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Mapping lichen in a caribou habitat of Northern Quebec, Canada, using an enhancement-classification method and spectral mixture analysis

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Abstract

Studies of caribou herds in northern regions are important to better understand population dynamics and define wildlife management strategies. Lichen is a primary food source for caribou and is a good indicator of caribou herd activity because of its sensitivity to overgrazing and overtrampling, its widespread distribution over northern areas, and its influence on herd demography. In this paper, we used Landsat TM imagery for mapping lichen in the summer range of the George River caribou herd in northern Quebec, Canada. Results from the enhancement-classification method (ECM) and from spectral mixture analysis (SMA) were evaluated for their suitability to characterize lichen land cover and for their potential to be applied over large territories. ECM and SMA are assessed individually and also for potential synergistic use. ECM is based on guided unsupervised classification of enhanced satellite images. Validation based on 3536 pixels from a relatively smaller number of field sites (20) showed an overall accuracy of 74.5% (kappa=0.70) for 10 classes and good discrimination between lichen and nonlichen classes, although we interpret these results with caution due to spatial autocorrelation and nonrandom sampling within field sites. However, discrimination amongst different lichen classes using ECM was more problematic. SMA derives the proportion of individual scene components at subpixel scales. This method provided good results in characterizing variations in lichen abundance validated against field observations and provided additional and new information not provided by ECM which is important since the abundance of lichen as a primary food source is a key indicator of migration and demographic patterns essential for effective wildlife management. We concluded that the ECM and SMA methods are appropriate for different aspects of lichen mapping. ECM provided good discrimination between lichen and nonlichen classes, whereas SMA provided additional lichen information not available by classification yet critical to the environmental application, which is also appropriate for application over much larger areas and in spatiotemporal studies. A synergistic use of SMA and ECM is therefore recommended for future research.

Keywords: Spectral mixture analysis; Enhancement classification method; Lichen mapping; Caribou habitat; Northern Quebec

1. Introduction

Studies on caribou herds in northern regions are important for a better understanding of population dynamics and wildlife management. Factors affecting the populations of migratory caribou herds are not well understood (Messier et al., 1988). Predation, hunting, climate, human activities, and winter food availability are known to influence migratory caribou population dynamics (Bergerud, 1980; Dyer et al., 2002; Messier et al., 1988; Skogland, 1986). In northern Quebec, Canada, the George River Caribou Herd (GRCH), the focus of this study, is regulated by summer habitat food availability (Crête & Huot, 1993; Manseau et al., 1996; Messier, 1995). Lichen (dominated by *Cladina* sp.) is the main food source for caribou (*Rangifer tarandus*

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caribou) in winter when no green plants are available, accounting for 75% of its diet, while in summer, this proportion is only 25% (Gauthier et al., 1989). However, lichen is very sensitive to trampling in the summer, especially under dry conditions when it becomes easily broken. Pegau (1970) observed that a herd of 500 caribou can damage between 15% (wet conditions) and 75% (dry conditions) of the lichen mat in a single passage. Damage to lichen plays an important role in caribou herd demography, affecting fat and protein storage in females as well as lactation and the growth rate of calves.

Lichen growth is very slow, and in northern regions, the growing season is short. Lichen mats can take up to 50 years to regenerate in the case of a strong degradation (Moser et al., 1979). For example, on St. Matthew Island in the Bering Sea, Klein (1987) estimated that only 10% of the lichen was regenerated after 22 years of overexploitation by caribou. In a similar study conducted on Rideout Island in Northwest Territories (NWT), Canada, Henry & Gunn, 1991 estimated that a 20-year regeneration period would be necessary for initial lichen mats to recover following degradation by caribou.

Since lichen is used almost exclusively by caribou, evidence of overgrazing and overtrampling is accepted as being good indicators of caribou activity and habitat health (Boudreau et al., 2003; Henry & Gunn, 1991; Klein, 1987; Morneau & Payette, 1998, 2000; Moser et al., 1979; Nordberg & Allard, 2002). Damaged lichen also takes time to recover, offering the potential for detecting and monitoring regrowth and recovery over time. Lichen have a circumpolar distribution (Longton, 1988) similar to that of *R. tarandus* (Banfield, 1961), thus the implications of assessing lichen for monitoring caribou herd dynamics may also be applicable over vast and remote areas in northern lands. Previous studies successfully used various indicators of caribou habitat degradation to assess caribou activity. Morneau and Payette (1998, 2000) used trampling scars produced by caribou hooves on superficial roots and low branches of conifers to study caribou activity in the summer range of the George River herd in northeastern Quebec–Labrador over the last 100 years; a period during which the herd underwent large fluctuations in its size and distribution. The area occupied by the herd in summer is not easily accessible for fieldwork studies and covers a very large

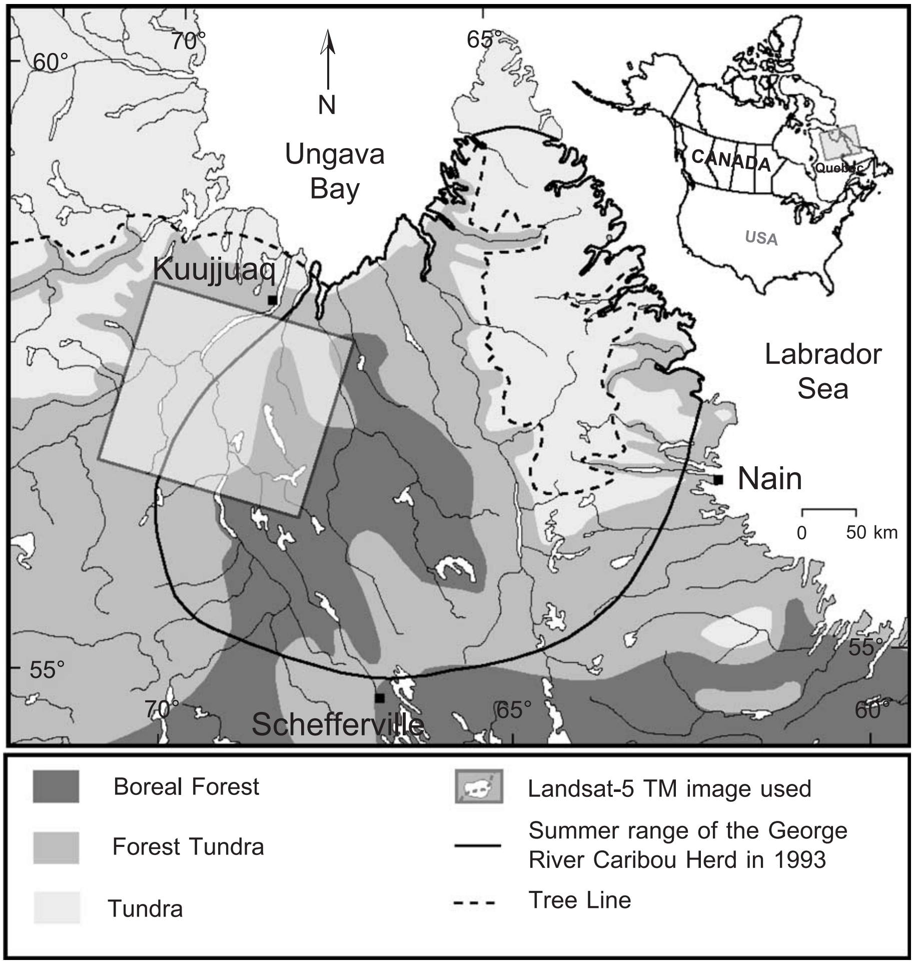

Fig. 1. Study area and location of Landsat TM image used in this study. The summer range of the George River Caribou Herd (Russell et al., 1996), biomes, and tree line (Payette, 1983) are also indicated.

territory (Fig. 1). As a result, field studies over the entire area are limited, and aerial surveys cannot be conducted frequently, providing only fragmented information on the demographics and physical condition of the herd. Satellite remote sensing offers the synoptic view and temporal resolution necessary for mapping and monitoring the land cover in caribou habitats. In this paper, we present a new approach, based on spectral mixture analysis (SMA), and we compare its potential for the detection and mapping lichen with a classification method. These methods are then discussed in terms of potential for a synergistic classification and SMA approach.

2. Background

Most remote sensing studies of lichen land cover have been conducted in Scandinavia. For example, Nordberg and Allard (2002) used Landsat TM imagery in Sweden to detect lichen degradation above tree line by correlating differences in normalized difference vegetation index (NDVI) between two dates with changes in lichen cover. Käyhkö and Pellika (1994) studied reindeer habitats for herd and pasture management and found that although SPOT multispectral (XS) imagery was not entirely suitable due to spectral confusion between vegetation and lichen in the near infrared band, they were able to map some of the distinct vegetation patterns on both sides of the Finland–Norway border caused by different grazing pressures and pasture management practices in the two countries. Colpaert et al. (1995) used vegetation survey data associated with Landsat TM images to assess the quality and area of reindeer habitats in Finland.

In North America, a limited number of studies have been conducted on caribou and large mammal habitats using remote sensing data. Thompson et al. (1980) performed a classification of caribou habitat in the Northwest Territories (NWT), Canada, using Landsat MSS imagery. They accurately mapped vegetation complexes related to seasonal use by caribou. However, the study covered only open areas used during the summer and part of winter. Traditional winter habitats located in woodlands were not included in the study. In northern Quebec, Saucier and Godard (1992a,b) mapped vegetation based on caribou habitats using Landsat TM imagery. They produced vegetation maps with 14 classes (six of them containing lichen), using a methodology based on image enhancement. Final maps were provided at a scale of 1:500,000 and showed only general vegetation patterns. The quality of the results obtained was difficult to evaluate since no accuracy assessment was provided. Muskox (*Ovibos moschatus*) habitats have been studied by Ferguson (1991) and Pearce (1991) on Banks Island and Devon Island, NWT, using Landsat TM and SPOT HRV imagery, respectively, and gave similar results. They successfully discriminated lichen and other land cover using image enhancements and classification. However, the discrimination of shrub areas and lichen shrub areas was more problematic using Landsat than SPOT imagery, possibly due to the lower spatial resolution of Landsat. Matthews (1991) successfully classified bison (*Bison athabascae*) habitat in the NWT using Landsat TM imagery. However, lichen woodlands were not included in these results because of confusion with other classes and because of its reduced relevance for bison habitat.

In all of these studies, classification was the main method used to map lichen. However, previous studies have shown that misclassification due to pixel heterogeneity can be significant (Chhikara, 1984; Cross et al., 1991), especially for coarser resolution imagery and boundary pixels. Spectral mixture analysis (Adams et al., 1989) addresses this issue by providing subpixel scale information on the spatial abundance of different cover types. The method has been used successfully in various fields such as geology (Bryant, 1996; van der Meer, 1995), forestry (Hall et al., 1995, 1996; Nelson et al., 1994; Peddle et al., 1999, 2001; Radeloff et al., 1999), agriculture (Maas, 2000; Peddle & Smith, 2004), mountain applications (Peddle & Johnson, 2000), semiarid land degradation (Tromp & Epema, 1999), and arctic and tropical ocean studies (Peddle et al., 1995; Piwowar et al., 1998). Some studies have also compared SMA and classification. van der Meer (1995) found that classification limitations such as the need for ground truth, representativeness of training data, and the presence of mixed pixels can be overcome using SMA. Tromp and Epema (1999) found that SMA provided more information on the content of classes, compared to the "hard" labels associated with classification. SMA provides quantitative information in the form of land cover component fractions, which is not the case for the thematic (nominal level) classification output.

However, to our knowledge, SMA has not been previously used in studying lichen, and further, in this paper, we go beyond this to also study both classification and SMA results for lichen land cover in a caribou habitat for the first time. Our research is set in the context of caribou habitat studies; however, in this work, our focus is primarily on lichen land cover, with the more complex associations between land cover and habitat to be addressed in future papers from this work. In other studies, these associations and the concept of habitat have been variable in terms of interpretations and nomenclature, as reported in other fields (Hall et al., 1997). Most land cover studies have used classification only, and these encountered limitations (Beaubien et al., 1999; Thompson et al., 1980). Nordberg and Allard (2002) conducted a study on monitoring lichen cover change in Sweden using Landsat TM classification and NDVI with some success. However, their study only considered heath communities above tree line, without significant canopy cover. As illustrated in Fig. 1, our study area is located below the tree line, which makes lichen detection more difficult because of the contribution of variable canopies to pixel reflectance. Käyhkö and Pellika (1994) encountered this problem during their classification of reindeer habitat in Scandinavia using SPOT XS imagery. Lichen distribution was accurately determined only in treeless areas. They found that several combinations of tree density and ground-cover flora had similar spectral characteristics, and this resulted in misclassification.

In this paper, the main objective was to overcome these limitations by (i) using a classification method specifically developed for large areas in boreal environments, and (ii) testing spectral mixture analysis as a new approach to overcome limitations found in previous classification studies. A secondary objective in this analysis was to explore the strengths and weaknesses of each method and identify a possible synergistic classification and SMA approach if appropriate.

3. Methodology

3.1. Study area

The GRCH summer habitat is located on the northeastern Quebec–Labrador peninsula (Fig. 1). Despite large spatiotemporal variations of the population in the last century, the area used by caribou in summer is known to be primarily the tundra plateaus between George River and the Labrador Sea (Banfield & Tener, 1958; Couturier et al., 1996; Elton, 1942; Low, 1896; Messier et al., 1988). The study area considered in this paper encompassed an area of 34,225 km^2 centered at coordinates 57°17′ N 69°09′ W (North American Datum, NAD 1983) and located in the western part of the caribou summer range. This area encompasses the diversity of vegetation encountered across the summer habitat and has sustained only minimal damage by caribou activity during the past two decades (Morneau, 1999). From northwest to southeast, the area is characterized by a vegetation gradient between the northern forest tundra and the boreal forest. Black spruce (*Picea mariana*) is the dominant tree species, while Tamarack (*Larix laricina*) and white spruce (*Picea glauca*) are common. *Cladina stellaris* is the dominant lichen species on well-drained sites, and the shrub layer is dominated by *Betula glandulosa*. The geology of the area encompasses three physiographic divisions. The western part belongs to the Ungava plateau, and the eastern part is situated on very old erosion surfaces in granitic and gneissic rocks on the Whale River plateau. The Labrador trough occupies the central part of the study area and is characterized by ridge-and-valley relief, with drumlins and eskers oriented north–northwest (Gouvernement du Québec, 1983; Hare, 1959). The climatic conditions are severe and responsible for very slow vegetation dynamics. The mean annual temperature is −5 °C, with approximately 40 frost-free days and a mean annual growing season of 100 days (Gouvernement du Québec, 1983).

3.2. Remote sensing data

A cloud-free and snow-free Landsat-5 TM scene (path 15, row 20) acquired on July 11, 1996 was used. Bands 3, 4, and 5 were selected to generate a false-colour image and for the image analysis because of the suitability of these bands for vegetation and lichen studies (Beaubien et al., 1999; Nordberg & Allard, 2002; Petzold & Goward, 1988; Richards & Jia, 1999). The scene was geometrically corrected and georeferenced to the UTM coordinate system (NAD 1983) at 25 m spatial resolution, using ground control points extracted from 1:50,000 topographic maps. Resampling was performed using the nearest neighbour method at a mean elevation plan using OrthoEngine software (PCI, 2001). The root-mean-square (RMS) error in geometric registration was 0.75 pixels and 0.72 pixels for *X* and *Y*, respectively.

3.3. Field data

Field data were collected during summer 2001 in support of image classification and spectral mixture analyses as well as for validation of results. The Landsat image and field data were not obtained simultaneously due to several factors typical of northern study areas. Field investigations in northern regions have to be planned well in advance because access can be difficult and expensive. In addition, few cloud-free Landsat images from the summer period were available. However, northern environments are characterized by relatively slow vegetation dynamics and are typically not disturbed by intense human activities. Moreover, our study area was not intensively frequented by the GRCH in the last decade (Morneau, 1999; Saucier & Godard, 1992a,b). Habitat degradation was therefore limited in this region during this period. These slow changes permit the use of images acquired at different times, even over several years.

Six areas were chosen for field visits by considering their representativeness of the land cover classes and lichen areas of interest, their spatial distribution over the image, and their accessibility by air. Within each area, sites were surveyed from helicopter at a mean altitude of 200 m. The location of each site was determined before the aerial surveys to make a flight plan and to ensure sufficient characterization of land cover diversity. Site selection was done using enlarged colour prints of enhanced Landsat images, with each site consisting of homogeneous groups of pixels. Site locations were delineated on the colour prints and topographical maps to aid with navigation. Site location was within one pixel accuracy with reference to the image georeferencing performed (Section 3.2). Observations were made looking out the window while the helicopter flew around each of the selected sites. For each site, several parameters were observed and recorded from the air, including land cover class, the type and percent coverage of the canopy layer as well as the type and percent coverage that comprised the ground layer (lichen, mosses, exposed mineral soils). All percent coverages were determined by visual estimation with a nadir or near nadir view angle and served to provide a representative value for each component for checking the SMA results. Quantitative estimates of coverage layers were made at a precision of 10% and later refined to 5% using photographs of each site that were taken from the helicopter. All sites were characterised by the same observer to ensure consistency. Regarding the ground cover, it was determined that the yellow lichen mat observed from the air was *C. stellaris* based on surface observations and known associations that the lichen mat in this mature and intact pasture is dominated by this lichen species. Areas with damage or regeneration were not widespread in this portion of the summer range; however, we note here (and for future studies) that these small areas had a different appearance from the air (dominated by grey and dark colours). Lichen under the canopy was not taken into account; however, this was not of concern since these areas do not constitute a major food source for caribou because these locations are unfavourable for lichen growth (Foster, 1985), and furthermore, they are not readily accessible to grazing and trampling. Any lichen obscured by the canopy also has a minimal or no contribution to pixel level reflectance. Sites were visited on the ground when a layer estimate or identification was ambiguous from the air, especially for the ground layer in more dense woodlands. However, it was not possible to observe lichen abundance for individual pixels in the field, and as a result, the SMA validation was based at the site-level and not for individual pixels, which was deemed appropriate for this large study area. In total, 37 sites with a mean area of 0.09 km^2 (minimum=0.03 km^2, maximum=0.54 km^2) were characterized. For a given site, the largest possible homogeneous area was determined, and this varied by site due to the natural variability and the spatial arrangement of these surface cover classes. While this is to be expected and is common in classifications, variable sample sizes can affect the classification accuracies and error levels reported. However, in our case, this was not a large factor since, with the exception of the largest site (lichen heath, LH), the differences amongst site areas were not great (second largest site was 0.20 km^2), particularly given the size of the study area. Of these 37 sites, 24 were lichen sites, and 13 were nonlichen sites.

Seventeen of these sites (1703 pixels) were used as training areas to perform the supervised classification, with the remaining 20 sites (3536 pixels) retained for the purpose of mutually exclusive, independent validation of the classification results. These pixels were not selected independently but instead were pooled from different sites. For the spectral mixture analysis, all 24 of the available lichen sites (4799 pixels) were used.

We acknowledge that the number of field sites is low according to traditional classification studies and causes limitations in generalizing these results to the entire scene due to spatial autocorrelation and nonrandom sampling. However, we had to deal with large, northern, remote, and inaccessible areas for which extensive field sampling was not possible or practical. Instead, the characterization of field sites was designed to maximize the surface area surveyed within the available flight time by characterizing large homogeneous areas (the mean area of validation sites was 0.09 km^2) instead of a larger number of smaller, more variable sites which would take substantially more flight time to characterize. Our approach therefore maximized the use of expensive helicopter time. Within each homogeneous site, spectral variability nonetheless existed, as expected. This is useful and important for capturing within-class variability for classification training and testing to augment the variability from utilizing multiple sites to characterize each class. As a result, for our classification products, we report results (Table 2) with respect to field sites per class and also the total number of pixels within validation sites—the latter of which we interpret with caution due to possible spatial autocorrelation. The results obtained in this research are of particular interest to the growing number of regional-scale studies in such environments where the benefits of being able to obtain this information that otherwise would be impossible to obtain far out-weigh the constraints imposed by classification sampling.

3.4. Enhancement-Classification Method (ECM)

The Enhancement-Classification Method (Beaubien et al., 1999) was used to perform image classification since it is an approach specifically developed for thematic land cover extraction from Landsat TM images, over large areas, in boreal environments. A detailed description of ECM is presented by Beaubien et al. (1999) and is not repeated here. Briefly, the method involved four general steps (Beaubien et al., 1999). First, a linear digital contrast enhancement was performed on three bands (TM bands 3, 4, and 5) to maximize visual discrimination amongst bands. The sampling of cover types with high and low values in each band was used to perform this enhancement. The second step consisted of performing an unsupervised K-means classification. The large number of clusters produced (150 in this study) was representative of the variability of spectral information visible on the enhanced image. These clusters were displayed with a pseudocolour table based on the enhanced image to facilitate initial cluster groupings. A supervised reclassification was performed in the third step to reduce the number of clusters to about 50. The selection of significant clusters was performed using mode and sieve filters on the classification. Reclassification was then performed using a minimum distance to means algorithm. Finally, cluster agglomeration and labeling was performed based on the analyst's interpretation with respect to the classes contained in the land cover legend (Table 1), which were selected to emphasize lichen cover. The classes were based on the structural properties of vegetation layers and were adapted from Saucier and Godard (1992a,b). Lichen classes were defined with different tree, shrub, and lichen horizontal coverage combinations, with other classes

Table 1
Description of classes used for Landsat TM classification

Class	Code	Description
Lichen heath	LH[a]	Dominated by a well-developed lichen mat. Tree and shrub layers represent less than 10% of horizontal coverage.
Lichen dwarf shrub heath	LDSH[a]	Dominated by a well-developed lichen mat. The shrub layer represents more than 10% and the tree layer less than 10% of horizontal coverage.
Lichen woodland	LW[a]	Dominated by a well-developed lichen mat and a tree layer representing between 10% and 35% of horizontal coverage. The shrub layer represents less than 10% of horizontal coverage.
Lichen dwarf shrub woodland	LDSW[a]	Characterized by a higher tree density (more than 25% of horizontal coverage) and a co-dominance of lichen and shrub levels.
Shrub forest	SF	Areas of very high shrub density (more than 75% of horizontal coverage). Can contain lichens in low density (less than 10%).
Burn without lichen regeneration	BWLR	Recent burn (less than 30 years). Dead trees and exposed soil dominate the ground layer. Lichen regeneration is present but is not suitable as potential food for caribou. The shrub layer coverage is variable.
Moss woodland	MW	The ground layer is dominated by mosses. The shrub layer is generally well developed (more than 30% of horizontal coverage). Tree density is variable.
Wetland	Wet	Includes various types of bogs.
Rock	R	Areas dominated by rocks. Can contain lichens and shrub but in low densities (less than 10%).
Water	W	Lakes and rivers.

[a] Denotes classes containing most of the lichen.

regrouped according to land cover variability. Moss Woodland, for example, characterized humid areas dominated by black spruce and moss, and some occurrences of a variable shrub layer. The primary lichen areas were contained in four of the classes (Table 1). In some cases, areas classified as shrub forest or rock also contained lichen but in lower proportions. Any occurrences of lichen in the class 'burn without lichen regeneration' were not taken into account because it does not represent potential food for caribou.

3.5. Spectral mixture analysis

Image pixels often cover areas that include a variety of surface cover types within a given land cover class (e.g., canopy, shadow, surface vegetation such as lichen). Factors that influence the degree of heterogeneity and its importance for a particular application include the field of view of the sensor (spatial resolution), the level of required land cover information (e.g., the class structure), and the spatial arrangement of surface features. These factors can introduce confusion and error with per-pixel classifiers and compromise classification accuracy (Chhikara, 1984). Spatially heterogeneous, or mixed, TM pixels were common in our study area due to the patchy nature of lichen, forest, and other vegetation species in this sensitive northern environment.

Spectral mixture analysis (SMA) involves retrieving the spatial fraction of individual scene elements (surface cover components or end members) within each pixel, based on knowledge of the individual reflectance values of these elements and the overall pixel-scale reflectance. Linear mixing occurs when there is only a single set of interactions between incoming radiation and the surface, in which a given incident photon is reflected or absorbed by one type of material only. Although this is not always the case in nature, linear models are often used due to their simplicity and also because they have been shown to provide good estimates of scene fractions in a variety of complex environments (Hall et al., 1996; Peddle & Johnson, 2000; Peddle & Smith, 2004; Peddle et al., 1995, 1999; Piwowar et al., 1998). In this study, the amount of nonlinear mixing was deemed minimal, owing to the lower stand densities and the presence of open areas. Further, it would not have been practical to use more complex nonlinear models both in terms of the additional parameters required and the minimal benefits that might be expected.

The general form of the equation for linear mixing is (Adams et al., 1989):

$$\mathrm{DN}_c = \sum_{i=1}^{n} F_i\ \mathrm{DN}_{i,c} + E_c \text{ with the following}$$

$$\text{constraints: } \sum_{i=1}^{n} F_i = 1 \text{ and } 0 \le F_i \le 1$$

where: DN_c=the digital number of the pixel value in channel c; F_i=the fraction of end member i; $\mathrm{DN}_{i,c}$=the digital number value of end member i in channel c; n=the number of end members; E_c=the error of the estimate for channel c.

The selection and spectral characterization of end members is a critical process in SMA. The individual components of the surface must first be identified. Then, the spectral properties of these end members need to be obtained. In this study, we chose lichen, canopy, and shadow as end members, which are the simplest and most representative components of the areas of interest. The options to obtain spectral values for these end members included field measurement, use of image-based values, and modeling (Peddle et al., 1999). We used image-based end member spectra because adequate and representative field spectra were difficult to obtain in this remote, northern area, and also because this approach has been successful in other environmental studies (Bryant, 1996; Tromp & Epema, 1999). In this approach, one or more pure or nearly pure pixels must be present in the image for the selected end members, from which spectral values are obtained for all wavelength bands used in the analysis. An advantage in using image end members is that image radiometric calibration is not required, unlike spectral end members measured in the field for which both the field spectra and the image data must be converted to a common measurement unit (usually reflectance).

In this study, SMA was used to provide lichen abundance information that was not possible to obtain by classification but which is an important indicator of lichen food availability and therefore quality of the caribou habitat. The three end members used in this study (sunlit lichen, sunlit canopy, and shadow) were obtained as image end members derived from a scatter plot of TM bands 3 and 4 spectral space (Fig. 2). Selection of TM bands 3 and 4 for SMA was made based on initial tests that showed these bands provided better discrimination between end members compared to other band combinations. Lichen and sunlit canopy end members were selected at the vertices of the triangle formed by these three characteristic surface end members, assuming that the purest pixels were located in these areas of spectral space. Pixels that represented image noise or other spurious occurrences of different surfaces were excluded from the candidate image end members by linking spectral and image space in software (ENVI, 2002) and identifying these individual pixel occurrences. Confirmation of these image end members was made with reference to image locations visited on the ground during field campaigns. For the shadow end member, the darkest pixel in a deep clear lake was selected as a surrogate for the low reflectance values associated with image shadows, similar to the work of Hall et al. (1995, 1996) and confirmed with reference to the spectral space scatter plot. The mixture analysis was performed on TM bands 3 and 4, using an unconstrained SMA algorithm (Boardman, 1989, 1992) provided in the ENVI software package (ENVI, 2002). Theoretically, for an appropriate end member model, the fractions of each end member should sum to one (or 100%). However, if one or more end members are not representative of the actual surface constituents within an image pixel, then the SMA fractions may contain either underflow (<0), overflow (>1), and/or the sum of all fractions will not equal unity. The unconstrained algorithm provided the original or "raw" fractions for assessing this, without any internal adjustments that are performed by constrained algorithms. In this study, the SMA software used (ENVI, 2002) did not report an error term for the mixture analysis involving three end members and two spectral bands, and so, that error indicator was not available for use. Instead, in cases where the fractions did not sum to unity, we tolerated some deviation in the form of fraction errors, similar to that of Bryant (1996) and Koch (2000), who both tolerated errors ranging to 6–7%. In our work, we tolerated slightly more deviation (±10%) interpreted as fraction variability owing

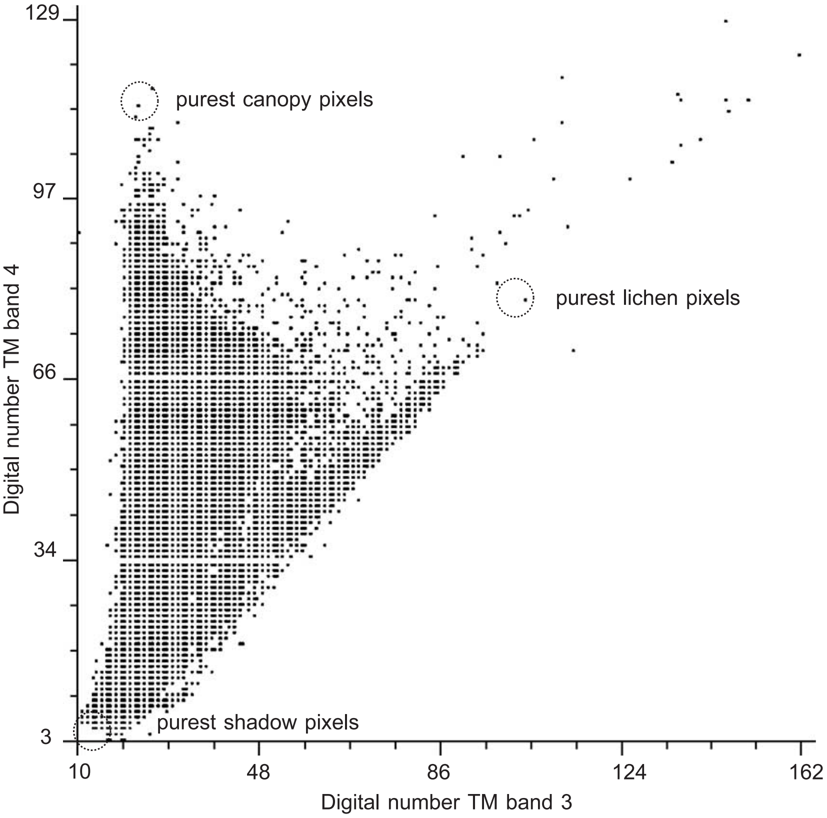

Fig. 2. Scatter plot of 2D spectral data used for identifying image end members. Purest pixels are located at the vertices of the triangle formed by all valid image values (e.g., noise excluded).

to the much larger study area under consideration and based on our knowledge of the greater diversity of scene fractions observed in the field and in aerial photography used as validation, and also with reference to the deviation between these validation products and the SMA scene fractions obtained at these sites. Pixels outside this range were excluded and considered as nonlichen areas.

4. Results

4.1. ECM classification

The overall ECM accuracy was 74.5%, kappa coefficient=0.70 (Table 2) based on the pooled sample of pixels (3635) obtained from a lower number of field sites (20). It was not possible to label a full site as "correct" or "incorrect" since each field site area contained numerous pixels for which some were correct and others were incorrect within the mutually exclusive, independent test sample. Although this is comparable to other studies (Beaubien et al., 1999; Colpaert et al., 1995), the reporting of results based on pixel counts should nonetheless be interpreted with some caution due to spatial autocorrelation and nonrandom sampling, as discussed earlier in the paper. Overall, the lichen classes were well discriminated from nonlichen classes (Table 1). When lichen classes (LH, LDSH, LW, LDSW) were combined, the overall accuracy increased to 87%. The six nonlichen classes (Table 1) were also mapped well, showing individual class accuracies between 40% and 100%. Fig. 3 presents classification results for two areas in the Landsat image. Based on an initial visual comparison of the false colour composite image (Fig. 3a) and the 10 ECM classes (Fig. 3b), there was good overall correspondence of land cover class and image spatial patterns. In terms of the specific validation results by class (Table 2), confusion between moss woodlands and lichen dwarf shrub woodlands was explained by the fact that lichen spots are frequent in moss woodlands, occupying dry spots generally on the top of ridges. As a result, lichen can have a relative contribution to the reflectance of moss woodland cover. Confusion between rocks and lichen heath can be explained in a similar way since rocks and lichen often occur in exposed areas. In these cases, the relative contribution of each surface component to the overall pixel reflectance is variable and not easily characterized. Minor confusion also occurred between water and the BWLR (burned without lichen regeneration) classes. Spectral similarity between these two classes could explain some of this confusion since the BWLR class occurs in areas of recent fire and have a dark appearance and low values in TM bands 3, 4, and 5, similar to that of water.

The accuracies of the individual lichen classes were lower and varied between 30% and 92% (Table 2). This was attributed in part to the more sophisticated class structure that contained a higher level of detail for the various lichen classes, some of which were physiologically similar and would be expected therefore to be spectrally similar. However, our goal was to test a more rigorous set of classes that was more relevant to the caribou habitat features of interest, instead of generalizing these to fewer classes that, despite having higher accuracies, would be less meaningful. Most of the confusion was between the lichen dwarf shrub heath (LDSH) class and the lichen heath (LH) class. Of all the classes, these two heath classes were amongst the most similar on the ground owing to the continuum in shrub density that makes their distinction less obvious, and therefore, confusion between them was not unexpected. Although site characterization was performed during aerial surveys and from the visual estimation of layer coverage, the reduced field accessibility constrained visits to only a limited number of sites. Visually, homogeneous groups of pixels were chosen and characterized as the same class in the validation data. However, some spectral heterogeneity may have not been detected visually in these groups, and this could have caused some pixels to be incorrectly characterized in the validation data. This issue was less problematic in nonlichen sites because of the

Table 2
Contingency matrix for ECM classification based on field site characterization

Ground Sites (*n*)	LH	LDSH	LW	LDSW	BWLR	MW	Wet	SF	Rock	W	Total	%
LH(1)	804	191	15	0	0	0	3	7	67	0	1087	74.0
LDSH(2)	60	127	1	84	0	0	0	26	7	0	305	41.6
LW(2)	2	29	122	1	15	4	9	0	8	0	190	64.2
LDSW(4)	0	56	9	412	6	34	33	36	9	0	595	69.2
BWLR(1)	0	0	0	0	126	0	13	0	0	0	139	90.6
MW(2)	1	0	0	31	6	283	1	0	0	0	322	87.9
Wet(2)	0	0	0	0	0	0	160	0	0	0	160	100.0
SF(2)	0	0	0	17	0	31	0	299	17	0	364	82.1
Rock(2)	2	19	0	0	0	0	0	0	72	0	93	77.4
W(2)	1	0	0	1	46	3	2	0	0	228	281	81.1
Total	870	422	147	546	199	355	221	368	180	228	3536	
%	92.4	30.1	83.0	75.5	63.3	79.7	72.4	81.3	40.0	100.0		74.5
												K=0.70

Class codes (left column) and descriptions listed in Table 1. Validation is based on pooled pixels from validation sites (number of sites shown in brackets, next to class codes). Individual and overall class accuracies shown as percent agreement, with the kappa coefficient (*K*) shown at bottom right for all classes.

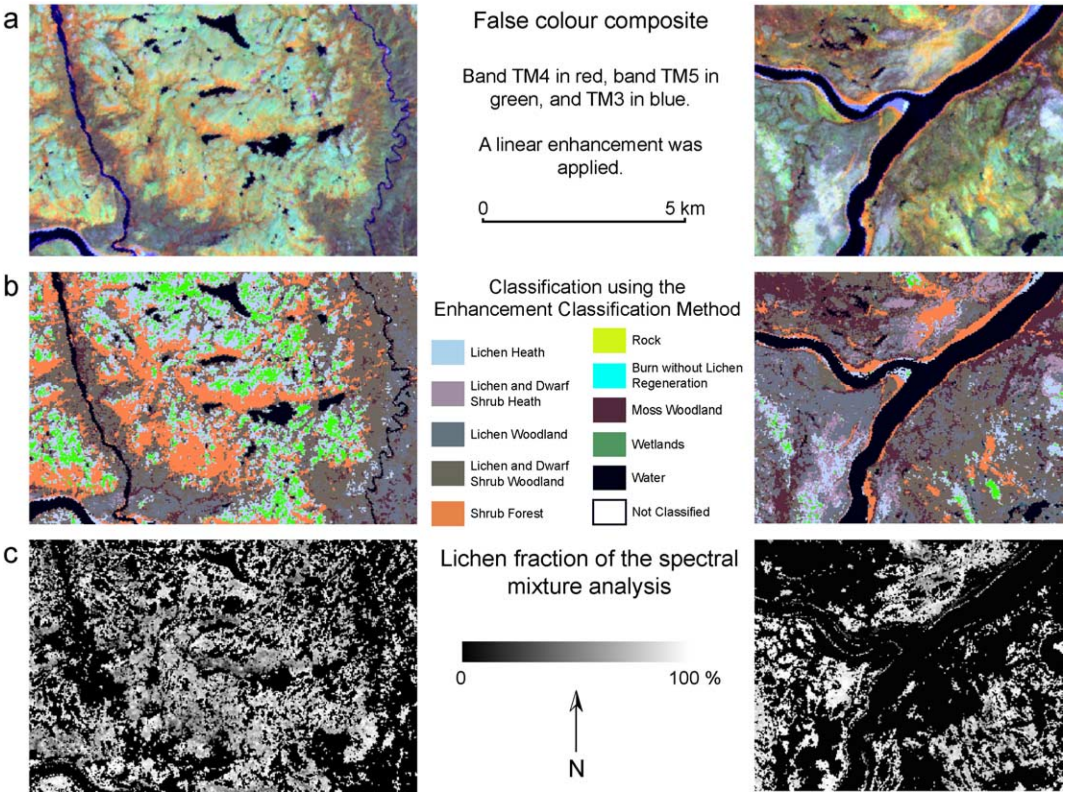

Fig. 3. Image data and results for two test areas. (a) False colour composite of Landsat TM bands 3, 4, and 5; (b) ECM classification map; and (c) SMA lichen fraction abundance maps.

greater visual and spectral discrimination amongst classes. For example, black spruce Krummholz formations are common in northern Quebec but are mixed with shrubs and therefore were difficult to detect in the aerial survey site characterization, resulting in an underestimation of the tree layer and the possible misclassification of the Lichen Dwarf Shrub Woodland class into the lichen dwarf shrub heath class. Any reduction in "true" accuracy resulting from internal errors in the validation data may be offset to some extent by the potential for overestimation of accuracy due to the issues of spatial autocorrelation discussed earlier.

4.2. Spectral mixture analysis

The field validation data identified each site in terms of lichen presence or absence and membership in one of the 10 classes (Table 1). For lichen sites, a spatial estimate of lichen abundance was performed to facilitate SMA fraction validation. The SMA results by site are summarized graphically in Fig. 4, in which the aerial survey lichen fractions are plotted against the SMA lichen fractions. The diagonal line in Fig. 4 represents the line of exact correspondence between the field and SMA fractions, with the distance from this line corresponding to the magnitude of deviation between the field and SMA lichen results, by site. Using SMA, nonlichen sites were accurately discriminated from lichen sites. Of the 13 nonlichen sites, 10 of them (or 77%) were correctly identified by SMA as being nonlichen based on the sunlit lichen, canopy, and shadow fraction sum violating the ±10% threshold rule (described in Section 3.5). Two shrub forest sites were not excluded as nonlichen because the SMA analysis identified small occurrences of lichen in these pixels. According to field data, these contained less than 10% of lichen coverage, but we did not consider this class as a major lichen source for caribou. The remaining nonlichen site that SMA identified as containing lichen was characterized in the field as a moss woodland cover. The presence of small lichen spots often observed in dryer areas dominated by moss could explain the detection of lichen by spectral mixture analysis. These results indicate a good sensitivity of SMA to detect even a small proportion of lichen per pixel.

Of the 24 field-verified lichen sites, 18 (or 75%) of them were correctly identified by SMA as containing lichen (Fig. 4). Of the six lichen sites not considered to be lichen by the SMA, five were characterized in the field as lichen heath (LH). According to field data, a significant area within these sites (approximately 25%) contained mineral soil and/or rock. In these cases, the end members used for the SMA (lichen/canopy/shadow) were probably not sufficiently representative of the overall pixel content in these cases since the mineral soil and rock covers were spectrally very different, thus making a disproportionately larger contribution to the model error that forced the fraction estimates to exceed the 10% threshold rule.

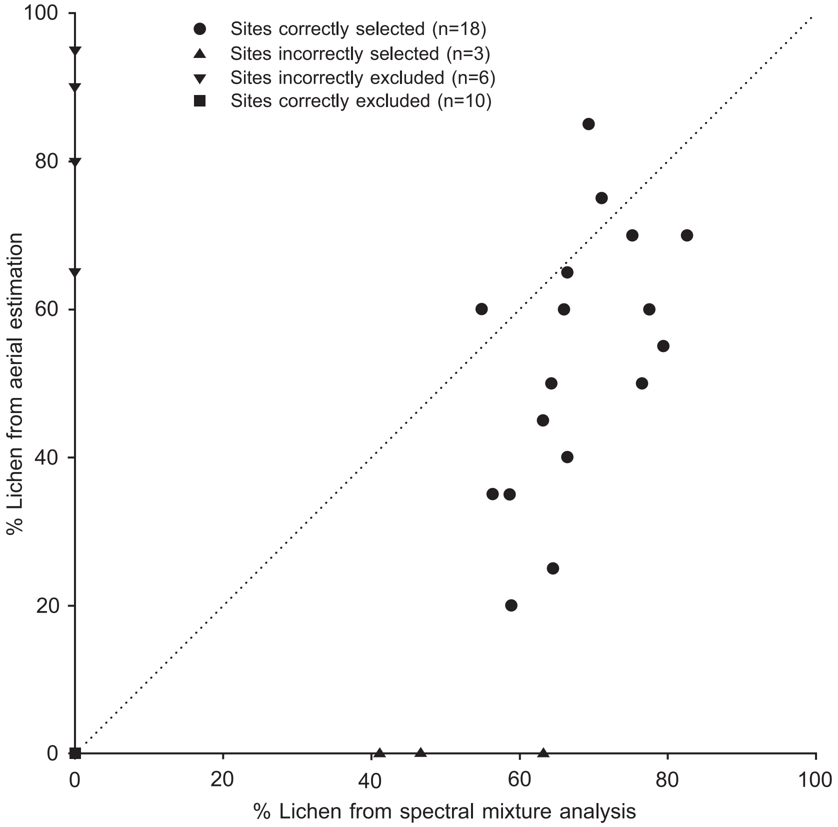

Fig. 4. Scatter plot between mean percent lichen abundance coverage estimated in test sites using aerial survey plotted against fraction values obtained from spectral mixture analysis. Each plot represents a mean percentage observed and computed at one site. Diagonal represents line of correspondence between SMA and field validation results.

As shown in Fig. 4, SMA fraction results tended to overestimate lichen coverage compared to the field values estimated by aerial survey. This might be partly due to a systematic underestimation of lichen coverage in the field. However, obtaining absolute lichen fraction values was not the goal of the SMA procedure. Instead, relative values between sites were of greater interest in this study, and this information is highly useful for lichen mapping, particularly over larger areas. Fig. 3c presents the lichen fraction of SMA results for the two areas of the Landsat image. Darker areas indicate low lichen coverage, whereas lighter areas indicate higher lichen abundance. Black pixels indicate excluded areas. A visual comparison with the false colour composite and the ECM classification also showed a good representation of lichen areas.

5. Conclusion

The purpose of this paper was to assess spectral mixture analysis and a classification method for various aspects of mapping lichen in a northern heterogeneous environment. The enhancement-classification method gave good results in discriminating lichen from nonlichen classes. This was useful in providing a broad, spatially comprehensive land cover map that is required in land cover studies. However, the ECM was limited in its capability to accurately discriminate amongst specific lichen classes. Spectral mixture analysis also showed good results in separating lichen from nonlichen classes while also providing additional information within the lichen class itself. Given that ECM represents an advanced classification approach for large areas in boreal environments, the fact that it was unable to provide acceptable classification results for the lichen classes provides greater significance to the SMA results. In the absence of being able to classify the various lichen classes, the SMA provides important new information on lichen abundance that may indeed be more relevant to the environmental application. The basis for this is the critical dependence on lichen as a major food source for caribou and the influence of spatial patterns of lichen abundance on caribou migration and demographics. From this perspective, the amount (or abundance) of lichen is more important than the particular land cover class that it occurs in. This suggests that the classification of detailed lichen classes (such as those attempted in the ECM with minimal success) is not as relevant as the more fundamental issue of lichen food abundance. Accordingly, the ability to provide new and unique (in terms of fraction abundance) discrimination amongst the various lichen areas was deemed to be the major strength of the SMA method. We selected *C. stellaris* as an indicator because it is the dominant lichen species distributed over the study area, it is vulnerable to trampling, and it is eaten by caribou. If this methodology is to be applied elsewhere, it should be adapted to the lichen community by selecting the dominant or most representative species related to habitat use by caribou. We also reiterate the potential limitations of these results, owing to the smaller number of field sites that were possible to obtain in this remote, northern, inaccessible study region. This could have affected the validation and subsequent classification accuracies reported; however, this is typical of studies in this type of setting where there is no other way to obtain such comprehensive information. Accordingly, the capability to provide this level of information is significant, and as a result, it is realistic to tolerate a greater level of constraint in field sampling. Additional and complementary studies in classification and SMA to provide further insight into the advantages of this type of approach are warranted.

These two methods could also be used in a synergistic fashion to allow a stratification of analysis and possible refinement of results. Firstly, ECM could be used to make discriminating maps between lichen and nonlichen areas. SMA could then be used to give quantitative information on lichen cover. SMA could be modified to refine lichen characterization by selecting one end member set for each lichen class. Nonlichen classes would be excluded at the first step and not considered for the SMA analysis. As in any coupled approach, the level of error can propagate through the analysis and in some cases be multiplicative, and so, intermediate error assessment would be recommended.

Another area for future research involves use of multiple sets of end members representative of the combinations of surface features that characterize individual classes, whereby the SMA would provide an initial classification based on a minimum error rule. This would provide absolute lichen fractions for a variety of lichen species.

Based on the encouraging results obtained in this study, current attention in this research is focused on applying SMA to a large area mosaic of 13 Landsat TM scenes encompassing the entire summer range of the George River Caribou Herd, and doing a spatiotemporal analysis of lichen pastures that to date have been characterized in a limited fashion based on image classification only.

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