Mapping Permafrost in the Boreal Forest with Thematic Mapper Satellite Data

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ABSTRACT: A geographic data base incorporating Thematic Mapper (TM) satellite data was used to develop and evaluate logistic discriminant functions for predicting the distribution of permafrost in a boreal forest watershed. The data base included both satellite-derived information and ancillary map data. Five permafrost classifications were developed from a stratified random sample of the data base and evaluated by comparison with a photo-interpreted permafrost map using contingency table analysis and soil temperatures recorded at sites within the watershed. A classification using a TM thermal band and a TM-derived vegetation map as independent variables yielded the highest mapping accuracy for all permafrost categories.

INTRODUCTION

PERMAFROST, or perennially frozen ground, is widespread in the boreal forests of interior Alaska, and its discontinuous distribution results in a marked heterogeneity of ecosystem processes (Slaughter *et al.*, 1983; Van Cleve *et al.*, 1983; Kreig and Reger, 1982; Van Cleve and Viereck, 1981). Permafrost is defined exclusively on the basis of temperature. It is rock, soil, or other material that has remained below zero degrees Celsius continuously for two or more years (Muller, 1947). Mapping permafrost directly from ground temperature measurement and borehole logs is expensive and time-consuming, and is generally limited to small areas. For inventories of larger areas, indirect methods of analysis must be used which rely on the interpretation of various environmental variables that are correlated with permafrost (Kreig and Reger 1982; Ferrians and Hobson, 1973; Brown and Péwé, 1973; Brown, 1969).

The distribution of permafrost is controlled by climatic, geologic, hydrologic, topographic, and botanical factors. An understanding of the complex interrelationships among these factors is needed to map permafrost accurately using indirect methods. The cold, semi-arid climate of interior Alaska sets the stage for abiotic and biotic processes. Topography, primarily through its effect on direct solar insolation, modifies the regional climate so that permafrost, vegetation, and soil types are closely related to slope, aspect, and elevation (Viereck and Van Cleve, 1983; Dingman and Koutz, 1974; Rieger *et al.*, 1963). In an idealized scheme, black spruce (*Picea mariana*) forests occur on cold, wet soils on both north-facing slopes and valley bottoms underlain by shallow permafrost while white spruce (*Picea glauca*), paper birch (*Betula papyrifera*), and aspen (*Populus tremuloides*) forests occupy warmer and drier soils on south-facing slopes that are generally unfrozen (Viereck and Van Cleve, 1983; Van Cleve and Viereck, 1981).

Generalized relationships among permafrost, vegetation, and topography are altered by secondary successional processes related to the time since and intensity of the last fire. For instance, areas of equal incoming solar radiation on similar topographic positions could be expected to offer similar conditions for temperature-dependent processes such as soil development, vegetation growth, ground temperature regime, and seasonal snowpack ablation (Koutz and Slaughter, 1973). However, soil temperature depends on a number of other factors such as the thickness of the insulating organic mat, tree canopy cover (shading), and drainage characteristics. Prolonged fire-free intervals in black spruce forests result in the development of surface organic layers of the feathermosses, *Hylocomium splendens* and *Pleurozium schreberi* (Viereck, 1983; Foote, 1983). This organic layer reduces soil temperatures, causing a corresponding rise in the permafrost table (Viereck and Dyrness, 1979). Fire dramatically alters this sequence. Destruction of the vegetation and insulating organic layer by fire results in an increased thaw of the underlying permafrost (Dyrness, 1982; Brown, 1983). These post-fire conditions prevail for many years with a gradual increase in vegetation and organic surface layer thickness and a corresponding decrease in soil temperature and depth to permafrost.

The objective of this study was to develop and

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evaluate models predicting the occurrence of permafrost using environmental information derived from Thematic Mapper (TM) satellite data. Logistic discriminant functions were developed to predict the distribution of permafrost in a late successional boreal forest using a potential insolation index and a vegetation classification derived from TM satellite data. Five permafrost classifications were generated to evaluate the contribution of each variable, individually and in combination. These five classifications were assessed by comparison with a permafrost map prepared using terrain analysis and ground temperatures.

STUDY AREA

The Caribou-Poker Creeks Research Watershed (CPCRW) is located within the Yukon-Tanana Uplands of central Alaska, at 65° 10′ N latitude and 147° 30′ W longitude, approximately 48 km north of Fairbanks. The CPCRW was established in 1969 and has been the site of much research aimed at an ecological understanding of hydrologic, climatic, and biologic relationships of upland areas in the subarctic, discontinuous permafrost region of interior Alaska. The CPCRW (Figure 1), an area of 106 km^2 with elevations ranging from 210 m to 826 m, includes the entire watershed of Poker Creek and its principal tributary, Caribou Creek. The study area is characterized by large diurnal and annual temperature variations, low annual precipitation, and low humidity (Haugen *et al.*, 1982). Shallow (commonly less than 1 meter) eolian silts deposited during the Quaternary overlay metamorphic Precambrian schists. Soils are poorly developed silt loams belonging to the soil orders Inceptisols and Entisols (Rieger *et al.*, 1972).

The vegetation of the study area is characteristic of the taiga or boreal forest and corresponds to variations in topography, drainage, fire history, and successional stage. Paper birch and aspen forests occur generally on south-facing slopes, while black spruce forests occupy cold and wet north-facing slopes. Mixed coniferous and deciduous forests occur on sites of intermediate soil temperature and moisture. Birch (*Betula glandulosa*) shrub communities are found along the ridges, while tall shrubs (*Alnus* and *Salix* ssp.) grow along the creeks. The last severe fire recorded in the watershed occurred in 1908, the long term result of which is widespread areas of even-aged forest stands (Jorgenson *et al.*, in press). Black spruce forest stands up to 280 years in age have been noted in the watershed.

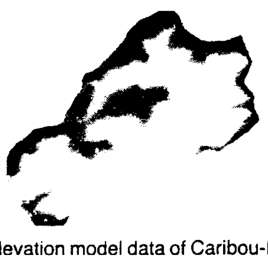

FIG. 1. Digital elevation model data of Caribou-Poker Creeks watershed. Dark areas represent high elevation, light areas represent low elevation.

GEOGRAPHIC DATA BASE

A digital geographic data base consisting of TM satellite data, digital elevation data, and digitized maps of permafrost and vegetation was constructed for the CPCRW. All data sets were spatially registered to a common grid of 30-m cells in the Universal Transverse Mercator (UTM) projection. Most analytical tasks were performed using the Interactive Digital Image Manipulation System (IDIMS) software package implemented on a VAX 11/780.

Three TM scenes, representing two phenological states and one diurnal cycle, were incorporated into the data base. The 12 August 1984 scene provided imagery of lush, green deciduous vegetation. The deciduous vegetation had senesced by the time of the second TM scene acquisition on 22 September 1984. TM data acquired on 23 September 1984 provided nighttime thermal imagery (10.2 to 12.5 μm) to complement the daytime scene acquired the previous day.

A vegetation map for the CPCRW was obtained from the Institute of Northern Forestry, U.S. Forest Service (Jorgenson *et al.*, in press) and used to evaluate the TM-derived vegetation classification. The map was generated through interpretation of black-and-white aerial photography (1:14,070) and high altitude color infrared imagery (enlarged to 1:15,840), and extensive ground checking. The vegetation map categories, based on physiognomic and taxonomic characteristics, included nine vegetation types and three density classes.

A TM-derived classification of the vegetative cover within the watershed was developed using supervised clustering and maximum likelihood classification techniques. Fifty-eight training sites, identified from ground surveys and delineated on aerial photographs, were located and the multispectral data extracted for all fifteen channels (two seven-band scenes and the thermal band for the nighttime scene). For each training site, a mean vector and covariance matrix was calculated. Optimal band subsets were selected using two methods: (1) optimization of classification accuracy by means of Monte Carlo simulation of spectral data based on actual training statistics, and (2) maximization of overall pair-wise transformed divergence (Card and Angelici, 1983). TM channels 3 (0.63 to 0.69 μm), 4 (0.76 to 0.90 μm), and 5 (1.55 to 1.75 μm) for the August scene, and channels 3, 4, 5, and 7 (2.08 to 2.35 μm) for the September daytime scene were found to best differentiate forest communities. Following image classification, the individual spectral classes were verified through photointerpretation of aerial photography and comparison with field information. The spectral classes were grouped by cover type:

closed conifer forest, open conifer forest, conifer woodland, closed deciduous forest, mixed conifer and deciduous forest, riparian shrubland, tall alder shrubland, low birch shrubland, barren land, and cloud and shadow. The classified image was filtered to remove isolated single pixels.

The vegetation classification was evaluated by contingency table analysis with the vegetation map of CPCRW developed by the U.S. Forest Service. This comparison yielded an overall agreement of 88 percent for all classes, with individual class agreements of 85.6 percent for coniferous forest, 88.9 percent for conifer woodland, 93.1 percent for deciduous forest, 77.4 percent for mixed coniferous and deciduous forest, and 50.7 percent for tall shrublands.

The digital terrain data used in this study was a 30-m digital elevation model (DEM) obtained from the U.S. Geological Survey. The DEM was produced from 1:120,000-scale photos using a Gestalt photo mapper. The data were interpolated to provide elevations at 30-metre intervals with five-metre vertical accuracy. An averaging filter was passed over the data to minimize apparent banding. Slope and aspect values were then calculated for each elevation point using a nine-cell elevation matrix.

An equivalent latitude image was generated from the slope and aspect images. Equivalent latitude is an index of the long-term potential direct beam solar radiation incident on a surface and, hence, is related to ground temperatures and the distribution of permafrost (Dingman and Koutz, 1974; Koutz and Slaughter, 1973). The function accounts for the departure of a surface from a horizontal plane. The equation used to calculate equivalent latitude was

$$\theta' = \sin^{-1} (\sin k \cos h \cos \theta + \cos k \sin \theta)$$

where k = slope of the surface,
h = aspect of the surface,
θ = actual latitude of the area, and
θ' = equivalent latitude of the area

All variables are expressed in degrees.

Koutz and Slaughter (1973) noted a strong correspondence between the presence or absence of permafrost and equivalent latitude in the CPCRW. Areas underlain by permafrost corresponded to equivalent latitudes above 65 degrees; unfrozen ground occurred in areas with equivalent latitudes of less than 60 degrees.

Topographic features are emphasized on thermal imagery acquired during daylight hours as a result of differential solar slope heating; therefore, it was hypothesized that daytime thermal imagery could be used as a surrogate for equivalent latitude (Morrissey and Card, 1985). To test this hypothesis, thermal channels for the two daytime TM scenes (12 August and 22 September 1984) were correlated with equivalent latitude based on 843 random samples. The 22 September 1984 daytime thermal channel had the highest correlation ($r = -0.83$) with equivalent latitude, and it was incorporated into the subsequent analyses as a surrogate for equivalent latitude. Topographic effects in the thermal imagery were more pronounced in the September scene acquired after the deciduous leaves had dropped, exposing the underlying ground surface, than in the August scene with closed forest canopies. The lower sun angle in September also produced more topographic shadows, further enhancing the differential slope heating.

Terrain analysis, based on interpretation of 1:60,000-scale color infrared and 1:15,840-scale natural color aerial photography and experience drawn from knowledge of several thousand boreholes drilled in Interior Alaska for geotechnical purposes, was used to prepare a 1:60,000-scale permafrost map with a minimum mapping resolution of 4 hectares (R. Kreig, unpublished map, 1984). The criterion used to distinguish permafrost classes was the percentage of the area underlain by permafrost based on a control section depth of 15 m (Kreig, 1985). Six map units were delineated: continuously frozen (100 percent frozen), generally frozen (95 to 100 percent frozen), discontinuously frozen (50 to 94 percent frozen), sporadically frozen (6 to 49 percent frozen), generally unfrozen (0 to 5 percent frozen), and unfrozen (0 percent frozen). Areas of uncertainty were also noted during photointerpretation, resulting in a total of ten possible map units. Nine of these ten units occur in the CPCRW.

DATA ANALYSIS

A stratified random sample of single-pixel observations was used to investigate the relationships among environmental variables and permafrost in the CPCRW. One hundred pixels were randomly selected from each of the nine categories of the photo-interpreted permafrost map. Each observation was a vector of the environmental data layers in the geographic data base. Editing of the 900 samples for clouds, cloud shadows, misregistration of the data base layers, and missing observations from one or more of the data sources, reduced sample size to 505 observations.

Logistic discriminant functions predicting the distribution of permafrost as a function of environmental variables were developed following the method of Anderson (1972). The nine map units of the photo-interpreted permafrost map were combined to form three categories: frozen (95 to 100 percent frozen), discontinuously frozen (6 to 94 percent frozen), and unfrozen (0 to 5 percent frozen), representing 28, 44, and 28 percent of the watershed, respectively. Sample sizes from the stratified random sample were 117, 268, and 120 pixels for the frozen, discontinuously frozen, and unfrozen categories, respectively. Logistic discrimination is based on expressing the probability of class membership for a pixel as multivariate logistic functions:

$$P_r(C_i|x_1,\ldots,x_p) = \text{EXP}\,[\beta_{i0}+\beta_{i1}x_1+\ldots+\beta_{ip}x_p]\; P_r\,(C_k|x_1,\ldots,x_p)$$

$$P_r(C_k|x_1,\ldots,x_p) = 1/(1+\sum_{s=1}^{k-1}\text{EXP}\,[\beta_{s0}+\beta_{s1}x_1+\ldots+\beta_{sp}x_p])$$

where C_i = class i, $i=1,\ldots k$;

x_j = independent variable j, $j=1,\ldots,p$;

k = number of classes (Permafrost classes in the present context); and

β_{sj} = regression coefficient for class s, independent variable j.

$P(C_i|x)$ is the probability of the pixel whose independent variables are $x=(x_1,x_2,\ldots,x_p)$ being a member of class C_i, for $i=1,\ldots,k$. One advantage of this formulation is that the independent variables can be either continuous or discrete, thereby allowing the use of ancillary data such as soils and vegetation in the discrimination process. Another advantage is that the procedure is nonparametric in the sense that coefficent estimates do not depend on the assumption of multivariate normality of the underlying distributions for each class.

Five logistic models predicting permafrost distribution in the watershed were developed. Three of the models used only a single independent variable: (1) equivalent latitude (Figure 2a), (2) September TM daytime thermal channel (Figure 2b), and (3) TM-derived vegetation classification (Figure 2c). The two other logistic discriminant functions combined the TM-derived vegetation classification with equivalent latitude (Figure 2d), and with the September TM daytime thermal channel (Figure 2e). The five classifications were evaluted by contingency table analysis with the photo-interpreted permafrost map.

Field evaluation of permafrost maps is a very difficult task. Short of expensive drilling and temperature monitoring projects, the techniques for field determination of permafrost have involved probing with a steel rod for the presence of frozen ground during the period of maximum thaw at the end of the summer (Koutz and Slaughter, 1973; Dingman and Koutz, 1974). However, the determination of permafrost using probes is complicated by the difficulty in distinguishing permafrost from rock and is restricted to shallow depths, typically less than one metre. To incorporate field measurements in the evaluation of the permafrost classifications, soil temperatures at one-metre depth were recorded during August 1985, at 29 sites. Soil temperature was measured at 10-metre intervals along a 100-metre transect at each site. One-way analysis of variance (ANOVA) was used to test for differences between mean soil temperatures by predicted permafrost category.

RESULTS

Comparative Analysis of Map Accuracy

Overall classification accuracy*, and omission and commission errors†, for the five permafrost classifications are shown in Table 1. Overall classification accuracy varied from 62 percent when equivalent latitude (Figure 2a) was the independent variable, to 78 percent when the TM vegetation classification and the thermal data (Figure 2e) were used together as predictors of permafrost distribution. The permafrost classification using the thermal data only (Figure 2b) had an overall accuracy 8 percent higher than permafrost classifications from either equivalent latitude or the TM vegetation classification (Figure 2c). Accuracies exceeded 75% when the TM vegetation classification was combined with either equivalent latitude (Figure 2d) or the daytime thermal channel. The TM vegetation and thermal channel classification yielded 2 percent higher overall classification accuracy than the TM vegetation and equivalent latitude classification, primarily from more accurate mapping of the unfrozen and discontinuously frozen categories. To further understand the contribution of each variable and their combined effects on the classification process, the strengths and weaknesses of each classification were assessed through an analysis of omission and commission errors by permafrost category.

Frozen Ground Category. Frozen ground omission errors for the five models varied from a low of 20 percent when the TM vegetation classification and thermal data were used together as permafrost predictors, to 81 percent when the TM vegetation classification was the sole independent variable. The TM vegetation classification incorrectly categorized frozen north-facing slopes supporting open black spruce forests as belonging to the discontinuously frozen category (Figure 2c). This is a result of the relative frequencies of the vegetation types among the three permafrost categories calculated from the training

* Although classification accuracy is referred to throughout the results section, a more accurate description is the assessment of the degree of association between the photo-interpreted permafrost map and the five classifications. The assessment assumes the photo-interpreted permafrost map is an accurate representation of permafrost conditions within the watershed.

† An omission error for a particular class implies an underestimation of that class, while a commission error implies an overestimation. The error of identifying a class as, for instance, frozen when in fact it is not frozen is an error of commission. An omission error occurs when, for example, the class is identified as discontinuously frozen or unfrozen, when it is really frozen.

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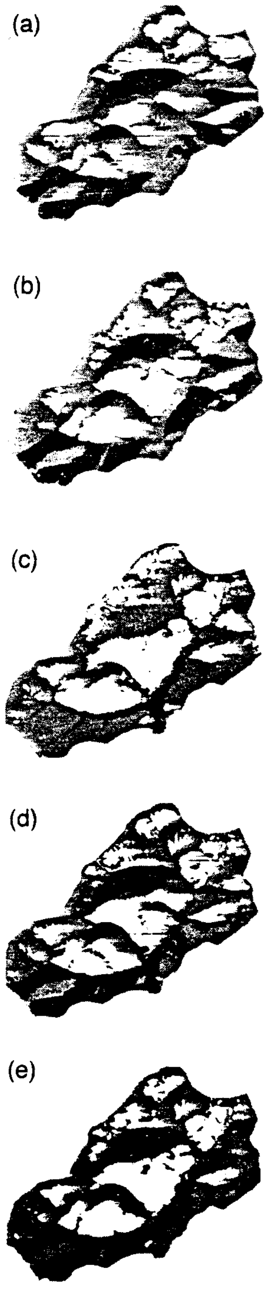

FIG. 2. Three-category permafrost classifications developed from logistic discriminant functions incorporating select data base layers: (2a) Equivalent latitude model, (2b) Thermal channel model, (2c) TM-derived vegetation model, (2d) TM-derived vegetation and equivalent latitude model, and (2e) TM-derived vegetation and thermal channel model. For each image, black represents frozen ground, gray represents discontinuously frozen, and white represents unfrozen ground.

data (Table 2). Specifically, more open conifer forest pixels occurred in the discontinuously frozen category than in either the frozen or unfrozen categories. Frozen valley bottoms supporting conifer woodlands with thick sphagnum mats were correctly classified as frozen ground using the TM vegetation classification.

Equivalent latitude and the thermal channel predicted similar distributions of frozen ground with omission errors of 37 and 35 percent, respectively. Both variables correctly classified frozen north-facing slopes, but incorrectly classified frozen valley bottoms as belonging to the discontinuously frozen category (Figures 2a and 2b). The equivalent latitude of these frozen valley bottoms is approximately 62.5 degrees, falling in the transition between frozen and unfrozen according to Koutz and Slaughter (1973).

Frozen ground predictions using the TM vegetation classification with either equivalent latitude (Figure 2d) or the thermal data (Figure 2e) had a 20 percent omission error. Nineteen percent of these errors were frozen ground classified as the discontinuously frozen category (Table 1). The 1 percent omission error for frozen ground classified as unfrozen occurred along a boundary between a conifer woodland valley bottom and a deciduous southeast facing slope and is the result of misregistration between the data sources in the geographic data base.

Discontinuously Frozen Category. Omission errors for the discontinuously frozen category were similar among the models, varying from a high of 30 percent when equivalent latitude was the independent variable to 22 percent when the TM vegetation classification and the thermal data were used together as predictors of permafrost. Omission errors for the discontinuously frozen category using equivalent latitude or the thermal data were approximately equally distributed between the frozen and unfrozen categories and were similar in their spatial locations. Omission errors classified as frozen occurred along the ridges and mid-slope positions on northwest to northeast-facing aspects. Omission errors for the discontinuously frozen category classified as unfrozen were located on south-facing slopes. The location of these errors, when the TM vegetation classification was the independent variable, differed from error locations when either equivalent latitude or thermal data were the predictors. The TM vegetation classification assigned deciduous forest occurring on discontinuously frozen ground as belonging to the unfrozen category; when the independent variable was equivalent latitude or the thermal data, the errors were primarily in areas of open conifer forest.

Unfrozen Category. Omission errors for the unfrozen category varied from 17 percent when the TM vegetation classification was the independent variable to 51 percent when equivalent latitude was the predictor. The high omission error for the equivalent latitude classification was the result of south-

TABLE 1. CLASSIFICATION ACCURACY FOR FIVE PERMAFROST MODELS

Model	Permafrost Category			
	Frozen	Discontinuously frozen	Unfrozen	Overall
Equivalent Latitude				
Percent Correct				62.0
% Commission Error	24.4	44.3	36.5	
% Omission Error	36.9	30.3	51.0	
Daytime Thermal Channel				
Percent Correct				70.1
% Commission Error	23.2	35.8	24.3	
% Omission Error	34.5	26.4	30.6	
TM Vegetation Classification				
Percent Correct				62.3
% Commission Error	25.2	43.5	29.9	
% Omission Error	81.2	22.7	17.3	
TM Vegetation Classification and Equivalent Latitude				
Percent Correct				75.5
% Commission Error	18.9	27.9	24.4	
% Omission Error	20.2	24.5	28.9	
TM Vegetation Classification and Thermal Channel				
Percent Correct				77.9
% Commission Error	18.9	25.2	19.8	
% Omission Error	19.5	21.9	25.0	

east and southwest slopes being classified as discontinuously frozen. Omission errors for the thermal classification occurred primarily on south slopes with deciduous and open coniferous forests. Despite having the lowest omission errors for the unfrozen category, predictions from the TM vegetation classification had the greatest number of omissions for the unfrozen category classified as frozen. This result is a reflection of the misregistration of the TM data to other data layers of the geographic data base and the low probability of being frozen for deciduous forests.

GROUND TEMPERATURES

Further evaluation of the TM-derived permafrost classification was undertaken using soil temperature as a direct measure of shallow permafrost status. Soil temperatures for 29 sites were grouped by predicted permafrost category. Based on a one-way analysis of variance, significant differences ($p<0.01$) in mean temperature were found between each of the three permafrost categories. A subset of these sites, representative of the major vegetation communities on various topographic positions, is shown in Table 3. Forest stands occur along a soil temperature gradient from cold black spruce forests to warm deciduous forests. Variation in soil temperature with slope orientation within each forest type is evident, with south-facing slopes being warmer and north-facing slopes being cooler. Black spruce forests, with a high probability of being frozen, had the lowest soil temperatures. One black spruce site on a west-facing slope with a frozen substrate was incorrectly classified as discontinuously frozen. Another black spruce site, occurring on an unfrozen south-facing slope, had similar probabilities for unfrozen (52 percent) and discontinuously frozen (47 percent), but was correctly classified. Shrub tundra along the ridge had a wide temperature range (1.5 to 5.5°C) and was correctly classified as discontinuously frozen . The riparian shrub site, with

TABLE 2. RELATIVE FREQUENCIES OF VEGETATION TYPES AMONG THREE PERMAFROST CATEGORIES IN A STRATIFIED RANDOM SAMPLE (N = 505 PIXELS)

Vegetation Type	Sample Size	Frozen	Discontinuously frozen	Unfrozen
Closed Conifer Forest	32	0.34	0.63	0.03
Open Conifer Forest	250	0.34	0.60	0.06
Conifer Woodland	12	0.83	0.08	0.08
Closed Deciduous Forest	158	0.01	0.39	0.60
Mixed Forest	38	0.05	0.76	0.18
Riparian Shrubland	9	0.78	0.11	0.11
Low Shrub	6	0.17	0.67	0.17

TABLE 3. LOGISTIC PROBABILITY OF PERMAFROST CLASS ASSIGNMENT AND SOIL TEMPERATURES MEASURED AT ONE METRE DEPTH IN AUGUST, 1985
(SITES ARE RANKED ACCORDING TO MEAN SOIL TEMPERATURE)

Forest Type	Aspect	Class	Probability F	Probability D	Probability U	Temperature (°C) Mean	Temperature (°C) Range
Black Spruce	East	F	91	6	1	0.45	0.0 - 1.0
Black Spruce	North	F	91	8	0	0.50	0.0 - 1.0
Black Spruce	Valley	F	83	11	5	0.75	0.0 - 2.0
Black Spruce	West	D	33	66	0	0.75	0.0 - 2.0
Low Shrub	Ridge	D	0	81	17	3.35	1.5 - 5.5
Black Spruce	South	U	0	47	52	4.30	3.5 - 5.0
White Spruce	South	D	0	86	12	4.55	4.0 - 6.0
Riparian Shrub	Valley	F	68	20	10	4.55	0.0 - 6.0
Deciduous Forest	West	D	3	92	4	5.60	4.0 - 7.0
Mixed Forest	South	U	0	47	52	6.25	4.0 - 8.0
Deciduous Forest	East	U	0	28	71	7.25	6.5 - 8.0
Deciduous Forest	South	U	0	12	87	7.70	7.0 - 8.5
Tall Alder Shrub	South	U	0	0	99	8.55	8.0 - 9.0

Note: F = Frozen, D = Discontinuously frozen, U = Unfrozen

a warm mean temperature of 4.55°C, was classified as frozen. However, a closer examination of the temperature range (0.0 to 6.0°C) revealed several frozen samples along the transect. Aspen and birch deciduous forests and tall alder shrublands, regardless of aspect, had consistently high soil temperatures.

CONCLUSIONS

Environmental variables derived from Thematic Mapper satellite data predicted the distribution of three permafrost categories (frozen, discontinuously frozen, and unfrozen) in a boreal forest watershed with 78 percent accuracy. Classifications incorporating both a vegetation map and a solar irradiance index into the logistic discriminant function resulted in 5 to 13 percent higher mapping accuracies than the use of either variable individually. The TM thermal band was correlated with equivalent latitude and resulted in an 8 percent higher overall classification accuracy than equivalent latitude. The combination of TM thermal data and the TM-derived vegetation map provided an overall permafrost classification accuracy slightly higher than the combination of equivalent latitude and the TM-derived vegetation map.

Ideally, the most reliable way to verify the permafrost classifications would be to compare each to a direct determination of permafrost status, i.e., a set of ground temperatures acquired deep enough to be below the active layer and with enough temperature readings throughout the seasonal cycle to obtain average temperatures for each site. Barring an extensive and expensive drilling and thermistor monitoring program, the method used to prepare the photo-interpreted permafrost map represents the state-of-the-art as used for major engineering projects in Alaska. Given the high degree of correspondence between the photo-interpreted permafrost map and the TM-derived permafrost classification, this model has promise for mapping permafrost distribution within the Yukon-Tanana physiographic province. One complicating factor, not encountered in the present study but occurring throughout the Yukon-Tanana physiographic province, involves recently burned areas where soil temperatures and related site conditions may change dramatically. As vegetation communities and topography become increasingly different from those in the Caribou-Poker Creeks watershed, modification of the model will be required.

Application of this technique to other regions would require the development of logistic coefficients based on the incorporation of appropriate environmental data. For instance, equivalent latitude would have little value for predicting permafrost distribution in a flat, lowland region, whereas soil moisture or some other factor may be of more value. The ability to predict permafrost distribution through the analysis of environmental variables derived from satellite data requires an understanding of the relationships among permafrost, terrain, and vegetation unique to each region. Further evaluation of this technique, in particular its extension to other regions, is required to establish its limitations and the scope of its application.

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ERRATUM

Plate 2 on page 510 of the article, "Orthographic Terrain Views Using Data Derived from Digital Elevation Models," in the April 1986 issue of *PE&RS* was inadvertently rotated 180 degrees so that the top edge is at the bottom.