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A Neural Network Method to Determine the Presence or Absence of Permafrost near Mayo, Yukon Territory, Canada

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ABSTRACT

A neural network was used to predict the presence or absence of the permafrost table within 1.5 m below the ground surface, over two study areas near Mayo, Yukon Territory. Input sources used in neural network classifications included land cover (derived from Landsat Thematic Mapper (TM) imagery), equivalent latitude, aspect, and TM band 6 (thermal infrared imagery). For the first study area, maximum median agreement between predicted and field-measured permafrost-table conditions, produced using land cover and equivalent latitude data as input to the neural network, was over 90%. The agreement percentage produced by classification of the second study area, using land cover and equivalent latitude, and using correlative permafrost–surface relations from the first study area, was 60%. Training data, the portability of which is critical in region-wide predictions of active-layer conditions, cannot be transferred between the two study areas examined here. © 1997 by John Wiley & Sons, Ltd.

RÉSUMÉ

Un réseau neural a été utilisé pour prédire la présence ou l'absence d'une table de pergélisol dans le 1,5 m qui se trouve sous la surface du sol dans deux sites étudiés près de Mayo, dans le Yukon. Les données introduites dans le réseau comprennent la couverture du sol (d'après un image Landsat TM), la latitude équivalente, l'aspect et l'image thermique infra-rouge (TM bande 6). Pour la première région étudiée, l'accord maximum médian entre les conditions prédites par le modèle et les conditions mesurées sur le terrain en utilisant seulement la couverture du sol et la latitude équivalente a été supérieure à 90%.

Le pourcentage de concordance résultant de l'utilisation des mêmes données dans le second site en utilisant les relations utilisées dans le premier site, n'a été que de 60%. Les relations obtenues en un endroit pour prédire les conditions de la couche active ne sont donc pas transférables entre les deux régions qui ont été considérées ici. © 1997 by John Wiley & Sons, Ltd.

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KEY WORDS: discontinuous permafrost; neural network; remote sensing

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INTRODUCTION

The spatial distribution of near-surface permafrost in Canada's north is of interest for economic and scientific reasons. Permafrost conditions often determine the suitability of land for development, so the creation of regional databases of permafrost information would be useful for the development and management of northern areas. In addition, because permafrost distribution is a function of climate, accurate monitoring and mapping of near-surface permafrost parameters may help support investigation of long-term changes in the earth's climate.

This research used known correlative relations between surface properties and permafrost to determine effective combinations of data sources for the prediction of the presence or absence of the permafrost table within 1.5 m of the ground surface, over two study areas, using a neural network. The potential application of the neural network toward a regional mapping exercise is examined here in a preliminary manner by looking at the portability of permafrost–surface relations from one study area to another.

BACKGROUND

Permafrost is soil or rock that has remained cryotic (at or below 0 °C) for a minimum of two years, and the permafrost table is the upper boundary of permafrost (ACGR, 1988). The active layer is the layer of ground in areas underlain by permafrost that is subject to annual freezing and thawing (ACGR, 1988). By strict use of these definitions, some thaw is possible within upper levels of permafrost, since melting points are normally depressed very slightly below 0 °C (Williams and Smith, 1989). In this research, depth to the frost table (measured *in situ* in late summer) was used as an approximation for depth to the permafrost table.

Climate is the dominant factor influencing the continental distribution of permafrost, generally resulting in an increase in permafrost occurrence and thickness with increasing latitude. In areas where permafrost occurrence is discontinuous, the distribution of permafrost is strongly influenced by local factors such as slope, aspect, hydrology, vegetation, geology, and snow cover (Mollard, 1960; Ferrians and Hobson, 1973; Smith, 1975; Hall and Martinec, 1985; Williams and Smith, 1989; Williams and Burn, 1996).

Approximately 50% of Canada is underlain by permafrost (ACGR, 1988). Extensive ground surveys of permafrost conditions are precluded owing to expense, logistical difficulties, short field seasons, and time constraints (Rinker and Frost, 1969; Ferrians and Hobson, 1973; Morrissey, 1983). Many numerical models of permafrost distribution (e.g. Nelson and Outcalt, 1987) make broad generalizations and assumptions concerning ground and climate properties and conditions, and are applicable to continental scales. Other, more complex models of the ground thermal regime (e.g. Smith, 1977) are applicable at local scales.

Models able to correlate remotely sensed surface characteristics with near-surface permafrost conditions could provide high-resolution permafrost information over broad areas. If successfully applied, the remote-sensing process would be more practical than complete ground surveys, operate at a much higher resolution than climate-based permafrost models, and provide additional environmental information beyond that directly related to permafrost distribution.

Permafrost conditions cannot be directly imaged using optical airborne or satellite-based sensors. Therefore when applying correlative models, all permafrost information must be indirectly derived from other related geophysical or surface factors that are detectable using remote-sensing techniques. The derivation of near-surface permafrost conditions in the discontinuous permafrost zone is facilitated by the association between near-surface permafrost conditions and surface properties related to microclimate (Tarnocai and Thie, 1974; Morrissey, 1984; Hall and Martinec, 1985).

Aerial photography can be used to obtain general information about near-surface permafrost conditions. The inference of permafrost conditions can be made through the process of correlative pattern element analysis, in which landscape elements such as landforms, drainage, erosion, vegetation, tone, and special features are closely examined (Mollard, 1960; Frost, 1963). Unfortunately, mapping permafrost conditions over large areas using aerial photographs can be tedious and labour-intensive.

Although commercial satellite imagery does not yet have the spatial resolution of aerial photographs, the multispectral and digital nature of the imagery makes it potentially useful in the prediction of generalized near-surface permafrost conditions over large areas. Databases of georeferenced imagery from various sensors and platforms can be readily assembled and mathematically analysed, producing useful environmental information that itself can be used for further scientific inquiry, for decision making, or simply for mapping. The correlative techniques involved in the remote-sensing-based classification of near-surface permafrost conditions are quantitative (as opposed to the methods using aerial photography, for example), and thus can be applied in a more controlled and reproducible manner.

Two recent efforts to use modern satellite remote-sensing technology in the prediction of generalized near-surface frozen ground conditions are those of Morrissey *et al.* (1986) and Peddle and Franklin (1993). Morrissey *et al.* (1986) prepared maps of near-surface permafrost conditions in a 106 km^2 area in Alaska by submitting equivalent latitude, vegetation cover, and Landsat TM thermal imagery to logistic discriminant functions. Unfortunately, the classes predicted by Morrissey *et al.* (1986) are not particularly useful, comprising (percentage of area underlain by permafrost) '95–100% frozen, 6–94% frozen, and 0–5% frozen'. Peddle and Franklin (1993) attempted to predict four active-layer classes within a 100 km^2 study site in the Ruby Range, YT, based on the submission of land cover (derived from SPOT multispectral imagery), terrain aspect, and equivalent latitude to an evidential reasoning classifier. Unfortunately, the fieldwork of Peddle and Franklin (1993) was executed in early summer (Peddle, 1991), prior to the main thaw season, and thus the field measurements do not represent active-layer thicknesses. Furthermore, gathering of field data in the study was restricted to those regions of the study area that could be surveyed with a steel probe, narrowing the geographic scope of the study, and thus precluding the generation of an active-layer map of the study area.

The results presented in this paper are derived from an extensive late-summer field survey of a primary study area, and an additional late-summer field survey of a second study area. A commercially available neural network classifier was used to predict the presence or absence of near-surface permafrost in both study areas. A preliminary examination of the portability of permafrost–surface relations was made.

STUDY AREAS

The two study areas used in this research are both near Mayo, Yukon Territory. Mayo is in the zone of widespread discontinuous permafrost and the Boreal Northern Cordilleran Ecoclimatic Region (Ecoregions Working Group, 1989). The mean annual air temperature at Mayo is −4 °C, mean annual rainfall is 185 mm, and mean annual snowfall is 131 cm (Wahl *et al.*, 1987). Figure 1 is a map indicating the location of the two study areas.

Both study areas are part of the Selwyn Fold Belt of the Cordilleran Orogen. The study areas are underlain by quartzite, argillite, shale, and phyllite (Bostock, 1946; Gabrielse *et al.*, 1980). Quaternary sediments blanket much of the Stewart River valley, and bedrock exposures are found only on steep slopes.

Regional topographic effects associated with the mountains of the western Cordillera maintain the severe winter temperatures and low winter snowfall that favour permafrost conditions in the valleys of southern and central Yukon and the upper Mackenzie District (Burn, 1994). In central Yukon, permafrost is often found on north-facing slopes vegetated by spruce trees and extensive moss cover, whereas south-facing slopes are usually not associated with permafrost and are commonly vegetated by deciduous trees or mixed forests (Brown, 1967). Permafrost is extensive in valleys of central Yukon where permafrost thicknesses can range between 30 and 40 m in areas where Holocene surface erosion has not occurred (Burn, 1991).

Burn (1991) found permafrost thickness in alluvial sediments near Mayo to be 20 m, while thickness near the Mayo Group Home, east of Mayo, is 37 m. Active-layer thicknesses measured at permafrost-underlain forest sites located ~3 km south-east of Mayo in glaciolacustrine silty clay typically range from 35 cm to ~100 cm (Burn and Friele, 1989). A quantitative analysis of the relation between surficial characteristics and the occurrence of permafrost in the Mayo region is given by Williams and Burn (1996).

Study Area 1

The primary study area is ~18 by 18 km in dimension (Figure 1). It is bounded along its northern and southern limits by east–west oriented hills. These hills enclose the Stewart River which runs westward across the study area. Elevations range from ~500 m ASL in the Stewart River valley to ~1200 m ASL at the hills to the north. The study area is within the limits of the Reid and McConnell Glaciations (Bostock, 1966; Hughes,

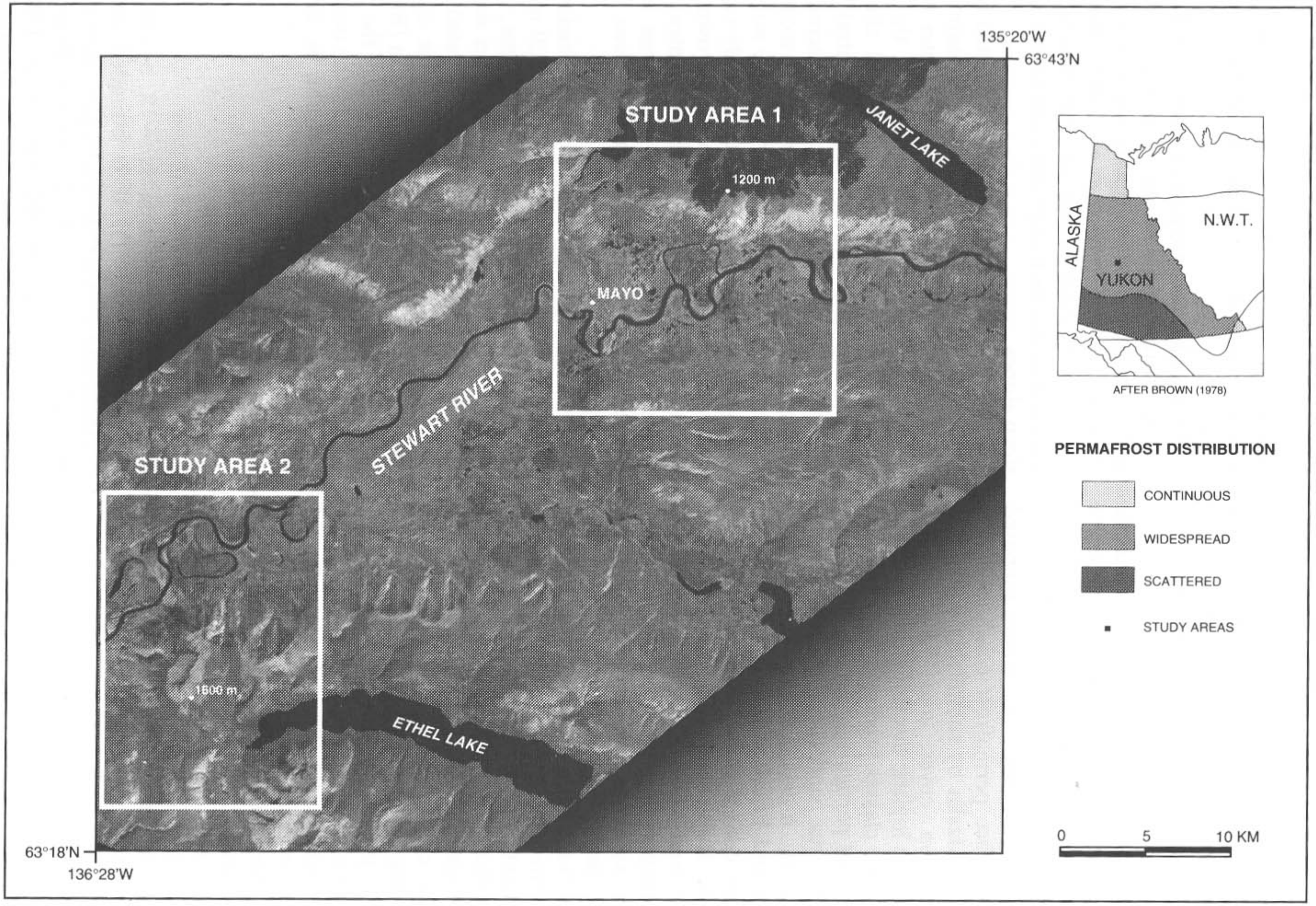

Figure 1 Study area boundaries overlain on Landsat TM band 4 imagery. Black features are water bodies. The dark grey region in the north represents the extent of a recent forest fire. Vegetation is generally depicted through a gradation from darker shades (coniferous stands) to lighter shades (mixed and deciduous stands, and clearings). UTM projection.

1983). Valley deposits are primarily alluvial and glaciolacustrine in origin, while hillside deposits are primarily colluvial and morainic (Hughes, 1983).

The forest vegetation of study area 1 is characteristic of much of the Mayo region. The study area's coniferous forests are composed of both black spruce (*Picea mariana*) and white spruce (*Picea glauca*). Deciduous stands are composed primarily of the following three species: balsam poplar (*Populus basamifera*), trembling aspen (*Populus tremuloides*), and paper birch (*Betula papyrifera*). Willows (*Salix* spp.) tend to dominate especially wet and poorly drained zones in the study area.

Study Area 2

The secondary study area is ~13 by 20 km in dimension, and its eastern boundary is 15 km west of study area 1 (Figure 1). The Stewart River meanders in a south-west direction across the northern half of the study area, while hills characterize the southern half. Elevations range from ~500 m ASL in the Stewart River valley to ~1600 m in the hills to the south. Tundra conditions occur near the peaks of several hills. Although within the limits of the Reid Glaciation, the study area is outside the limits of the more recent McConnell Glaciation (Bostock, 1966). Near-surface valley deposits consist primarily of loose alluvial sands, while hillside materials are colluvium and exposed bedrock.

All tree species of study area 1 are found in study area 2. White spruce (*Picea glauca*) represents a greater proportion of the study area's coniferous stands as compared with study area 1. Small numbers of lodgepole pine (*Pinus contorta*) may be found scattered throughout the study area, particularly in the southern half.

Study area 2 was selected as a supplemental area for testing the utility of the transfer of permafrost–surface relations from one study area to another. This testing was intended to be a first step in the determination of the portability of training data to proximal regions within central Yukon.

DATA COLLECTION

Field Observations

Between 19 July and 29 August 1994, 325 field sites were visited in study area 1, and 100 field sites were visited in study area 2. Virtually no sites underlain by a shallow permafrost table were sampled prior to early August, and thus the effects of premature measurement of depth to the frost table were reduced. All sites used in the study have generally uniform slope, aspect, and vegetation cover at scales of at least ~50 × 50 m. An additional 35 field sites with known thawed conditions within 1.5 m of ground surface were added to the site pool of study area 1 after the field season to ensure complete coverage of all otherwise unrepresented land cover types in the study area's field data set; the addition of these sites allowed concrete, sand pit, and beach sand covers to be included in the study. Thus, a total of 360 sites in study area 1 and 100 sites in study area 2 were available.

At each site, a pit was dug to the frost table (to a maximum of 1.5 m depth). Depths measured from ground surface to the frost table were used as approximations of depths to the permafrost table. At sites where a steel probe could easily penetrate upper surface deposits, i.e. at those sites not shallowly underlain by pebble-, cobble-, or boulder-sized sediments, pit-measured values were supplemented with 12 steel-probe measurements (three spaced at 5 m intervals, for each of the four cardinal compass directions). Each site was assigned a single permafrost-table depth, based upon a non-weighted average of all available values for that site. Permafrost-table depths at a given site were commonly found to cluster around a small range of values, with occasional outliers (Leverington, 1995). Those sites where the permafrost table was not found within 1.5 m of ground surface were given a best-estimate label of '>1.5 m depth, or absent'.

Since all depth measurements were made with reference to at least one hand-dug pit, it was possible to sample all settings (short of bedrock exposures, which are not common in the immediate Mayo region) within the two study areas. A study based solely on steel-probe measurements would have restricted the scope of this study to those areas underlain in the near surface by sediment layers easily penetrated by a probe.

Satellite Imagery

Landsat Thematic Mapper (TM) imagery, whose good spectral resolution is ideal for the discrimination of land cover, was used in this study. The pixel size of this imagery is 30 m by 30 m. TM bands 3, 4, and 5 were used owing to their strong applicability toward the differentiation of vegetative communities and general land cover (Baubien, 1994), while TM band 6 was used owing to its past employment as a proxy for equivalent latitude (Morrissey *et al.*, 1986). TM bands, 3, 4, and 5 are reflectance bands corresponding to spectral ranges 0.63–0.69, 0.76–0.90, and 1.55–1.75 µm, respectively, while TM band 6 is a thermal band corresponding to the spectral range 10.4–12.5 µm. The imagery was geometrically corrected and georeferenced to the UTM projection. A land cover image was generated from TM bands 3, 4, and 5 using a maximum likelihood classification algorithm in conjunction with training sites derived from 1993 and 1994 fieldwork.

Topographic Data

The topography of each study area was digitized from 1:50,000 scale National Topographic Series maps (105 M/12 and 115 P/8) using ARC-INFO software. A digital elevation model (DEM) of each study area was generated from the digitized maps using ARC-TIN. Each DEM was transformed from triangulated irregular network (TIN) format to raster format, with 30 m pixels.

Images of slope and aspect for each study area were generated from the raster-format DEMs. Using these images of slope and aspect, equivalent latitude images were calculated based on the algorithm used by Morrissey *et al.* (1986). Equivalent latitude, a function of actual latitude, slope, and aspect, is a good relative estimation of maximum potential direct solar radiation.

NEURAL NETWORK

In the research presented here, classifications are based on a connectionist model which comprises one-way vectors joining nodes within a feed-forward, layered network. Individual nodes emulate biological neurons by taking input data and performing simple operations on the data, passing the results on to other nodes. Weight values are associated with each vector and node, and these values constrain how input data (e.g. land cover classes) are related to output data (e.g. permafrost classes). Weight values are determined by the iterative flow of training data through the network (i.e. weight values are established during a training phase in which the network *learns* how to identify particular classes by their typical input data characteristics). Once trained, the neural network examines the individual properties of each pixel within the area of interest. Classifications are performed by (1) the activation of network input nodes by relevant data sources, (2) the forward flow of these data through the network, and (3) the ultimate activation of the output nodes. The pattern of activation of the network's output nodes determines the outcome of each pixel's classification.

The neural network employed here is a back-propagation network that uses the generalized delta rule for learning (e.g. see McClelland and Rumelhart, 1988; Maren *et al.*, 1990). The software is commercially available from PCI Inc., and was run on an IBM RS-6000 workstation. Particularly useful technical descriptions of neural network principles are given by McClelland and Rumelhart (1986; 1988) Rich and Knight (1991), Anzai (1992), Luger and Stubblefield (1993), Gallant (1993) and Richards (1993).

EXPERIMENTAL DESIGN SUMMARY

The stages involved in this research are generalized as follows:

(1) Field measurements of depths to the frost table, within 1.5 m of ground surface, were made at sites within both study areas between 19 July and 29 August 1994.

(2) Based upon the field measurements, the permafrost table of each site was characterized as being either 'present' or 'absent' within 1.5 m of the ground surface. In study area 1, the 'presence class' comprises depth values that are mainly restricted between 40 and 75 cm, as inferred by Leverington (1995).

(3) The neural network was used to generate a series of permafrost classifications over study area 1. Each classification used a different combination of the following four sources of input data: (a) land cover (derived from TM bands 3, 4, 5), (b) aspect, (c) equivalent latitude, and (d) TM band 6. In each classification, 240 *training sites* were used to train the neural network, and the remaining 120 *test sites* were used to evaluate the utility of the source combination in predicting the presence or absence of permafrost. Because classification results can vary depending upon which sites are used as training or test sites, each source combination was evaluated ten times

using ten different randomly selected sets of training and test data.

(4) The best source combination of stage 3 was used to classify permafrost presence or absence over study area 2. All 360 sites in study area 1 were used as training sites, and all 100 sites in study area 2 were used as test sites. This stage was designed to determine the portability of class–source relations from study area 1 to study area 2.

The 'success' of each classification was assessed in terms of the agreement between the predicted permafrost-table classes and the field-measured classes. Assessment involved the determination of the percentage of test sites that were labelled correctly for each classification. Median agreement percentage and interquartile range were calculated for each source combination evaluated at stage 3.

RESULTS AND DISCUSSION

Study Area 1

Seven different source combinations were used in the classification of the presence or absence of the permafrost table within 1.5 m of the ground surface, in study area 1. For each of these seven combinations, ten classifications (using ten different randomly selected training- and test-site data sets) were performed. By repeating each classification ten times, median agreement percentages could be calculated. A conventional 120/240 (i.e. 1:2) ratio of test to training sites was employed in all tests. Median agreement values and percentiles calculated for each source combination are shown in Figure 2. Results are discussed below to two significant figures.

Aspect, equivalent latitude, TM band 6, and land cover were each used alone in four sets of classifications. Aspect was found to produce a median agreement of 54% between predicted and field-measured permafrost classes, while equivalent latitude produced a median agreement of 62%. The use of TM band 6 produced a median agreement of 60%. The use of land cover as a sole classification source produced a somewhat higher classification 'success' than the other three sources, with a median agreement of 83%. Interquartile ranges associated with these median agreement percentages range from 2.9 (land cover alone) to 9.6 (aspect alone) (see Figure 2).

The combination of land cover with TM band 6 produced a median agreement of 83%. Land cover and equivalent latitude, in contrast, were found to be useful complementary sources, with an associated median agreement percentage of 91%. The addition of aspect to the above combination did not increase median agreement beyond this value. The use of TM band 6 as a proxy for equivalent latitude did not aid in classification success, with median agreement dropping from 91% (combination of land cover and equivalent latitude) to 83% (combination of land cover and TM band 6), despite the roughly equal agreement rates produced

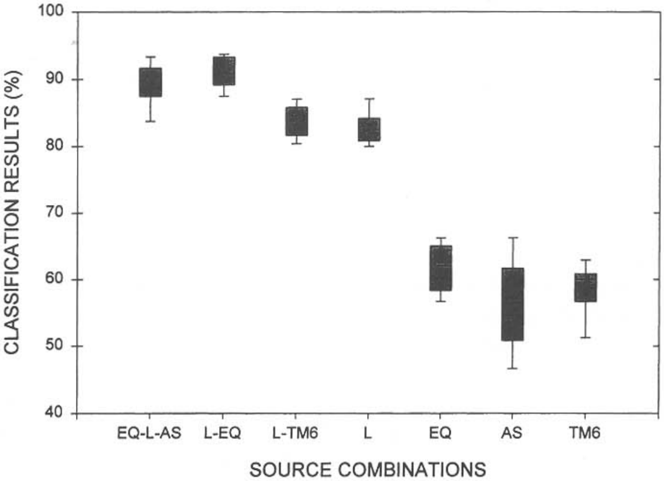

Figure 2 Agreement values associated with each source combination, for study area 1. Whiskers depict 10th and 90th percentiles, while boxes depict 25th and 75th percentiles. Median values are depicted by lines across the boxes. Labels: EQ, equivalent latitude; L, land cover; AS, aspect; TM6, thermal imagery.

through the use of each of these two sources alone. These results do not support those of Morrissey *et al.* (1986), in which TM band 6 was found to be useful in classifications as a proxy for equivalent latitude. Interquartile ranges associated with these median agreement percentages range from 3.3 (combination of land cover and TM band 6) to 4.0 (combination of land cover and equivalent latitude). A map portraying the distribution of the presence or absence of the near-surface permafrost table in study area 1 is given in Figure 3.

Study Area 2

The portability of training data from study area 1 to study area 2 was tested to quantitatively evaluate in a preliminary manner the consequences of mapping a study area without a local field survey. A single test was run using the best source combination of study area 1 (combination of land cover and equivalent latitude) to predict two permafrost-table classes in study area 2. All 360 sites from study area 1 were used as training sites, and all 100 sites from study area 2 were used as test sites.

The classification of study area 2 using the land cover and equivalent latitude sources produced 60% agreement between predicted and field-measured classes. The interquartile range associated with this result could not be calculated, given that all sites in both study areas were used, eliminating the possibility for multiple classifications with different training and test databases. Nevertheless, given the low interquartile values associated with results in study area 1, it would be quite unlikely that there is not a statistically significant drop in agreement percentages (from a median percentage of 91% to a percentage of 60%) between the results of the two study areas. This suggests that, in the Mayo region, a correlative permafrost-table image generated with training sites located outside a study area cannot be assumed to be valid, even when the training sites are located only 10 or 20 kilometres outside the area of interest. The spatial variability of subsurface properties is certainly a major influence on the portability of training data between the neighbouring Mayo study areas. For example, the change in valley sediment size, from the fine alluvial and glaciolacustrine sediments in study area 1 to the coarse alluvial sands of study area 2, is believed to be a key factor behind the difference in permafrost–surface relations between the two study areas.

It is not suggested here that correlative relations can *never* be validly extrapolated to outside areas. Rather, it is stressed that one cannot assume such an extrapolation to be valid without field investigation and extra classification tests (thereby possibly eliminating the advantages of attempting to extrapolate relations in the first place). This classification result for study area 2 suggests that correlative near-surface permafrost maps of large regions (e.g. central Yukon) should not be generated based solely on the extrapolation of the results of relatively small field efforts. Instead, a large field effort would be required for such an exercise, since all subregions of interest would require *in situ* fieldwork. The financial costs of this exercise could be prohibitive, far outweighing the amount of useful data produced.

The Utility of Near-Surface Permafrost Imagery

The digital map of the permafrost-table's near-surface presence/absence at study area 1 (Figure 3) is useful for visualizing the general geographic extent of shallow permafrost conditions in the area. In addition, such a digital map could itself be potentially useful as a realistic database in the study or simulation of near-surface hydrology, for example. Ideally, the procedures used in this research would also be applicable toward differentiating between numerous active-layer classes in an area; this could not be tested here, owing to the widespread dominance of a relatively shallow permafrost table at those sites where near-surface permafrost is present.

SUMMARY AND CONCLUSIONS

The prediction of the presence or absence of the permafrost table within 1.5 m of ground surface using a neural network has been shown to be possible in study area 1. The highest median agreement percentage between predicted and field-measured permafrost-table classes is 91%, produced using equivalent latitude and TM-derived land cover. The agreement results of the ten classifications used to produce this median result are characterized by an interquartile range of 4.0. TM band 6 was not found to be a useful proxy for equivalent latitude in this study, with the combination of land cover and TM band 6 producing a median agreement percentage of 83%, essentially equal to that produced by land cover alone.

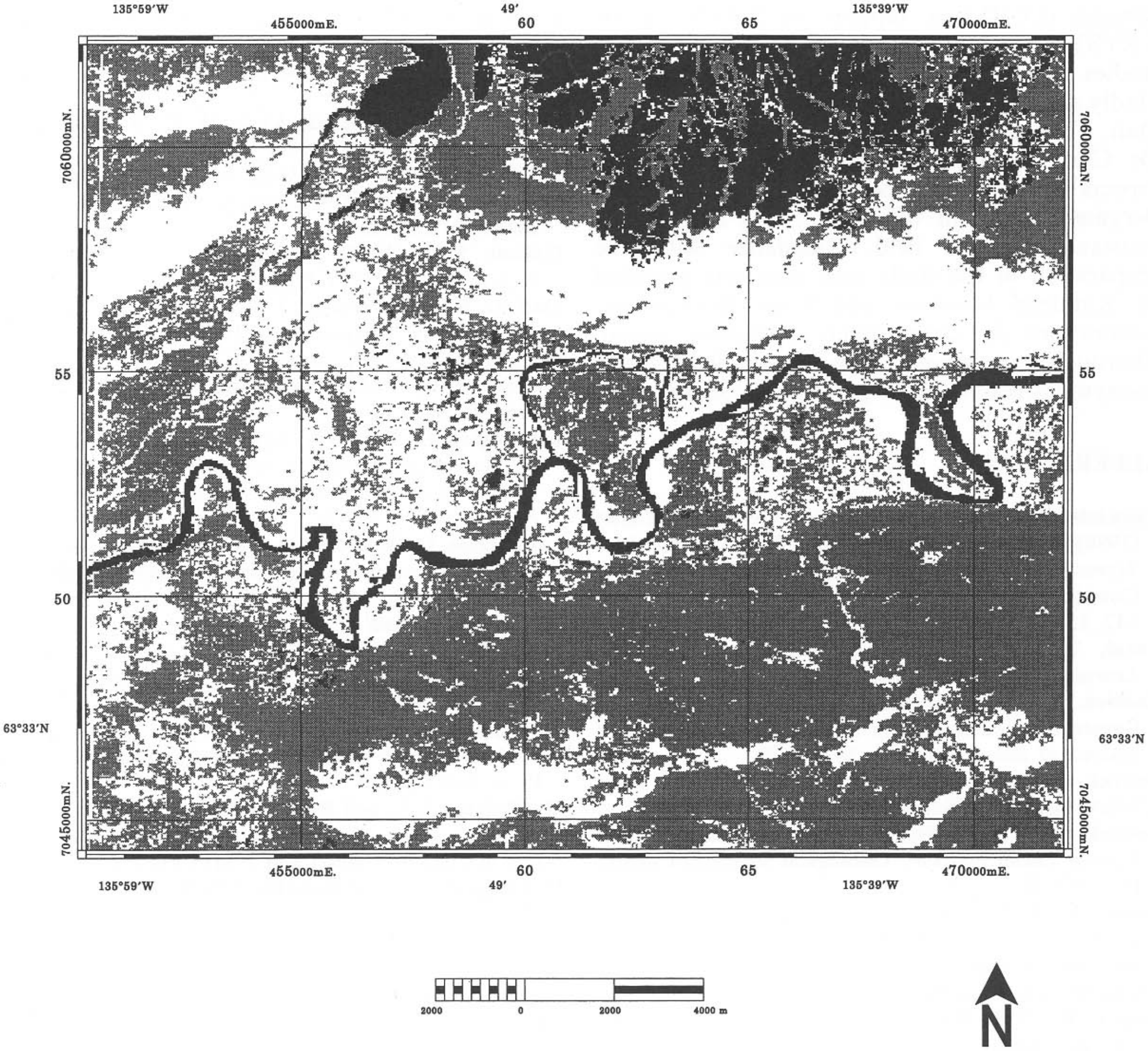

Figure 3 Near-surface presence/absence of the permafrost table in study area 1. The two darkest shades represent water bodies (black) and recently burned areas (dark grey), while the two lighter shades represent areas with (medium grey) and without (white) a permafrost table within 1.5 m of ground surface. The agreement rate of this image, based on comparison with 120 test sites, is 94%. UTM projection.

Classification of all sites at study area 2 using the correlative relations of study area 1 produced an agreement percentage of only 60%. Based on this result, it may be concluded that the correlative relations between surface cover and permafrost table at study area 1 cannot be extended to study area 2. This suggests that the valid portability of permafrost–surface relations should not be assumed in future regional correlative studies, and that *in situ* reconnaissance of any study area of interest is mandatory in the correlative generation of any meaningful permafrost database.

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