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Estimating the Extent of Near-surface Permafrost using Remote Sensing, Mackenzie Delta, Northwest Territories

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ABSTRACT

The extent of near-surface permafrost, or perennially frozen ground within 3 m of the surface, was estimated for the Mackenzie River delta by determining its association with riparian vegetation communities in the field, and by subsequently mapping these vegetation communities using SPOT-5 data and the supervised maximum-likelihood classification technique. Near-surface permafrost was absent beneath willow–horsetail (*Salix-Equisetum*) vegetation communities on point bars and alluvial islands throughout the delta and beneath horsetail (*Equisetum*) communities in the southern and central delta. Near-surface permafrost was found beneath all other vegetation communities and land surface types. Multispectral SPOT-5 data were classified with overall accuracies greater than 80 per cent. Using the remotely sensed vegetation community data, near-surface permafrost was estimated to occur beneath 93 per cent, 95 per cent and 96 per cent of the land surface within the investigation areas of the southern, central and northern delta, respectively. In contrast to the most recent *Permafrost Map of Canada*, these results indicate that the Mackenzie Delta is part of the continuous permafrost zone. Copyright © 2009 Her Majesty the Queen in right of Canada. Published by John Wiley & Sons, Ltd.

KEY WORDS: Mackenzie Delta; permafrost classification; remote sensing; vegetation mapping

INTRODUCTION

This paper investigates the proportion of the Mackenzie Delta underlain by near-surface permafrost (NSP), or permafrost within 3 m of the ground surface (Figure 1). Climatically, permafrost should be continuous in the Mackenzie Delta, and underlie more than 90 per cent of the land surface (Brown, 1967; Henry and Smith, 2001), but the most recent map of permafrost in Canada, using sparse ground temperature data, classifies the delta as discontinuous permafrost (Heginbottom *et al*., 1995). Lakes and channels are abundant in the delta, and as a result, ground temperatures and permafrost distribution at depth differ from conditions near the surface due to contributions to the temperature field from the warm temperatures beneath water bodies (Kanigan *et al*., 2008).

NSP is a key component of northern environmental systems because it influences terrain stability and surface hydrology (Carey and Woo, 1999; Lewkowicz and Harris, 2005). Its distribution is an important consideration for economic development in northern regions, because of its significance for the long-term integrity of infrastructure (Smith *et al*., 2001). The extent of NSP in the delta has not been field verified,

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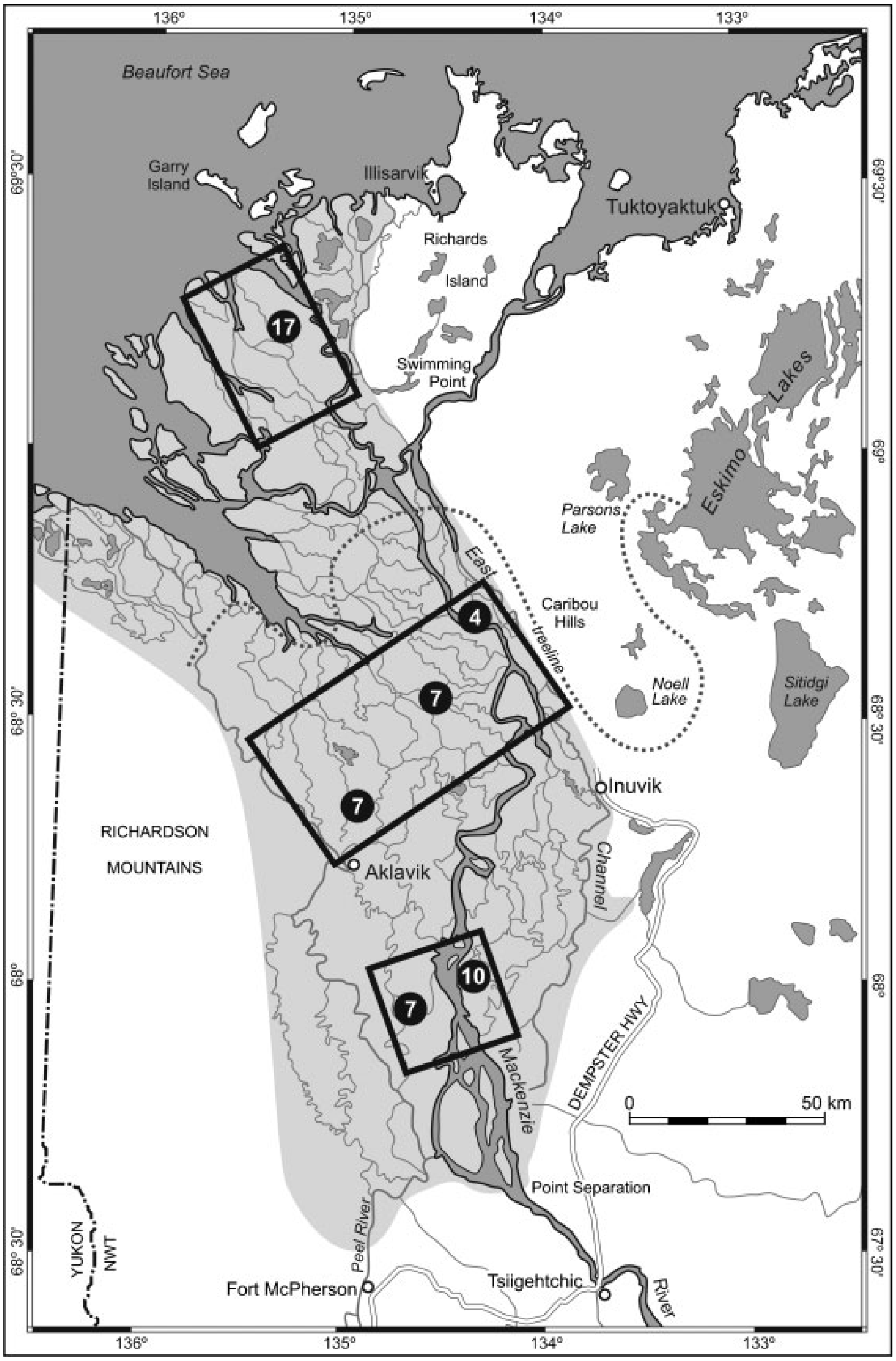

Figure 1 The Mackenzie Delta area. Permafrost in the delta is classified as discontinuous permafrost, whereas the uplands surrounding the delta are in the continuous permafrost zone (Heginbottom *et al*., 1995). Field investigations were clustered in six areas with the number of sites studied in each area appearing inside the circles. The extent of the satellite images is indicated by the rectangles. Treeline is indicated by a dotted line.

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although such verification is essential since the climate is warming rapidly in the area (Smith *et al*., 2005; Pisaric *et al.*, 2007), and the impact of such warming on terrain stability must be understood, given the proposed industrial development in the region (Imperial Oil, 2004).

The extent of NSP in the Mackenzie Delta was calculated: (1) using field associations of vegetation communities with permafrost to determine if the spatial distribution of vegetation could be used to predict the presence of NSP; and (2) applying remote sensing techniques to map these vegetation communities, and thereby estimate the proportion of ground underlain by NSP.

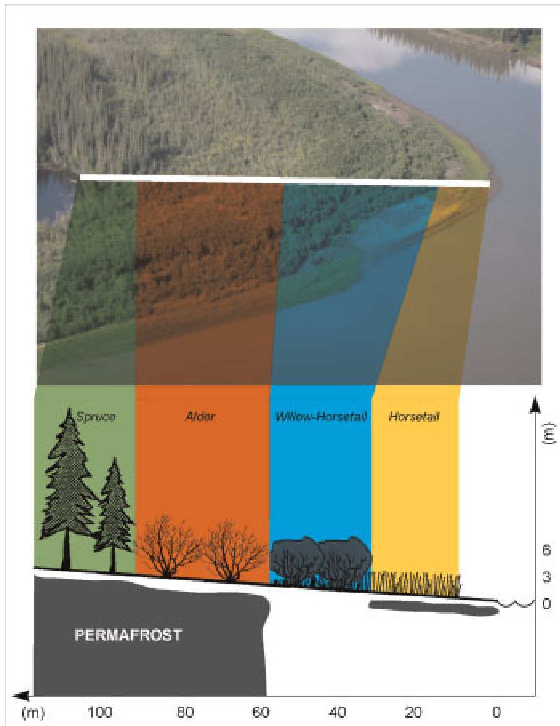

Figure 2 Plant succession on point bars south of the treeline. The photograph was taken on 20 August 2006 at a site in the southern delta. The talik near the river is due to slow thermal recovery of the ground following channel migration, combined with insulating effects of deep snow blown off the channel and trapped in willow stands. Frozen layers of less than 1 m underlie the horsetail communities due to low mean annual surface temperatures (Smith, 1975).

VEGETATION AND PERMAFROST DISTRIBUTION IN MACKENZIE DELTA

The Mackenzie Delta is a low-lying alluvial plain containing a myriad of channels and thousands of lakes, and is distinct from surrounding regions as it is flooded annually (Burn, 1995). The delta extends about 200 km north from Point Separation to the southeastern Beaufort Sea coast, with an average width of approximately 60 km (Figure 1). It is usually divided into three regions, corresponding with two major drops in levee height: the upper, or southern, delta with levees >7 m a.s.l., the middle, or central, delta with levees between 4 m and 7 m a.s.l. and the outer, or lower, northern delta with levees <4 m a.s.l. (Mackay, 1963). Spatial variation in channel shifting, flooding and sedimentation is indicated by the patterns of vegetation developed on terrestrial surfaces (Gill, 1973). There are three general ecological zones in the delta (Mackay, 1963): (1) the spruce (*Picea glauca*) forests of the southern delta; (2) the forest to tundra transition in the central delta, where the coverage of spruce forest is reduced and shrub species such as willows (*Salix alaxensis, S. pulchra*) and alder (*Alnus crispa*) are widespread; and (3) the tundra of shrubs and herbs, dominantly willow (*S. alaxensis, S. pulchra, S. richardsonii*) and sedge (*Carex aquatilis*) species, in the northern delta (Figure 1).

At a local scale, horsetail (*Equisetum arvense, E. fluviatile*) communities, which can tolerate a high flooding and sedimentation rate, are the typical emergent plant communities on aggrading point bars (Figures 2 and 3a), whereas willow–horsetail communities are found at greater distances from stream channels (Figure 3b). Alder communities occur at slightly higher elevations than the willow–horsetail communities, since alder species are less tolerant of sedimentation (Figure 3c) (Pearce, 1986). Spruce forests represent the climax community in the central and southern delta (Figure 3d). North of treeline, land surfaces are flooded annually due to the low elevation of levees, and vegetation communities are adapted to these conditions. Sedges and horsetails are common adjacent to channels, and willow-horsetail and other low willow (*S. richardsonii*) communities are widespread at more elevated sites (Figure 3e and 3f) (Pearce, 1998).

Climate is the main factor determining the continental distribution of permafrost, and the extent of permafrost in the landscape typically increases with latitude (Zhang *et al*., 1999). However, site-specific factors, such as snow, vegetation, hydrology, and topography interact to buffer the effects of climate on the ground thermal regime at individual sites (Smith,

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Figure 3 Vegetation communities in the delta: (a) horsetail; (b) willow-horsetail; (c) alder; (d) spruce; (e) sedge; and (f) *Salix richardsonii*. Spruce forests are absent in the northern delta.

1975). In the Mackenzie Delta, the thermal effect of water bodies and the shifting nature of channels affect the age, distribution, temperature and thickness of permafrost (Smith, 1976).

Channel migration exposes unfrozen sediments, previously beneath water, to freezing conditions, leading to ground cooling and the growth of permafrost (Smith, 1975). In the Mackenzie Delta, taliks occur in aggrading point bars due to deep drifts of snow blown off channels and trapped by riparian willow communities (Gill, 1973; Smith, 1975; Dyke, 2000). These snow drifts retard heat loss from the ground and raise mean ground temperatures so that permafrost is not sustainable (Smith, 1975). Further away from channels, the land surface is older, the forest is developed and there is less snow accumulation, so the degree of thermal recovery is more advanced and permafrost is thicker. The absence of NSP beneath exposed ground in the delta is therefore a transient condition as the ground thermal regime adjusts to emergence from the channel and vegetation succession occurs. Taliks have not been reported beneath land surface types other than point bars and alluvial islands (Gill, 1973). A spatial correlation between willow-horsetail communities and the absence of NSP was established for a few sites in the central delta by Gill (1973) and Smith (1975).

REMOTE SENSING BACKGROUND

Remote sensing can provide land cover information over vast areas and is more practical than a full ground survey for spatially extensive mapping. In addition to spectral data produced directly by the remote sensors, data transformations via vegetation indices, texture analysis and principal component analysis (PCA) are commonly used to generate additional image information for classification.

Vegetation indices may be correlated with plant biophysical characteristics in a range of ecosystems (Laidler and Treitz, 2003). The most widely used of these indices is the Normalised Difference Vegetation Index (NDVI). NDVI is useful because it normalises the difference between maximum vegetation absorption within the red wavelengths and peak reflectance in the near-infrared (NIR). NDVI has been found to be sensitive to variations in soil reflectance in canopies of less than 100 per cent cover and, therefore, modified indices such as the Modified Soil Adjusted Vegetation Index (MSAVI) have been developed (Bannari *et al*., 1995). NDVI and MSAVI are useful for tundra and riparian vegetation mapping (Laidler and Treitz, 2003; Johansen and Phinn, 2006).

With fine spatial resolution data from satellites such as SPOT-5 and IKONOS, shadows resulting from topography and vegetation stand structures and the wide spectral variation within land-cover classes may produce significant overlap in spectral data distributions. Use of texture information can reduce this problem (Lu and Weng, 2007). Image texture is the spatial variation in tone around a given point and is a measure of the overall visual 'smoothness' or 'coarseness'. The main approach used in texture analysis is statistical, based on the grey level co-occurrence matrix (GLCM) (Jensen, 1996).

Permafrost cannot presently be directly imaged by airborne or satellite-based sensors, but its presence may be inferred using surrogate surface characteristics, especially vegetation (Duguay *et al*., 2005). However, in some regions variations in subsurface properties may prevent permafrost mapping from remotely sensed imagery (Leverington and Duguay, 1997). In the Mackenzie Delta, subsurface materials are relatively consistent, so ground temperatures may be assumed to correspond with specific vegetation communities (Johnston and Brown, 1965; Kokelj *et al*., 2007; Kanigan *et al*., in press). In this paper, relations between vegetation characteristics and NSP at various sites throughout the delta are reported, based on field surveys. In addition, remotely sensed images of the delta are interpreted in terms of these relations to estimate the proportion of ground underlain by NSP (Figure 1).

METHODS

Field Site Selection

Aerial colour photographs from 2004 and a Landsat 7 ETM+ satellite image from 1999 were used to select field sites. Sites that were chosen had several representative vegetation communities and spectral classes, and were accessible by boat. Because the sites were not selected randomly, a minimum distance of 1 km was maintained between them, to reduce the potential for spatial autocorrelation.

Vegetation and Permafrost Sampling

Field surveys were conducted from late June to late August 2006. Given the typically muddy and bushy terrain, a line transect methodology was adopted for efficient vegetation sampling and permafrost probing at each site. A total of 52 transects were laid out on point bars and alluvial islands, perpendicular to the shoreline and crossing the successional sequence of vegetation (Figure 4). Transects were divided roughly equally between the three delta regions, and the majority of transects were between 100 m and 200 m long depending on the width of the different vegetation communities. Vegetation sampling was conducted within generally uniform vegetation-cover plots, 20 x 20 m in size, along the central axes of each plot parallel and perpendicular to the channel as denoted by the cross in each plot in Figure 4. The large plot dimension was necessary for accurate location of the selected areas on satellite images which are typically georeferenced with registration errors on the order of half to one pixel (McCoy, 2005). The objective of the vegetation survey was to identify the physiognomic mixtures that could be determined by satellite. Vegetation was sampled using line intercept

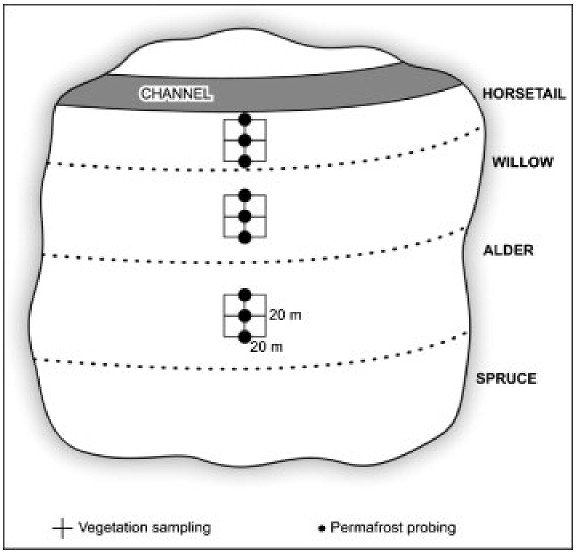

Figure 4 Near-surface permafrost was probed by water-jet drill, and vegetation was sampled in 20 m × 20 m plots along linear transects perpendicular to shorelines across several vegetation communities.

methods and was identified at the genus level for shrubs and trees, and at the functional-type level for herbs. Plant presence and frequency were recorded to provide an indication of how dominant a plant type was in a community (McCoy, 2005).

The ground was probed by water-jet drill to detect NSP in each vegetation community. Water-jet drilling was used successfully, with an estimated accuracy of 10 cm, to determine the depth to permafrost in the floor of a retrogressive thaw slump near Mayo, Yukon Territory (Burn, 2000). Given that the active-layer thickness rarely exceeds 1.5 m in the delta, NSP was considered absent if unfrozen ground was recorded to 3-m depth (Kokelj and Burn, 2005). Thin frozen layers found within 3 m of the ground surface but that did not extend deeper than 3 m were not considered as NSP. By selecting 3 m as the drilling depth, it was also possible to distinguish NSP from seasonal frost since the delta is a warm permafrost environment and seasonal frost cannot be found past the 3-m depth (Kokelj and Burn, 2005; Kanigan *et al*., 2008). In each plot, the water-jet hole drilled at the centre was complemented with two others, spaced at 10 m from the central hole. Each plot was assigned a single NSP presence or absence label based on the rule of majority. No excavations were required to locate the frost table, since the alluvial sediments were well suited for water-jet drilling.

Remote Sensing Methods

SPOT-5 imagery was used to extrapolate the results of field surveys (Table 1). For regional-scale mapping, SPOT-5 provides an ideal balance between high spatial resolution and wide-area coverage (60 km × 60 km). SPOT-5 data have a nominal ground pixel size of 10 m × 10 m and five spectral bands: panchromatic (0.51–0.73 μm), green (0.50–0.59 μm), red (0.61–0.68 μm), NIR (0.76–0.90 μm) and mid-infrared (1.58–1.75 μm). Four scenes comprising four panchromatic and four multispectral images were acquired in July 2006: one for the southern delta, one for the northern delta and two overlapping scenes for the central delta. For the overlapping scenes, a mosaic was created. The satellite scenes covered approximately 37 per cent of the Mackenzie Delta surface area.

The image data analysis is summarised in Figure 5. A land/water mask, using NIR information, was created to exclude all water bodies from analysis. In addition to spectral data produced directly by SPOT-5, NDVI and MSAVI vegetation indices, texture analysis and PCA were also used for classification. GLCM-derived texture measures such as Homogeneity, Contrast, Dissimilarity, Entropy, Angular Second Moment and Correlation were applied. They have been used elsewhere with spectral information in the mapping of wetlands and riparian vegetation (Dillabaugh and King, 2008).

Training and testing data were generated from the 2 × 2 pixel windows at locations of vegetation sampling and permafrost probing. Training and testing data

Table 1 Areal extent of the SPOT-5 images in portions of the Mackenzie Delta, July 2006.

Delta region	Area (km^2)	Area of satellite image (km^2)	Proportion of delta (%)
South	3025	662	22
Central	6500	2800	43
North	2475	920	37
Whole delta	12000	4382	37

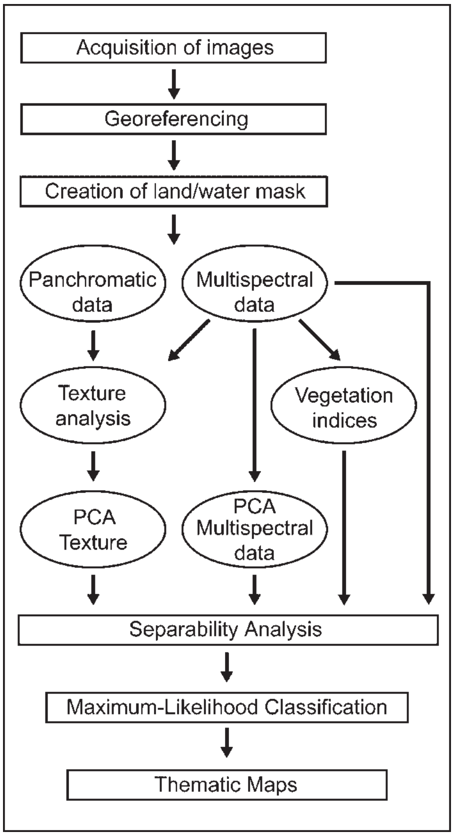

Figure 5 Image data analysis procedure. PCA = Principal component analysis.

were selected randomly from these plots. Separability analyses (SA) with the Bhattacharrya Distance, an index that accounts for class variance-covariance, were carried out to measure the statistical distinctiveness of each vegetation class. SA were used to determine the possible aggregations of the vegetation classes and the combinations of spectral bands, vegetation indices, textural data and principal components having the best potential to discriminate between these classes (Jensen, 1996).

Maximum likelihood (ML) classification was then used to generate maps of vegetation communities. The ML classification determines the probability distribution of the training data for each class and allocates each unknown pixel to the class in which it has the highest probability of belonging. ML generally gives better results than other parametric classifiers and is the most commonly used classifier for mapping riparian vegetation (Ozesmi and Bauer, 2002). Artificial neural networks and Linear Spectral Unmixing classification techniques were also evaluated and discussed in Nguyen (2007) but only the ML classification results are detailed in this paper since they were the most accurate.

Categorisation of permafrost zones only considers permafrost underlying exposed ground (Heginbottom, 2002). In the Mackenzie Delta it is important to define the boundary between water bodies and land because there is high seasonal variability in water levels (Marsh and Hey, 1989). Since the satellite images were acquired in July 2006 when the water level had fallen and stabilised following the spring flood, the shorelines in the imagery were taken as the water–land boundary. This ‘instantaneous shoreline’ (Boak and Turner, 2005) represents average conditions given that the water level of East Channel near Inuvik was recorded at 12.6 m a.s.l. in July 2006 with a median of 12.3 m and a mean of 12.5 m for the open water period of May to October 2006 (Environment Canada, 2008).

RESULTS AND ANALYSIS

Field Relations between Vegetation and Permafrost

In all three delta regions there was a clear association between the presence of permafrost in the upper 3 m at a site and the vegetation community (Table 2). Spruce

Table 2 Distribution of vegetation plots with and without near-surface permafrost (NSP) in the Mackenzie Delta. Frozen layers of less than 1-m thickness were found in less than 10 per cent of all drilled holes and were not considered as NSP.

	Plots with NSP	Plots without NSP
Southern delta		
Horsetail	0 (0%)	8 (100%)
Willow-horsetail	0 (0%)	19 (100%)
Alder	24 (96%)	1 (4%)
Total	24	28
Central delta		
Horsetail	1 (9%)	10 (91%)
Willow-horsetail	2 (10%)	18 (90%)
Alder	26 (100%)	0 (0%)
Total	29	28
Northern delta		
Horsetail	8 (100%)	0 (0%)
Sedge	10 (100%)	0 (0%)
Willow-horsetail	2 (17%)	10 (83%)
Salix richardsonii	15 (100%)	0 (0%)
Total	35	10

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forests were not the focus of this research as permafrost is ubiquitous beneath these communities (Kokelj and Burn, 2003; Kanigan *et al.*, in press). In the southern delta, no NSP was found beneath horsetail and willow-horsetail communities. In contrast, all alder plots except one (an alluvial island in Mackenzie River) were associated with NSP; Pearce (1986) only found permafrost on the highest elevations of such islands beneath spruce forest in the southern delta. Similarly, in the central delta, about 90 per cent of horsetail and willow-horsetail communities did not have NSP, but all alder communities were associated with NSP. In the northern delta, however, NSP was present at all horsetail, sedge and *S. richardsonii* communities. In contrast, 83 per cent of willow-horsetail plots did not have NSP.

Throughout the three delta regions, 15 of the 154 (~10%) plots showed variations in the occurrence of NSP between the three drilled holes. Nine of these plots were willow-horsetail communities, five were alder and one was in horsetail. Table 3 shows the relation between vegetation and presence of NSP with drilled holes grouped by vegetation community and by delta region.

In summary, field surveys demonstrated that point bars and alluvial islands, willow-horsetail communities throughout the delta and horsetail communities in the southern and central delta were not associated with NSP. NSP was present beneath all other vegetation communities. Thus, the field results indicated that riparian vegetation communities may be used to predict the presence of NSP in the Mackenzie Delta.

Satellite Data Analysis

It was difficult to discriminate between the horsetail and willow-horsetail communities in the southern and central delta. However, as field results indicated that both of these vegetation communities were not underlain by NSP, the two classes were merged into a single willow-horsetail class. In the northern delta, horsetail and sedge communities were also difficult to separate, but as both horsetail and sedge communities were underlain by NSP and they are the herbaceous classes located closest to shorelines, they were also merged into one horsetail-sedge class.

The ML classification indicated that the inclusion of image texture information and vegetation indices was essential to the separability of different vegetation communities. Input combinations comprising lowly correlated spectral and textural variables as well as MSAVI and NDVI led to classification of vegetation communities with accuracy levels of 84 per cent, 82 per cent and 83 per cent for the southern, central and northern delta images, respectively. In the southern and central delta, the majority of classification errors were between the willow-horsetail and alder classes. These two classes are both shrubby vegetation and are usually located in sequential order on point bars. In the northern delta, most of classification errors occurred between the willow-horsetail and the *S. richardsonii* class. As seen in the field, horsetail-sedge dominates on channel edges and *S. richardsonii* is the main vegetation class at slightly more elevated locations furthest away from channels. Figure 6 shows the images of the three regions classified using the ML algorithm and Figure 7

Table 3 Relation between near-surface permafrost (NSP) and vegetation communities with drilled holes grouped by vegetation community and by delta region.

	% of drilled holes with NSP	% of drilled holes without NSP
Southern delta		
Horsetail (n = 24)	0	100
Willow-horsetail (n = 57)	2	98
Alder (n = 75)	89	11
Central delta		
Horsetail (n = 33)	5	95
Willow-horsetail (n = 60)	9	91
Alder (n = 78)	98	2
Northern delta		
Horsetail (n = 24)	100	0
Sedge (n = 30)	100	0
Willow-horsetail (n = 36)	25	75
Salix richardsonii (n = 45)	100	0

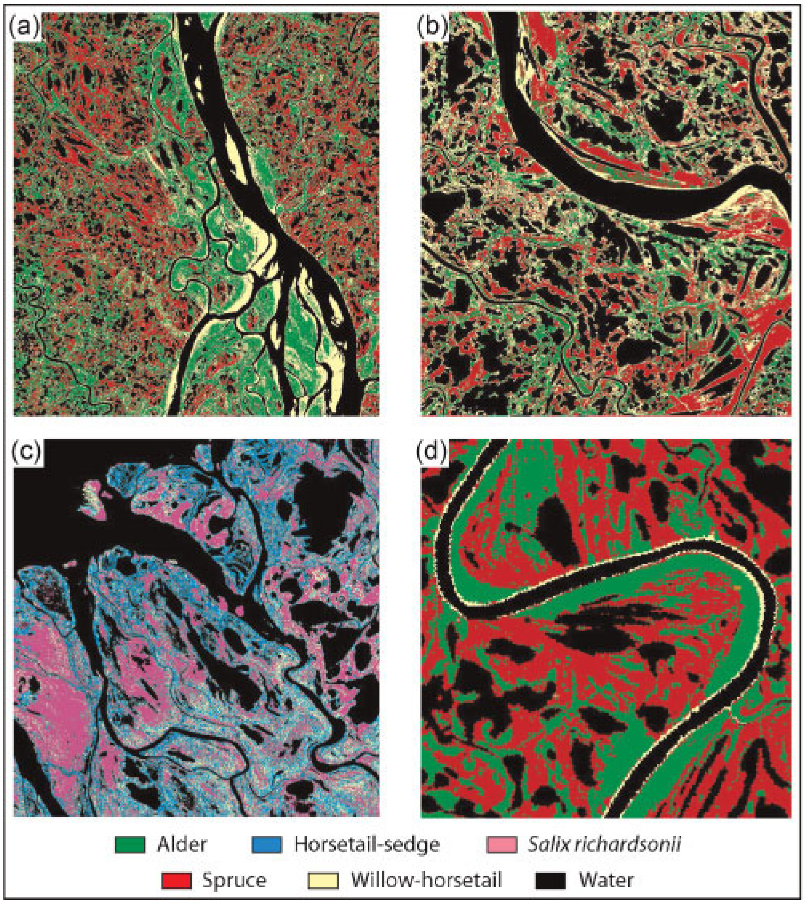

Figure 6 Mackenzie Delta areas classified using maximum-likelihood classification: (a) southern region; (b) central region; (c) northern region; and (d) close-up on a point bar in the southern delta where near-surface permafrost was present beneath alder and spruce communities, but absent elsewhere.

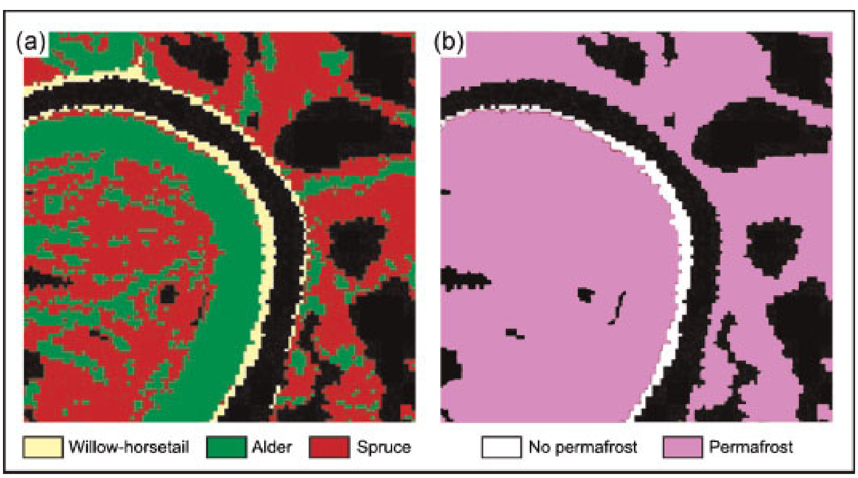

Figure 7 Vegetation zones and permafrost distribution at a point bar: (a) further close-up of Figure 6d; and (b) near-surface permafrost was absent only beneath willow-horsetail communities and water bodies (shown in black).

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illustrates permafrost distribution at a point bar based on mapped vegetation zones.

DISCUSSION: ESTIMATION OF NSP EXTENT

Point bars occupy about 18 per cent of the land surface in the Mackenzie Delta (Pearce, 1986), and the extent of alluvial islands in the southern delta was estimated to be approximately 5 per cent. Point bars and alluvial islands are transient features but are stationary at the timescale of interest to the definition of permafrost.

To estimate the extent of NSP in the delta, the area was divided into three regions (R): the southern, central and northern delta. The land surface in each region was divided into three categories (S): alluvial islands, point bars and all other surfaces. The areal extent of vegetation (V) classes underlain by NSP was identified for each delta region and land surface (P), and the extent of each delta land surface was determined (L).

The areal extent of NSP in the delta then is:

$$\sum_{i=1}^{R}\left(\sum_{j=1}^{S}\left(\sum_{k=1}^{V} P_{i,j,k} * L_{i,j,k}\right)\right) \quad (1)$$

Table 4 shows the total land area underlain by NSP for the satellite images of each delta region. In the southern delta, 93 per cent of the land surface represented by the extent of the satellite image was found to be underlain by NSP. In the central delta and northern delta, 95 per cent and 96 per cent of the land surface was underlain by NSP, respectively. V was determined by site, with each site allocated NSP by the rule of majority. Alternatively, the extent of NSP in the delta may be estimated from the percentages of drilled holes associated with NSP throughout each vegetation community in each delta region (from Table 3). With this method, NSP underlies 92 per cent, 96 per cent and 97 per cent of the land surface in the southern, central and northern delta, respectively (Table 5). This classification of permafrost is conservative, because the absence of NSP does not necessarily mean that permafrost is absent but only that it does not occur in the upper 3 m.

By definition, in the continuous permafrost zone permafrost underlies 90 per cent or more of the land surface (Heginbottom, 2000). This research therefore indicates that the Mackenzie Delta is part of the continuous permafrost zone. While the use of percentage cover in geographic characterisation of permafrost is resolution-dependent, for determination of distribution at a smaller scale, for which Landsat would be a more appropriate sensor, the Mackenzie Delta would also be classified as continuous permafrost. At a coarser scale than SPOT-5, the narrow vegetation communities associated with the absence of NSP may not be detectable and may be lumped in wider vegetation communities characterised by NSP.

Table 4 Extent of near-surface permafrost (NSP) for each delta region. S is the land surface type (AI = alluvial islands, PB = point bars), V the vegetation class underlain by NSP, P the land fraction occupied by V and L the land fraction occupied by S (eq. 1). The fraction area underlain by NSP (FA_{NSP}) is the product of the previous two columns.

S	V	P	L	FA_{NSP}	Cumulative total
Southern delta					
AI	Spruce	0.10	0.05	0.01	0.01
PB	Alder	0.37	0.18	0.07	0.08
	Spruce	0.44	0.18	0.08	0.16
Other	All	1.00	0.77	0.77	**0.93**
Central delta					
PB	Alder	0.33	0.18	0.06	0.06
	Spruce	0.37	0.18	0.07	0.13
Other	All	1.00	0.82	0.82	**0.95**
Northern delta					
PB	Horsetail-sedge	0.36	0.18	0.06	0.06
	Salix richardsonii	0.43	0.18	0.08	0.14
Other	All	1.00	0.82	0.82	**0.96**

Figures in bold represent total land fraction underlain by permafrost for each delta region.

Table 5 Extent of near-surface permafrost (NSP) using fractions of positive drilled holes (*H*) from Table 2 *S* is the surface type, *V* the vegetation class underlain by NSP, *P* the land fraction occupied by *V* and *L* the land fraction occupied by *S*. The fraction area underlain by NSP (FA_{NSP}) is the product of the previous three columns.

S	V	P	L	H	FA_{NSP}	Cumulative total
Southern delta						
AI	Spruce	0.10	0.05	1.00	0.01	0.01
PB	Willow-horsetail	0.19	0.18	0.02	—	0.01
PB	Alder	0.37	0.18	0.89	0.06	0.07
PB	Spruce	0.44	0.18	1.00	0.08	0.15
Other	All	1.00	0.77	1.00	0.77	**0.92**
Central delta						
PB	Willow-horsetail	0.30	0.18	0.14	0.01	0.01
	Alder	0.33	0.18	0.98	0.06	0.07
	Spruce	0.37	0.18	1.00	0.07	0.14
Other	All	1.00	0.82	1.00	0.82	**0.96**
Northern delta						
PB	Horsetail-sedge	0.36	0.18	1.00	0.06	0.06
	Willow-horsetail	0.21	0.18	0.25	0.01	0.07
	Salix richardsonii	0.43	0.18	1.00	0.08	0.15
Other	All	1.00	0.82	1.00	0.82	**0.97**

Figures in bold represent total land fraction underlain by permafrost for each delta region.

CONCLUSIONS

(1) On point bars and alluvial islands, permafrost was absent from the upper 3 m beneath horsetail communities in the southern and central delta, beneath alder communities on alluvial islands in the southern delta and beneath all willow-horsetail communities. NSP was present beneath all other vegetation communities and land surface types.

(2) Zones with the presence of NSP occupied about 93 per cent, 95 per cent and 96 per cent of the land surface, in the southern, central and northern delta, respectively. This indicates that the Mackenzie Delta is part of the continuous permafrost zone. The permafrost classification resulting from this research is in agreement with maps based on climate data as with Brown (1967) and Henry and Smith (2001). However, it differs from the map of Heginbottom *et al*. (1995) categorising the delta as discontinuous permafrost.

(3) The technique developed in this study was useful in mapping the distribution of NSP over large areas in a dynamic environment. Since the presence of permafrost in the upper 3 m is important for engineering design and biophysical applications, this research could form the basis of a mapping tool to assist land use planning.

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