The dominant changes are to class 3 (mixed forest) or class 4 (organic terrain). During the field season, numerous changes on the fans were noticed, especially the dieback of coniferous stands caused by flooding as the streams migrate across the fan depositional area. Other changes include the contraction of the gravel/alluvial deposits and concurrent expansion of the mixed forest class in the valley bottom. The band of montane grassland along the Slims River is more homogeneous in the 1989 image. This may be reasonable given the warming/drying trend in the past few summers.

In Figure 5b there are similar indications of changes from relatively wet classes to the dryer, more stable classes. This is apparent in the incursion of deciduous shrub pixels into the alpine meadows class and the contraction of the alpine tundra class to encompass pixels in the meadows and the barrens classes. The changes are quite small and subtle. One major change may be the sensing of classes that are more senescent (i.e., brown) in 1989 than in 1985. It is difficult to be certain if the changes are a result of different errors in the two classifications or are true physical alterations in the landscape. Without more controlled field studies — and a post-classification field check — it is not possible to be more definitive on actual change detection results.

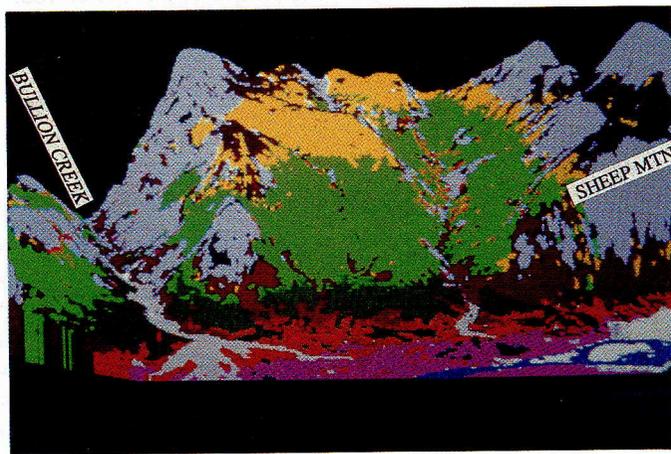


FIG. 4. A perspective view of the SPOT satellite image maximum likelihood classification results as seen from the southwest, with an observer elevation of 30° off the horizon and a vertical exaggeration of twice the elevation gradient. The area shown is the same as that contained in Figure 2 but with north to the right of the map. The class colours correspond with those in Table 1. The overall accuracy of this map was determined to be 80% when compared to field observations at 793 randomly sampled sites.

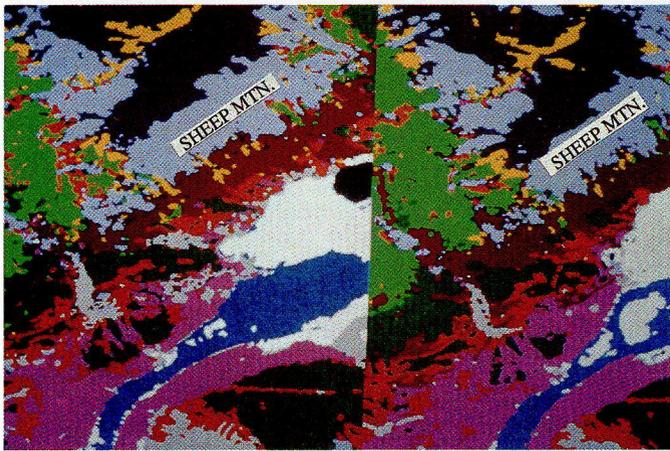


FIG. 5A. This figure shows a change detection comparison of the 1985 Landsat image classification and the 1989 SPOT image classification maps for the Sheep Mountain vegetation communities. In both cases the class colours correspond with those in Table 1 and north is to the top of the maps. A) Classification map showing the eastern half of the study area, with the Landsat image from 1985 on the left and the SPOT image from 1989 on the right. The major changes visible are the different levels of water in the river systems and on the delta and the fluvial action on the large alluvial fans.

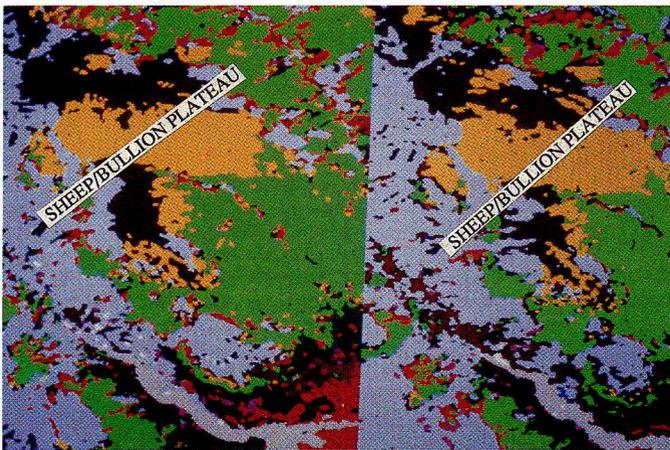


FIG. 5B. Classification map showing the western half of the study area, with the Landsat image from 1985 on the left and the SPOT image from 1989 on the right. The major changes visible are the different tundra and meadow communities in the centre of the image, which may be a result of climate-induced vegetation variation. The general interpretation is that there are small changes from relatively wet vegetation communities to relatively dry vegetation communities for the plateau and high ridges of Sheep and Wallace mountains.

Sheep Mountain Active Geomorphic Surfaces

Table 3 contains the discriminant results for the geomorphic set of classes studied on Sheep Mountain. These categories were based on the field identification of the dominant geomorphic activity in a reduced number of sites visited during the field seasons. A total of 68 pixels was sampled in areas identified on aerial photographs and in the field as representative of the ten process classes. The objective of the discrimination is to show that spectral response and geometric form can be used to predict the dominant process and morphology. The overall results indicate good potential for this idea; the accuracy with which these surfaces can be separated is 90% for the TM image with the DEM and 87% for the SPOT MLA image with the DEM. As before, the best results

are obtained when using both spectral and topographic data sets together.

The degree of improvement by adding DEM variables is consistent with the literature (e.g., Jadcowski, 1987, Table 26, recorded improvements from 71 to 77% using TM and DEM data). But the overall results are significantly better and, compared to the earlier discrimination of the vegetation communities, are probably overestimated as a consequence of 1) the small sample sizes involved, 2) the lack of an independent test data set, 3) the use of non-random sampling and 4) the fact that the effect of increasing the number of mapping variables has not been controlled. The importance of this table is in the indication that TM and MLA data when combined with digital elevation model data provide high levels of discrimination among surfaces undergoing active geomorphic disturbance of different intensity and type.

DISCUSSION AND CONCLUSION

Discrimination of vegetation communities and active geomorphic surfaces in a mountainous area of Canada's Yukon had the highest accuracies when satellite spectral response was combined with topographic variables extracted from a digital elevation model. Increases in accuracy ranged from a few percentage points to approximately 20% in discriminant analysis of biophysical units and vegetation cover when spectral variables were augmented with geomorphometric descriptors such as elevation, slope angle and incidence value. The average accuracies, when compared to field studies and aerial photo interpretation, ranged from 60% for spectral alone functions to 85% for spectral plus topographic discriminators. These accuracies are expressed as the percentage agreement between the digital and field methods of classification using a sufficiently large random sample of pixels. The discrimination of active geomorphic surfaces was conducted with a reduced number of sites, but the results are consistent with the literature and the hypothesis that processes such as landslides, debris flows, solifluction and talus sorting produce distinct surface characteristics. Spectral discrimination resulted in 87 and 81% overall accuracy for the Landsat and SPOT data sets; these increased to 90 and 87% overall respectively. Because of some of the assumptions in the classification procedures, these accuracy assessments, while significant, are known to be overestimated. However, the highly accurate separation of different surfaces undergoing exogenic degradation by a variety of geomorphic processes could yield valuable information on distribution of potentially catastrophic geomorphic conditions.

Visual interpretation of changes in the landscape detected by Landsat Thematic Mapper in 1985 and SPOT HRV MLA in 1989 were attributed to 1) running water in the alluvial

TABLE 3. Discriminant analysis of Sheep Mountain active geomorphic surfaces based on 68 randomly sampled field sites

	Percentage classified into class										
	1	2	3	4	5	6	7	8	9	10	Mean
TM alone	100	60	88	90	100	100	93	25	75	100	87
TM & DEM*	90	60	88	90	100	100	93	75	100	100	90
MLA alone	100	60	88	70	100	67	79	75	100	50	81
MLA & DEM*	80	80	100	80	100	100	71	100	100	100	87

*DEM = elevation, slope angle, incidence value.

deposits and organic terrain, 2) different water levels in the river, delta and floodplain and 3) a general trend of class change from wet to dry throughout the study area (such as alpine tundra to alpine barrens or meadow to montane grassland). This latter change may be the result of imaging the same classes under more senescent (i.e., brown) conditions and can be explained with reference to a warming/drying summer season in the intervening years.

This study provides baseline data on the power of satellite imagery coupled with digital elevation models for monitoring surface resources of mountain areas and providing updates for significant environmental changes. More detailed analysis of surface form and spectral response is presently being carried out in conjunction with field surveys of slope instability and susceptibility. The studies discussed here and the results of such future studies can be used to develop geographic information systems technology for northern environments and will ultimately provide insight into the processes of landscape evolution.

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