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Spectral properties of rock encrusting lichens and Woodland Caribou habitat

by

Robert Edward Bechtel

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

Department of Earth and Atmospheric Sciences

Edmonton, Alberta

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ABSTRACT

Reflectance spectra of rock encrusting lichens were acquired to determine the influence that this vegetation type can have on the reflectance properties of rock exposures located in high latitude and subarctic environments. The transmittance of lichens was assessed using foliose lichens (*Umbilicaria torrefacta*) and is estimated to be less than 3% through the 350-2500 nm spectral region investigated. Discrimination of lichen species (both crustose and foliose) is made possible using ratios of reflectance at 400/685 nm and 773/685 nm. An index using the band ratios 2132/2198 nm and 2232/2198 nm outlines the similarity of lichen spectra in the infrared and a distinguishing feature between rocks with OH^- bearing minerals and lichen. Thus, spectral unmixing of rock and crustose/foliose lichens can be successfully accomplished using a single lichen endmember for this spectral range.

Woodland Caribou (*Rangifer tarandus caribou*) habitat mapping in northern Alberta, Canada is incomplete and imprecise. Spectral information obtained through remote sensing observations makes possible the identification of important Woodland Caribou habitat over large areas. With the use of Global Positioning System (GPS) collars fitted on the animals, correlations between satellite observations from Landsat TM and Woodland Caribou locations were studied. It was concluded that the spectral classes derived from Landsat TM imagery can be related to Woodland Caribou occurrence and as such, could be used as a basis for habitat mapping.

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CHAPTER ONE

1.0 Introduction

1.1 Rationale

Prior to the 1960's, Earth observation was restricted primarily to visible wavelengths (Sabins 1997). Since then, a multitude of airborne and spaceborne sensors have been produced that can observe the Earth at wavelengths that are unseen by the human eye. The usefulness of the ability to sense the Earth at varying wavelengths has been recognized in most scientific fields and will help advance our understanding of the Earth system at a global scale (King 1999).

Colwell (1983) defines remote sensing as "the measurement or acquisition of information of some property of an object or phenomenon, by a recording device that is not in physical or intimate contact with the object or phenomenon under study". The primary advantage of observing from a distance is that it is an unobtrusive technique that does not disturb the object or area of interest (Jensen 2000). However, for remote sensing techniques to be useful, the interpretation of the image by the user, must be accurate and meaningful.

Image interpretation is the important step of converting an image into information that is meaningful and valuable for a wide range of users (Sabins 1997). Interpretation requires an understanding of the spectral characteristics that occur on the ground and an understanding of the data recorded at the sensor level. As Sabins (1997) points out, the interaction between matter and electromagnetic energy is determined by:

1. the physical properties of matter, and
2. the wavelength of electromagnetic energy that is remotely sensed.

The above concept of image interpretation precisely describes the motivation for this thesis. The first paper (chapter two) is intended to describe the *in situ* spectral characteristics of rock encrusting lichens that may compromise the ability of mapping the reflectance signatures of minerals forming the rock substrate (Rivard and Arvidson 1992). The second paper (chapter three) uses satellite imagery (Landsat 5 Thematic Mapper) to map Woodland Caribou habitat using a combination of satellite imagery, radiotelemetry locations, field work and Geographic Information Systems techniques, and in an ecological information context. This chapter relies on spectral signatures at the sensor level and makes no comparisons to on-the-ground reflectance. However, as demonstrated in this thesis, important Woodland Caribou habitat information can be obtained by unobtrusive, passive measurement (Jensen 2000).

1.2 Spectral Properties of Crustose and Foliose Lichens

Remote sensing for the purpose of mineral exploration is becoming increasingly available for regional geological mapping and mineral exploration (Staenz et al. 1998; Kruse 1999). Therefore, the physical properties of rock encrusting lichens must be fully investigated in the laboratory before remotely sensed image interpretation can be effectively performed. Chapter Two involves the spectral measurement and analysis of lichens on quartzite samples from the Gog quartzite formation in Jasper, Alberta, Canada. The measurements are in the 350-2500 nm range, and provide important baseline information necessary for the interpretation of lichens from remote observations through identifying key spectral features.

One of the integral underlying questions that has yet to be established is whether or not lichens transmit electromagnetic radiation (light) through their structure (thallus). If light is able to pass through the lichen thallus, then a spectral signature collected from above the target will be a combination of signatures from the lichen and the underlying rock, a situation referred to as spectral mixing (Smith et al. 1990; Mustard and Sunshine 1999). Another possibility is that light is not transmitted at shorter wavelengths (closer to 350 nm), but can transmit at longer wavelengths (closer to 2500 nm). The absence of light transmittance through lichen and its interaction with the rock substrate is a key assumption that is made whenever remote sensing analysis in lichen-dominated environments is performed, and this research helps address this crucial assumption. From the results, we propose that lichens do not transmit light to their rock substrate (between 350-2500 nm) and therefore effectively mask the mineral substrate.

While the above objective deals with mixing of lichen and its underlying substrate, remotely sensed observations introduce a different type of mixing. Because the sensor field of view (FOV) contains varying combinations of lichens and exposed rocks, mixing of spectral signatures occurs. Furthermore, different species of lichens can alter mixed pixels differently at various wavelengths. An in depth understanding of lichen spectral signatures is required for the use of spectral mixture analysis (SMA) (Smith et al. 1990; Mustard and Sunshine 1999). SMA assumes that mixed spectra result from the linear combination of spectral end-members (Singer and

McCord 1979). For my thesis, the relationship between rock encrusting lichens and their quartzite substrate was investigated. With the rock substrate representing one pure end-member and lichen representing another, spectral band ratios were used that were able to separate rock signatures from lichen signatures. Furthermore, band ratios were also used to examine the variation in lichen spectra in association with colour, type, and species of lichen. From the results, we suggest a set of spectral indices to discriminate lichens and a set of spectral indices to guide the selection of a single lichen endmember for use in the spectral mixture analysis of rock and lichen. With an understanding of the key spectral characteristics of lichens in place, we can further our research and understanding in geological and mineral mapping techniques.

1.3 Woodland Caribou Habitat Classification

Chapter Three describes a technique in which remote sensing imagery is used to determine Woodland Caribou (*Rangifer tarandus caribou*) habitat in a northeastern Alberta landscape. Woodland Caribou in Alberta are considered 'threatened' by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC 2000) and are also considered 'threatened' in Alberta (Dzus 2001). As a result, effective conservation strategies are requiring input from accurate habitat maps. Unfortunately, present Woodland Caribou habitat maps are considered to be imprecise, as consistent land cover mapping specifically designed for Woodland Caribou is not available.

As a result, this paper uses a combination of satellite imagery, GPS (Global Positioning Systems) and VHF (Very High Frequency) radiotelemetry locations, field work, Geographic Information Systems techniques, and ancillary ecological information to develop a Woodland Caribou habitat classification. The process is unique in that the habitat selection is entirely driven by Woodland Caribou (GPS) locations, not by human interpretation of what is believed to be suitable Woodland Caribou habitat (e.g. habitat suitability indices).

The result is a large-scale habitat mapping technique that is capable of detecting Caribou occurence from remotely sensed observations. The technique provides a reproducible methodology that requires minimum user input and allows unobtrusive evaluation of Woodland Caribou habitat.

Furthermore, the analysis was repeated with lower spatial resolution VHF data, which showed similar results to the higher spatial resolution GPS data (White and Garrott 1990). The ramifications of these findings are twofold. First of all, the independent VHF dataset verifies the GPS procedure by producing similar results. Secondly, the similarity in results indicates that VHF location datasets will be able to reproduce the procedure in areas where GPS location data are not available. This is important since VHF location data are more widely available and have a much longer historical record than GPS location data.

Finally, the results from the habitat selection that occurred within the study area can be extrapolated to areas outside of the study area through image interpretation. This allows areas of known Woodland Caribou occurrence to be used as training sites to find areas with similar spectral characteristics where no Caribou location data exist. In essence, we can predict Woodland Caribou habitat in areas outside of the study area by matching spectral signatures. This capability strengthens the usefulness of remote sensing interpretation for the purpose of habitat identification.

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CHAPTER TWO[1]

2.0 Spectral properties of foliose and crustose lichens based on laboratory experiments.

2.1 Introduction

Hyperspectral remote sensing systems are becoming increasingly available for regional geological mapping and mineral exploration where cost saving measures are key to commercial competitiveness (Staenz et al. 1998; Kruse 1999). The mixture of several materials within individual pixels can complicate the analysis of multi and hyperspectral information, often masking the diagnostic spectral features of materials of interest and hampering their classification. A widespread example of this problem in high latitude, subarctic regions is the ubiquitous presence of lichens covering exposed rocks that can compromise the ability to map the reflectance signatures of minerals from imaging spectrometer data (Rivard and Arvidson 1992). In tundra and open woodland habitats, lichens and mosses can cover 70% of an area (Solheim et al. 2000), making it difficult to develop comprehensive mapping exercises aimed at resource extraction. Fortunately, the use of spectral mixture analysis (SMA) as described by (Smith et al. 1990; Mustard and Sunshine 1999) addresses the complexity of target identification within mixed pixels and can allow detection of substances exposed at sub pixel resolution. Typically this approach assumes that mixed spectra result from the linear combination of spectral end-members (Singer

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R. Bechtel, B. Rivard, and A. Sanchez

and McCord 1979). The spectra of endmembers are either extracted from the imagery or measured in the laboratory or in the field.

Rock coatings (non-biogenic and biogenic) are scattering/transmitting layers with optical thickness that can vary with material properties and wavelength. Lichens and desert varnish are examples of biogenic and non-biogenic rock coatings. Desert varnish is a non-biogenic patina of mixed-layer illite clays and nanocrystalline iron and manganese oxides partially covering rock surfaces in Earth's deserts (Potter and Rossman 1977; Sultan et al. 1987; Rivard and Arvidson 1992). We know that varnish can, in instances, completely mask the spectral signature of underlying rock material, but in general, it is optically thin (between 400-2500 nm) to the underlying bedrock (Rivard and Arvidson 1992). The use of a representative spectral endmember for varnish in SMA and the simplifying assumption of linear mixing typically used for this analysis can therefore be complicated in instances where varnish is partially translucent to the rock substrate.

Lichens, mosses and cyanobacteria are specific examples of biological coatings known as lithobionts. The spectral properties of lithobionts have been the focus of a number of studies (Karnieli and Tsoar 1995; Karnieli et al. 1996; Tommervik et al. 1997) that report similarities with higher plants as well as key spectral distinctions. Examples of similarities and distinctions are discussed below in section 2.3.1. However, to date there is minimal literature that thoroughly describes the spectral characteristics of rock encrusting lichens (Solheim et al. 2000). A study of spectral characteristics specific to lichen on granitic rock surfaces was performed by Satterwhite et al. (1985), but the data were limited to the 400-1100 nm range which excludes the short wave infrared region exploited by many hyperspectral instruments relevant to the analysis of geological targets. Petzold and Goward (1988), focused on *Cladina* (a dominant boreal forest and low arctic tundra lichen), and also reported results limited to the 380-1100 nm region. Ager and Milton (1987) reported spectra covering the region from 400-2500 nm and attributed the variation of spectral characteristics of lichen solely to colour. While colour is a key spectral attribute of lichens, this study reports spectral distinctions in different species of lichens of the same colour. Rivard and Arvidson (1992) examined spectral features distinct to rock encrusting lichens based on a small number of measurements, but failed to identify the species of lichens used in their analysis, therefore limiting the use of their results.

An important issue in the study of the spectral reflectance of lithobionts is the lack of information on their ability to transmit light photons. The suggestion that lichens do not transmit light photons was made early on by Gates (1980) who reported that lichens have low transmittance, though no measurements were presented to support this statement. Ager and Milton (1987) reported unpublished transmittance results of green and brown foliose lichens acquired by J. Salisbury at John Hopkins University. The reported transmittance values did not exceed 0.15% between 2170 and 14500 nm. The determination of lichen transmittance is key in assessing the assumption that satellite reflectance measurements represent mixtures of lichen and rock reflectance linearly weighted by their respective surface cover. Therefore, the first aim of this paper is to study transmittance of lichens in the 350–2500 nm region. We have selected this spectral range because of its relevance to that of many current airborne hyperspectral remote sensing systems. From the results, we propose that lichen essentially do not transmit light to their rock substrate and therefore effectively mask the mineral substrate. The second aim of this paper is to examine the variation in lichen spectra in association with colour, type, and species of lichen. From the results, we suggest a set of spectral indices to discriminate lichens and a set of spectral indices to guide the selection of a single lichen endmember for use in the spectral mixture analysis of rock and lichen.

2.2 Experimental Approach

Lichen-bearing rock samples were collected in June 1999 from the Gog Quartzite Formation in Jasper, Alberta, Canada (52°12'N, 117°15'W). The quartzite substrate is ideal for an investigation of lichen spectral properties because it provides uniformly high reflectance and mineral absorption features are well understood and likely discernable from that of lichen. The quartzite samples are compositionally homogenous and, therefore, show little spectral variation within samples and between samples. Twenty-seven lichen-bearing rock samples were collected and measured within a two-week period to ensure a healthy condition of the lichens. While not in use, the samples were stored in an outdoor, natural environment with direct sun and exposed to wind and rain. Reflectance spectra were acquired from five different locations on each of the seventeen lichen patches, comprising a total of five different species (table 2-1). The measurements were taken using a FieldSpec FR spectroradiometer, which operates in the 350-2500 nm spectral range and is characterized by a resolution of 3 nm at 700 nm, 10 nm at 1500 nm, and 10 nm at

2100 nm (Analytical Spectral Devices, 2001). Measurements were recorded as an average of forty scans in order to minimize instrument noise.

To assess the transmittance of lichens, measurements of reflectance were acquired on lichen samples that could be excised from the rock substrate without damaging or altering the lichen. Each foliose lichen sample was placed on a white Spectralon reference panel (99% reflectance) and measurements were recorded. The sample was subsequently placed on a black Spectralon reference panel (2% reflectance) and a spectra was measured again. Each measurement was normalized to a bare 99% reflectance panel to calculate reflectance.

In order to measure pure patches of crustose and foliose lichen species, the field of view (FOV) of the spectroradiometer must be sufficiently small to preclude viewing a mixture of lichen and rock (figure 2-1). The FOV must also be sufficiently small to ensure that only a single species of lichen is being measured at a given time. For the lichen patches on our samples, a FOV of approximately 0.5 cm in diameter was required. This FOV condition was achieved by bringing a fiber optic (FOV 25°) into a position normal to the surface within 1 cm of the sample. The close proximity of the fiber optic to the sample implied a minimum angle of 35° from the zenith for the source of illumination to ensure the absence of a shadow in the FOV that would result from the tip of the fiber optic. For the experiments, two halogen lamps placed on opposite sides provided concurrent illumination from 0° and 180° azimuth. This measurement scenario was implemented to avoid the effect of shadows resulting from the microtopography of the sample. Reflectance spectra were obtained by determining the ratios of data acquired for a sample to data acquired for the 99%

reflectance spectralon panel under the same illumination and observation conditions. Measurement of the natural targets took place within minutes of the standard panel measurement to minimize the effect of instrument drift.

2.3 Results

2.3.1 Spectral Features of Rock Encrusting Lichens

Dark coloured crustose and foliose lichens display a reflectance between 3 and 7% in the visible range (figure 2-2). Both the grey-black crustose (eg. *Aspicilia cinerea* and *Rhizocarpon bolanderi*) and the brown-black foliose (e.g. *Umbilicaria torrefacta*) lichens exhibit a weak absorption feature at 685 nm attributed to the presence of chlorophyll. This absorption is not seen in the spectra of *Rhizocarpon geminatum. Rhizocarpon geographicum* is a mosaic of tiny green 'tiles' (areoles) set against a distinctly black background (Johnson et al. 1995). The green appearance of this lichen comes from the presence of these areoles, not from the lichen thallus itself. The reflectance is 4-5% at 400 nm and quickly rises to approximately 11-17% from 520 nm until the chlorophyll absorption at approximately 685 nm. *R. geographicum,* shows a green peak at approximately 550 nm that is more characteristic of vascular plants than some of the darker coloured lichens. Dark coloured lichen species (brown, grey, and black) do not have a green peak in reflectance. All lichens sampled in this study had a gradual increase in reflectance to 1380 nm followed by an absorption feature centered near 1445 nm caused by water in the lichen. The spectra then display an increase in reflectance reaching a maximum value around 1850 nm.

Beyond the water absorption feature near 1935 nm the spectra are similar in shape for all species investigated.

Ager and Milton (1987) identified three broad absorption features near 1730, 2100, and 2300 nm, which are attributable to the presence of cellulose in lichen. These broad features are seen in the spectra shown on figure 2-2, but there are also other subtle features. Specifically, for most lichen species, the absorption at 1730 nm occurs with two other absorption features at approximately 1690 and 1770 nm. The 1770 nm feature is also attributable to cellulose (Fourty et al. 1996) and its depth varies amongst species. A broad feature near 2300 nm is present in all lichens of this study but it encompasses two absorptions near 2300 and 2355 nm. However, an absorption feature at 2355 nm also appears in the quartzite spectra and it therefore cannot be uniquely associated with lichen. The specific feature near 2300nm was not observed in foliose lichens and was weak or absent in some crustose lichens. Although the amplitude of the subtle absorption features can vary among species, the overall shape of the spectra is very similar, particularly between 2100 and 2400 nm. This characteristic spectral shape can provide the possibility to determine a representative spectral endmember for lichens that might be used to solve mixtures of lichen and rock.

2.3.2 Transmittance of Light Through Lichen

Foliose lichen samples (*Umbilicaria torrefacta*) were well suited to assess the transmittance of lichens. *Umbilicaria* are attached to the rock substrate by a single holdfast called an umbilicus (Johnson et al. 1995), which can be cut without affecting the exposed surface of the lichen. The area of the samples covered the entire field of view of the sensor and no gaps in the lichen thallus were visible. Five samples were selected which displayed a relatively flat surface to minimize microtopographic variations, which could influence the magnitude of the reflectance.

Reflectance spectra of *Umbilicaria* on 2% and 99% reflectance reference panels show only small differences in magnitude ranging from 0% to 3% (figure 2-3). The greatest difference is observed near spectral peaks at 1380, 1660, and 1850 nm (figure 2-3). The small difference in reflectance for the two different panels indicates that foliose lichens transmit little or no light. In fact, some of the observed minor differences between the two measurements could be largely due to uncertainties in the sample alignment as it was moved from the white reference panel to the dark reference panel. An indication that this could be the case is that there are regions of the difference spectrum where the measurement for the dark panel has slightly higher reflectance than that of the white panel (e.g. at the bottom of the 1900 nm water absorption feature).

2.3.3 Discrimination of Lichen Species

For this study, a plot of the ratio of reflectance at 400/685 nm against 773/685 nm was used to isolate the spectral characteristics of different colours, types, and species of lichen. Wavelength bands selected are located in areas of the spectrum that are not influenced by water absorption features. The value of reflectance at the 400 nm wavelength was used because all lichens, regardless of colour or type, have a reflectance of less than 7% at this wavelength (figure 2-2). This low reflectance may be due to the presence of usnic acid, which occurs in many lichen species and depresses the reflectance of lichen (Ager and Milton 1986). Rock reflectance at this wavelength is often greater than 30% and is helpful in distinguishing rock signatures from lichen signatures. The value of reflectance at the wavelength of 685 nm is utilized because it is assumed to represent the absorption that is associated with the presence of chlorophyll. Reflectance at 773 nm is characterized with high reflectance in lichens and was chosen because its value of reflectance did not seem to vary among the lichen species. This is consistent with work by Gitelson et al. (1999) who found that reflectance of plants was no longer dependant on the chlorophyll content past 750 nm.

Reflectance for the quartzite rock samples shows moderate values for the 400/685 nm ratio and distinctly low values for the 773/685 nm ratio (figure 2-4), which are distinct from that of the lichen. The foliose lichen (*U. torrefacta*) spans a relatively large range in figure 2-4, with high values for both ratios. The green crustose lichen (*R. geographicum*) forms a group that has low values for both ratios. The index also appears to discriminate species of lichens of the same colour and type as indicated by the ellipse on figure 2-4 that show measurements common to a given species or to the rock (quartzite). For example, *R. bolanderi*, a grey to black crustose lichen, has high values for the 400/685 nm ratio and moderate values for the 773/685 nm ratio. *R. geminatum*, another dark, black crustose lichen has, however, high values for the 400/685 nm ratio, but lower values for the 773/685 nm ratio, forming a different group. *A. cinerea*, a greyish, black crustose lichen, assembles somewhere in between the *R. bolanderi* and the *R. geminatum*, with the 400/685 nm ratio ranging from high to mid values. *A. cinerea* appears anomalous because two samples plot in different locations than the other three samples of this species. The two anomalous samples came from the same rock sample and were identified as having a parasitic infestation. This may have led to an alteration in their spectral reflectance.

2.3.4 Discrimination of Rock and Lichen

Ager and Milton (1986) found that the reflectance of a group of lichens beyond 1400 nm differed by less than 5 percent. Rivard and Arvidson (1992) reached similar conclusions though they were unable to quantify the similarities due to the potential contamination of their lichen spectra by the rock substrate. This study explored the possibility of using this similar spectral character to distinguish lichen from rock.

An index using the band ratios 2132/2198 nm and 2232/2198 nm outlines the similarity of lichen spectra in the infrared and a distinguishing feature between quartzite rock and lichen (figure 2-5). In silicate minerals, vibrational absorptions in the 2200 to 2400 nm wavelength region related to combination bands involving the hydroxyl ion (OH^-) fundamental stretching mode have been well documented in the literature (Hunt 1977; Hunt and Salisbury 1970; Clark et al. 1990). The quartzite samples exhibit a strong OH^- related absorption feature centered near 2200 nm (figure 2-2). Reflectance at 2132 nm and 2232 nm were selected for the index because they represent spectral regions of high reflectance for this rock, which are located on each side of the diagnostic hydroxyl absorption feature centered near 2200 nm. In contrast, lichens display a particularly strong reflectance peak (Ager and Milton

1987) in this region that facilitates the use of a simple index for the discrimination of lichen from rock.

On figure 2-5, the majority of lichens cluster tightly in an area of low values for both ratios, whereas the rock signatures extend linearly from mid to high values. Variability in both ratios for the rock spectra reflects variability of the hydroxyl band depth. Spectra with greatest band depth display the largest ratios. The lichens, regardless of type (crustose or foliose), colour, or speciation, tend to cluster, with the single exception of *R. geminatum* which are located toward, but not into, the rock endmembers. The appearance of the *R. geminatum* as a separate group has two possible explanations. *R. geminatum* could have a spectral shape unique from that of the other lichens of this study. Alternately, the *R. geminatum* could have shrunk by means of being in a dry state differently from the other lichens samples, and allowed light transmittance between the fungal bodies. Mixing of lichen and rock in the FOV would thus result in a spectrum with ratio values distributed along a curvi-linear array between pure lichen and pure rock. There is a suggestion from figure 2-5 that some measurements of foliose and crustose lichens with ratio values above that of the dominant data cluster can yet record the influence of rock interstitial to lichen. The remainder of the lichen data defines a common lichen signature characterized by a limited range of ratio values.

2.4 Discussions and Conclusions

A key objective of this study was to determine the magnitude of light transmittance through rock encrusting lichens. The results have important implications for modeling lichen/rock mixed pixels in airborne and spaceborne hyperspectral data for the purpose of mineral mapping. For this study, a comparison of spectral measurements of excised foliose lichen on a 99% reference panel and a 2% reference panel indicates that foliose lichens transmit little or no light (between 0-3%). Unfortunately, the rock encrusting nature of crustose lichens has prevented a similar study from being performed, as removal of crustose lichens from rock substrate was not possible. However, the similarity in the overall spectral shape (in the longer wavelengths) of these lichens with that of foliose lichens (figure 2-2 and 2-5), suggests that crustose lichens also transmit little or no light. These findings support the use of linear mixture models for the deconvolution of lichen/rock mixtures because it shows that the optical thickness of lichen largely prevents the transmission of photons though the lichen mat. Therefore, the sub-pixel influence of lichen and rock within a scene can be considered linearly weighted.

Discrimination of lichen group (crustose versus foliose) colour, and species is made possible through the creation of a ratio of reflectance at 400/685 nm against 773/685 nm. It was found that different colours of lichen tend to plot in very distinct groups. This result was expected as the ratios exploit a chlorophyll absorption feature, which varies with pigmentation. The shape of the green peak in *R. geographicum*, a green, crustose lichen, is considerably more plant-like than the flat spectra associated with black crustose lichens. Also, the ratios were able to distinguish foliose lichen from crustose lichen, even though colouration between foliose types and some crustose types was very similar. Lichen samples of similar colour and type, but different species, can also be discriminated with these ratios. For example, three different species of grey to black crustose lichens (*R. geminatum, R. bolanderi*, and *A. cinerea*) were discriminated from one another. However, further measurements of the grey and black crustose lichen species are required to determine if the robustness of the proposed distinctions and provide statistical constraints to the fields delineating species spectral characteristics on figure 2-5. In fact, with the current data removal of the ellipses would limit the usefulness of this ratio for discriminating *A. cinerea and R. bolanderi.* The ratios also show separation of the quartzite substrate from all lichen samples.

Although it is possible to distinguish the three grey-black crustose species (*R. geminatum, R. bolanderi*, and *A. cinerea*) used in this experiment, it cannot be said that all lichen species can be distinguishable using this approach. A much larger sample of lichens, from various study sites, should be measured and compared using the ratio of reflectance at 400/685 nm against 773/685 nm. This would provide a better indication of the ability to separate lichens by species at these wavelengths. With the thousands of lichens species that exist (Hale 1983) it is unclear how many species can be spectrally identified given that many species can only be distinguished based on variations in physical parameters (Price 1994).

The limited range of the 2132/2198 nm and 2232/2198 nm ratio values for rock encrusting lichens supports previous observations by Rivard and Arvidson (1992), who show such lichens tend to have similar spectral curves in the longer wavelengths. This ratio plots lichen samples into a tight group (figure 2-5), separate from quartzite rock samples, suggesting that a single representative lichen endmember can be defined to model lichen and rock mixtures. The results of this study have a significant implication in the analysis of satellite or airborne remote sensing imagery. Much of the analysis of hyperspectral data for geological application is based upon the detection and identification of important OH features that occur in minerals within the 2000 to 2400 nm range. This study reveals the similarity of spectra for most foliose and crustose lichens species within this spectral range, which are distinct from those observed in OH bearing minerals. Thus spectral unmixing of rock and crustose/foliose lichens can be successfully accomplished using a single lichen endmember for this spectral range. The proposed infrared ratios applied to the analysis of hyperspectral data can provide a simple means to discriminate rock exposures with varying lichen abundances.

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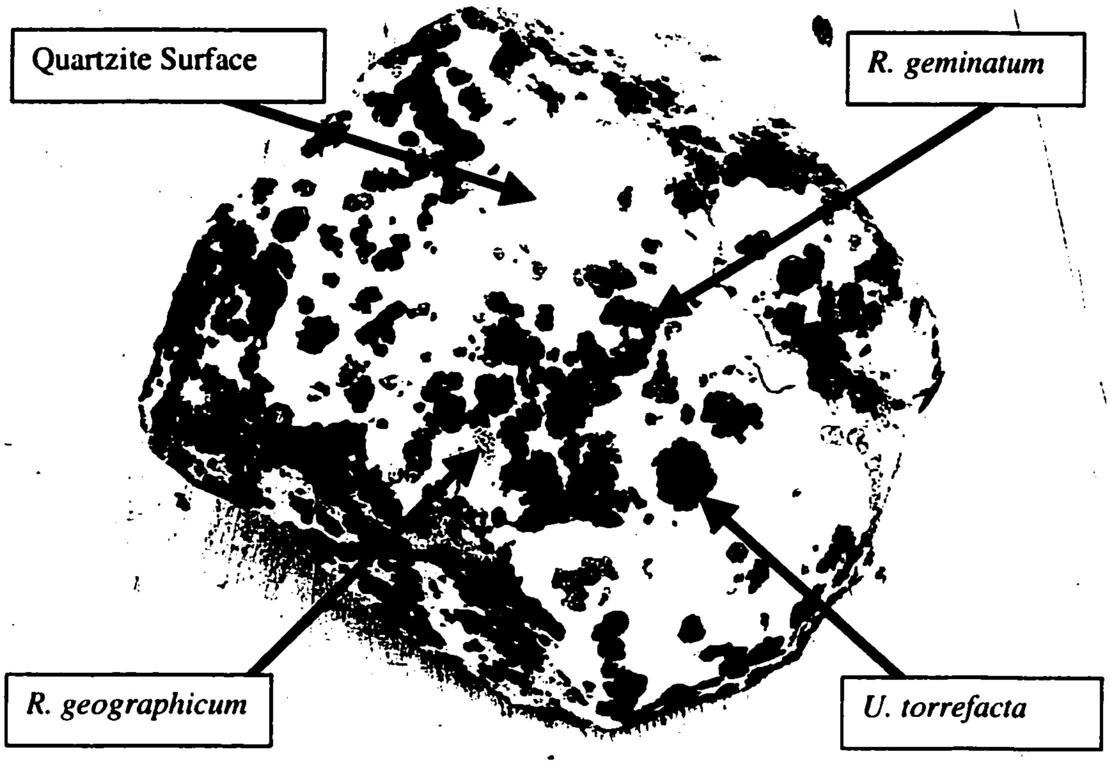

Figure 2-1: Quartzite sample partly covered by crustose (*Rhizocarpon geographicum* and *Rhizocarpon geminatum*) and foliose (*Umbilicaria torrefacta*) lichen. The sample has a width of 20 cm.

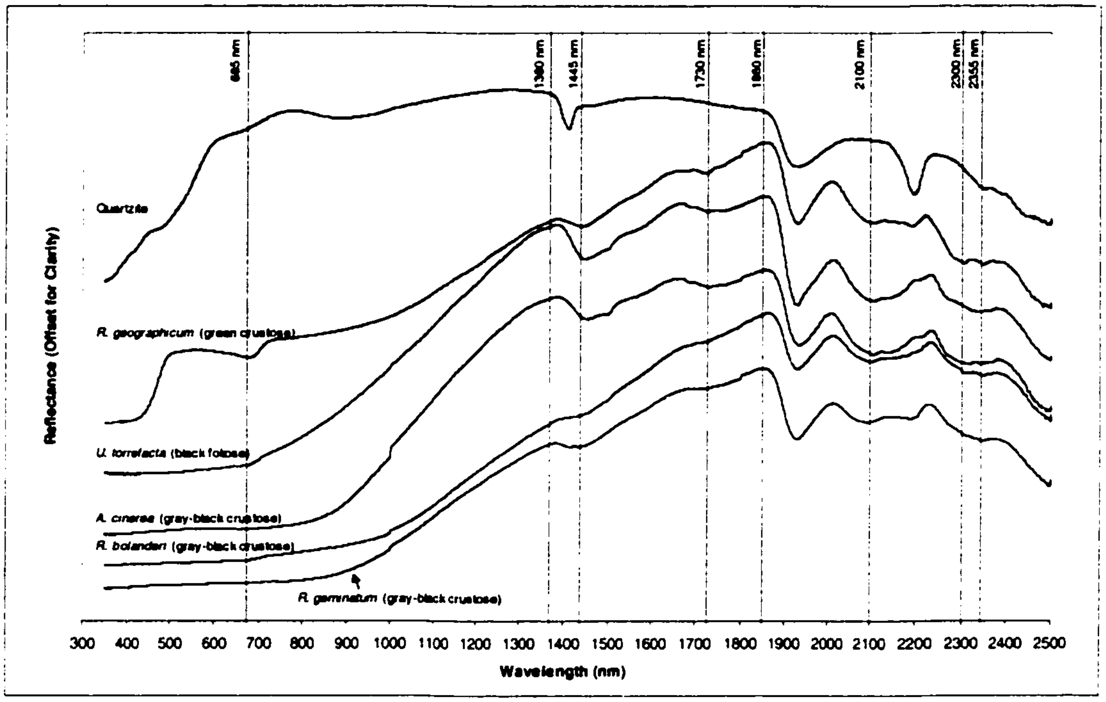

Figure 2-2: Spectral characteristics of five lichen species and quartzite (350-2500 nm). The vertical dashed lines mark the location of spectral features discussed in the text. Reflectance for y-axis is offset for clarity.

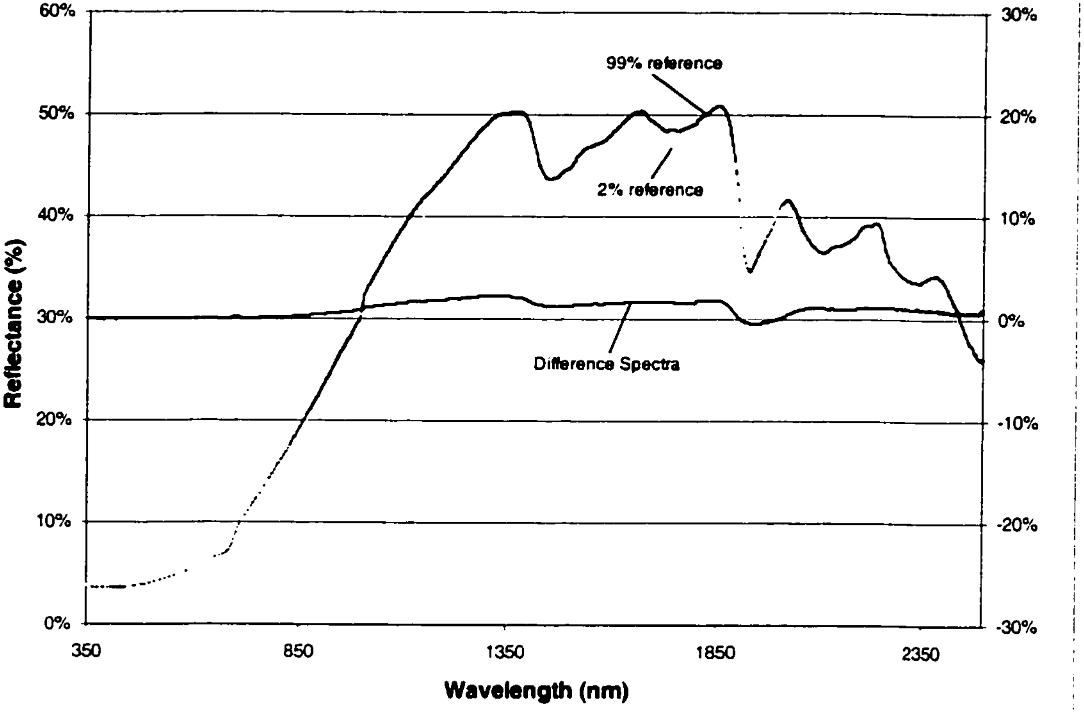

Figure 2-3: Reflectance spectra of foliose lichen on 99% reference panel and 2% reference panel. Reflectance for the difference spectra (99% – 2%) is displayed on the right.

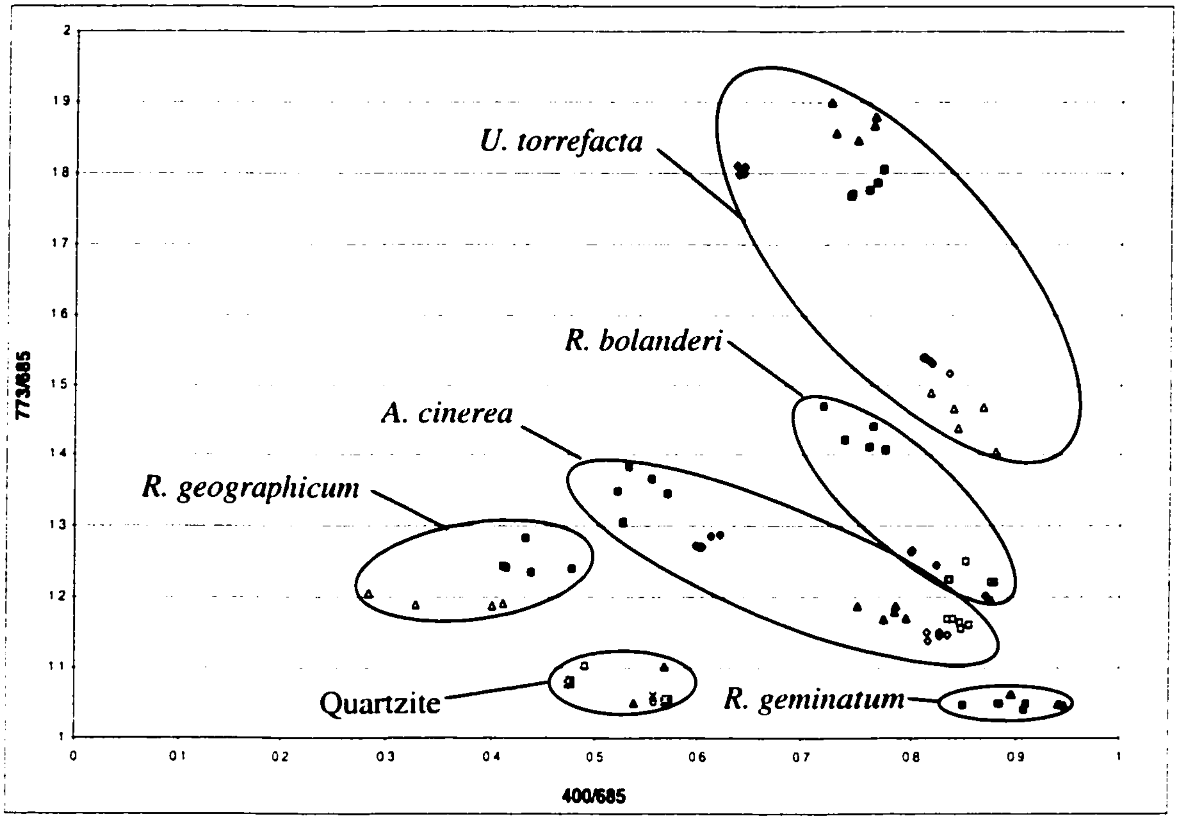

Figure 2-4: Index 400/685 nm vs. 773/685 nm showing the separation of rock from lichen and the separation of different lichens species. Foliose lichens (*Umbilicaria torrefacta*) are black in color. *Rhizocarpon bolanderi*, *Aspicilia cinerea*, and *Rhizocarpon geminatum* are grey-black crustose lichens. *Rhizocarpon geographicum* is a green crustose lichen. Five measurements from each lichen sample were taken and are separated from same species samples with different marker symbols. Ellipses encompass measurements common to a given species or for rock (quartzite).

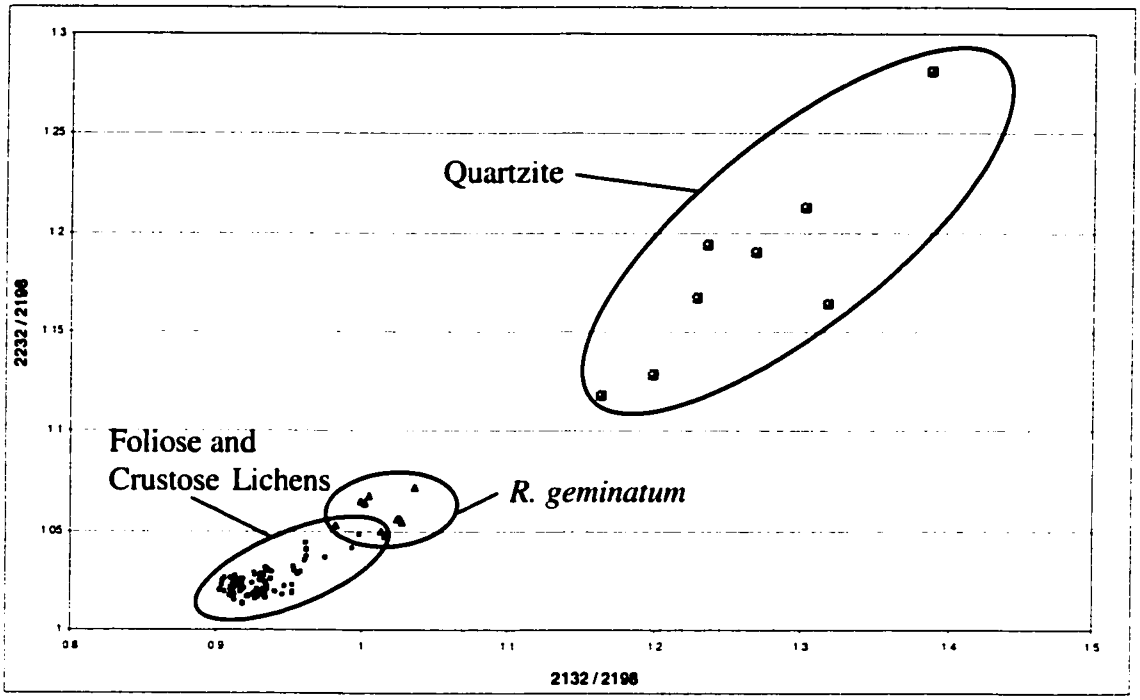

Figure 2-5: Index 2132/2198 nm vs. 2232/2198 nm showing the separation of rock from lichen. Individual measurements of lichens are shown as black squares except for *Rhizocarpon geminatum*, which is shown as small triangles. Five measurements are shown for each lichen sample.

Lichen Species	**Type**	**Colour**	**Number of Patches**	**Total Samples Measured**
Umbilicaria torrefacta	Foliose	brown-black	5	25
Rhizocarpon bolanderi	Crustose	grey-black	3	15
Rhizocarpon geminatum	Crustose	black	2	10
Rhizocarpon geographicum	Crustose	green	2	10
Aspicilia cinerea	Crustose	grey-black	5	25

Table 2-1: Lichen species investigated. Species that were identified on at least two different rock samples. A total of 85 individual lichen measurements were used.

CHAPTER THREE

3.0 Woodland Caribou Habitat Classification Using Landsat TM Imagery and GPS Data.

3.1 Introduction

Woodland Caribou (*Rangifer tarandus caribou*) in Alberta, Canada are considered 'threatened' by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC 2000) and are also considered to be 'at risk' in Alberta (Dzus 2001; Alberta Sustainable Resource Development 2001). As a result, effective Woodland Caribou conservation strategies rely on input from accurate habitat maps and there is a pressing need for such maps in Alberta. Unfortunately, present Woodland Caribou habitat maps are considered to be imprecise, as consistent land cover mapping specifically designed for Caribou is not available.

The precision of caribou habitat mapping is limited by our understanding of detailed habitat relationships. Incomplete or crude land cover mapping exacerbates this problem. Analysis of correlations between Woodland Caribou locations and Landsat Thematic Mapper (TM) can improve our understanding of habitat characteristics and the extent of suitable habitat over large areas. This kind of information is necessary to help develop appropriate conservation strategies (Bradshaw et al. 1995).

Habitat mapping through the use of remote sensing has been performed in a number of settings and on a variety of vegetation and animal species. Satellite imagery has been used to assess habitat characteristics of white-tailed deer

(*Odocoileus virginianus*) based on previously classified land cover maps (McClain and Porter 2000). Satellite data have also been used, in combination with fire data, to estimate lichen biomass and grazing potential for Woodland Caribou in Northern Quebec (Arsenault et al. 1997). However, the imagery was not used to identify particular habitat selection of classes and there were no telemetry data utilized. Hansen et al. (2001) performed a detailed Mountain Caribou habitat mapping project in British Columbia, Canada using Landsat TM and Multi-Spectral Scanner (MSS) data as input for landscape analysis. However, caribou preference was based on a Habitat Suitability Index (HSI) using the four parameters of elevation, slope, habitat unit, and stand age, as opposed to actual caribou locations.

Much of the current Woodland Caribou habitat mapping in northern Alberta is based on peatland inventory maps (Schneider et al. 2000; Bradshaw et al. 1995), as peatland complexes have been identified as being extremely important to Woodland Caribou (Fuller and Keith 1981; Bradshaw et al. 1995; Anderson 1999; Stuart-Smith et al. 1997). While effective at a gross level, this approach is limited to information directly related to peatland classification. For example, Schneider et al. (2000) used only the highest level of classification, from a low spatial resolution peatland map, resulting in categories of Bog, Fen, Marsh, Swamp, Non-wetland, and Non-peat. In Bradshaw et al. (1995), seven peatland habitat types were used. Stuart-Smith et al. (1997) observed a positive correlation between home ranges and fen complexes, but used only two categories of land cover, fens and upland, to represent ground cover. While all of these approaches provide a reasonable approximation of peatland types as representative of Woodland Caribou habitat, they are limited by a map classification that was not intended for wildlife habitat mapping. For example, upland areas and other non-peat areas are simply categorized as such. Forest inventory data have also been used to identify vegetation types available to Woodland Caribou (Rettie and Messier 2000) and although the vegetation cover was descriptive of forest cover, it included only one class to represent open peatlands. Our intent is not aimed at replacing existing caribou mapping projects, but rather to supplement existing work in order to derive the most accurate assessment of caribou habitat in Alberta.

Woodland Caribou habitat maps for Alberta have been created based on expert knowledge without considering field information on the confirmed presence or absence of Woodland Caribou in the landscape (Hansen et al. 2001). For this study, GPS and Very High Frequency (VHF) location data for Woodland Caribou are correlated to spectral satellite data to determine if Woodland Caribou habitat can be predicted in Alberta. This approach deviates from that of previous studies in that it allows the animal to directly indicate the preferred or avoided habitat. It could be interpreted as "inverse modelling" in which the Woodland Caribou locations confirm habitat utilization, as opposed to a predictive approach to determining where Woodland Caribou should occur in the landscape. The proposed approach would provide a technique that does not require *a priori* knowledge of land cover or habitat relations. If the correlations are strong, then the use of spectral signatures from satellite imagery can become useful baseline information for producing realistic Woodland Caribou habitat mapping. The validity of the procedure is assessed using an independent VHF dataset obtained from the same study area. A positive correlation will indicate that the classification process is effective, and more importantly, will provide evidence that VHF location datasets, which have lower positional accuracy than GPS, may also be useful in identifying Woodland Caribou habitats. Finally, the results of the habitat classification within the study area can be used to train a classification outside the study area and allow detection of possible or likely caribou habitat in areas where no GPS or VHF telemetry data are available.

3.2 Study Area

The study area is located in the Wabasca area (centered at 56°18'00" N, 113°12'00" W) in northeastern Alberta, Canada (figure 3-1) and extends for approximately 8600 km^2. It has a perimeter of approximately 375 km that was defined by connecting the outer telemetry locations of thirty-six collared caribou to form a convex polygon that included 100% of all GPS locations (White and Garrott 1990). The landscape is relatively flat, varying between 500 and 700 m elevation above sea level (Bradshaw et al. 1995). Black spruce (*Picea mariana*) peatlands dominate, with inclusions of trembling aspen (*Populus tremuloides*), white spruce (*Picea glauca*) and a small amount of jack pine (*Pinus banksiana*) in the upland areas.

3.3 Satellite Imagery

Two Landsat 5 Thematic Mapper (TM) images acquired on May 2, 1998 (Path 43, Row 20 and Path 43, Row 21) were needed for the spectral analysis of habitat occurrence. Landsat 5 TM utilizes six 28.5 m resolution bands in the visible (bands 1, 2 and 3; 450 to 690 nm) and reflected infrared (bands 4, 5 and 7; 760 to 2350 nm) wavelengths and one 120 m resolution band in the thermal infrared (band 6; 10.4 - 12.4 microns). Imagery used in this study was resampled to 25 x 25m pixels. The images used in this study have uniform and clear conditions over the entire study, and therefore were not atmospherically corrected. Recorded at a satellite altitude of 705 km, the images have a nominal swath width of 185 km. Both images were georectified using existing road and access coverage (scale 1:20,000). The resulting root mean square rectification error was less than half a pixel (RMSE = 14.25 m). The two images were merged and the minimum convex polygon required for the analysis was then extracted from the mosaic. Spectral signatures from the images were derived from 8-bit (0-255) Digital Numbers (hereafter referred to as DN).

3.4 Telemetry Data

Woodland Caribou location information came from 36 different animals fitted with GPS collars (Alberta-Pacific Forest Industries Inc. 1999). Data were collected between February 22, 1998 and August 22, 1999. Telemetry data were acquired as part of the Boreal Caribou Research Program and have been used in previous caribou studies (Anderson 1999; Dyer et al. 2001). The locations were measured using a Lotek Engineering GPS animal location system in combination with a Trimble base station. Locations were recorded approximately every two hours, except for a ten-day period when data were collected every twenty minutes. The dataset contained 98,803 locations, after removing the locations without differentially corrected fixes (Johnston 1998). The differentially corrected locations have a positional accuracy of less than 10 m. The database was divided into two samples, one half used for the caribou habitat analysis and the other to test the validity of our analysis. 18 animals were used in sample A (analysis) and another 18 were used for sample B (validation).

The distribution of Woodland Caribou locations were weighted equally for each individual animal to ensure that an animal that recorded more location data (i.e. was collared throughout the entire study period) did not get over-represented compared to an animal that recorded less location data (i.e. the animal was killed during the study period, GPS unit malfunctioned, etc.). This was done by first determining the percentage of occurrence for each individual within each specified class, and then taking the average of all animals for each class. Therefore, all 36 animals used in the analysis had equal weighting, regardless of the total number of points collected for a particular individual.

While the validation (sample B) allows an assessment of reproducibility, another validation was performed using a VHF caribou location dataset, also collected from the Wabasca area. Data were collected from a period between 1991 and 2000 and have a positional accuracy of approximately 100 metres. The 118 animals used were never equipped with a GPS unit, thus ensuring that different individuals were being tracked. The initial dataset included 7326 locations, with 5206 locations falling within the minimum convex polygon that was created from the GPS dataset. Spatial auto-correlation was not applied to the VHF dataset, because independence of successive observations is already achieved by having relatively long temporal intervals between observations (collected 2-5 times per month as opposed to every two hours for GPS) (White and Garrott 1990).

3.5 Methodology

Independence between successive observations is an important assumption in animal movement and home range studies, because frequent successive location data can be positively correlated (Swihart and Slade 1985). Because this study does not attempt to define home ranges and does not analyze animal movement, the need for auto-correlation analysis is lessened. However, the effect of spatially correlated data was investigated by removal of locations that occupied pixels of the same spectral signature from one location to the next. Location data were only used if the individual moved from one pixel signature to another (figure. 2). This reduced the likelihood that a caribou that was bedding, resting, injured, or for any other reason not changing its location, would produce a biased estimate of its occurrence within a particular habitat type. Although numerous spatial auto-correlation techniques exist for use with telemetry data (Johnson 1980), the above technique is better suited for satellite-based, data rich environments.

Habitat resource preferences (Johnson 1980) were not used in this study because availability is based on 100% of all pixels within the study area. In other words, the entire study area is composed of 25 x 25m pixels that are categorized into one of many possible spectral groupings. Naturally, this assumes that all pixels are equally available to all individuals within the study sample, which in reality, is unlikely to be the case. However, because remotely sensed observations cover the entire landscape, a hierarchical selection system is unnecessary since all possible habitat types (i.e. all pixels within the image) are observed and available for use.

The GPS location dataset was initially divided into four seasons in order to evaluate the effect of different seasons on Woodland Caribou locations. The locations were divided into four broad seasonal groups (spring, summer, winter, and fall) and an analysis of variance was performed.

Our approach to quantify the extent of Woodland Caribou habitat used a statistical approach to automate the classification of each pixel in the satellite imagery and to generate a suite of land cover classes based on characteristic spectral signatures. The determined classes were correlated with the sample A GPS data and used to create a Woodland Caribou habitat classification that indicates greater or lesser caribou occurrence. For our approach, "greater occurrence" refers to habitat types where disproportionately more time is spent in a particular type than would be expected, based on the availability of each habitat type in the study area. As a result, the animal spends less time in the remaining habitat types, which are considered "lesser occurence" (White and Garrott 1990).

The goal of this study was to determine if the relationship between Woodland Caribou locations and DN signatures is strong enough that habitat occurrence can be predicted without user input. Therefore, an unsupervised classification of the satellite data was performed using an ISODATA algorithm. The ISODATA method is an iterative classifier that performs an entire classification and then recalculates the statistics with each pass. Trials of 10, 15, 20, 25 and 30 classes were examined. Twenty-five classes gave the best separation of spectral signatures without needless repetition of similar groupings. For example, when only ten or fifteen classes were used, pixels were grouped into broad spectral classes that did not distinguish areas with enough detail. When thirty classes were used, pixels were separated into different classes, though they appeared to have very closely related spectral signatures and likely represented the same vegetative cover type. Therefore, twenty-five classes were chosen as the optimal number to be used to discern land cover features without repetition.

Labeling of greater occurrence classes was performed to qualitatively combine the chosen spectral classes in logical groupings. Labeling was conducted using a combination of visual interpretation of the imagery, field photographs and observations of the area from two helicopter surveys, ancillary data (e.g. peatland and forest inventory maps), and the authors' knowledge of the area. The labeling was performed for reference purposes only and did not influence the classification process or the assessment of occurrence.

The final step was to take the class occurrence information from the first phase (i.e. the Wabasca study area) and apply it to the remainder of the Landsat TM image to indicate spectral classes that indicate potential Woodland Caribou habitat. For this goal, the results from the unsupervised classification were used to perform a supervised classification on the surrounding area of the southernmost image (Path 43 Row 21), an area of approximately 34,000 km^2. A supervised classification requires the user to input known training sites or selected areas of spectral similarity, and then allow an algorithm to locate pixels of similar spectral signatures. A total of 51 sites were selected from all 25 unclassified classes within the study area to be used as training sites for the supervised classification of the entire Landsat TM image.

3.6 Results

The removal of caribou locations that could contribute to spatial auto-correlation had very little effect on the overall results of the study. Table 3-1 summarizes the occurrence of Woodland Caribou in each of the twenty-five spectral classes for the respective datasets. Results are shown for samples A and B prior to and following the spatial auto-correlation analysis. Also shown are the results for a combination of samples A and B (i.e. the entire GPS dataset) and the results of the VHF dataset.

The division of the Woodland Caribou locations into four seasons (winter, spring, summer, and fall) shows that Woodland Caribou tend to occupy similar spectral classes, regardless of season (figure 3-3). Although there are variations in the number of occurrences within specific spectral classes, the variation occurs mainly within classes that are of greater occurrence. The classes with less occurrence have consistent percentages of occurrence throughout all four seasons. An analysis of variance between the four seasons was performed using an ANOVA single factor test (P-value = 1.00, df = 3). As a result, it was decided that the separation of the data into different seasons was unnecessary because of the similarity between seasons.

By intersecting the Woodland Caribou location data with the classified Landsat TM scene, it was possible to determine how often caribou were located within each of the twenty-five spectral classes. Tables 3-2 and 3-3 show the total area of each spectral class within the entire study area and therefore represent the availability of those classes (White and Garrott 1990). Tables 3-2 and 3-3 also show the percentage of pixels that contain caribou locations and thus represent caribou use. The 11 greater occurrence spectral classes occupied 48.2% of the total landscape and accounted for 73.1% of the caribou locations in sample A. The 14 avoided spectral classes occupied 51.8% of the total landscape and accounted for only 26.9% of the caribou locations in sample A. Figure 3-4 shows an example subset of the Woodland Caribou location data in relation to the greater and lesser occurrence classes. The subset was chosen on the basis that is was centrally located and contained the largest proportion of Woodland Caribou locations.

There were four cases from samples A and B where the greater/lesser occurence classification was unclear. In sample A, spectral class 13 was used marginally more than its availability (5.0% vs. 4.7%, respectively). In sample B, it was used less than expected (3.8% vs. 4.7%, respectively). Therefore, it was classed as lesser occurence because the standard deviation of usage was higher in sample A (σ=3.3) than it was for sample B (σ=1.1) (tables 3-2 and 3-3). It was also classed as lesser occurrence in the combined GPS dataset and in the VHF dataset (table 1).

Spectral class 6 comprised 5.7% of the landscape and accounted for 6.9% of the caribou locations in sample B. In sample A, it accounted for only 4.2% of the locations. The standard deviation in sample A was much lower than in sample B (σ=2.5 and σ=8.5 respectively) and therefore is likely more representative of the average use by Woodland Caribou. As a result, spectral class 6 was labeled as lesser occurence. The large variance in sample B is the result of one of the 18 individuals who used the class 23.1% of the time.

Class 18 made up 4.3% of the study area and accounted for 5.0% and 3.8% of the locations in samples A and B, respectively. The differences in standard deviations were not helpful in making a choice because sample B had a lower standard deviation (σ=2.1) than did sample A (σ=3.0), and sample B determined the class to be lesser occurence. Ultimately, it was labeled as greater occurence based on the result of the combination of the two GPS samples and on the greater occurence determined by the VHF sample.

Class 21 made up 4.3% of the study area and accounted for 7.0% and 4.7% of the locations in samples A and B, respectively. As with class 18, the standard deviations were not helpful in making the greater/lesser occurrence decision. The class was selected as greater occurrence on the basis of its greater occurrence in sample A, the entire GPS dataset, and in the VHF dataset.

A comparative regression analysis between the analysis data set (sample A) and the validation data set (sample B) shows a significant relationship (P=0.99) with an r^2 value of 0.88. This shows that the percentage of Woodland Caribou occupation within a particular class is highly correlated from one sample to the other.

The VHF dataset (table 3-4) also correlated well with the GPS derived analysis (sample A) dataset. A regression analysis plotting sample A results against that of the VHF data shows a significant relationship (P=0.99) with an r^2 value of 0.92. The correlation technique used in sample A and sample B was again used for the VHF data. The results show the same greater/lesser occurrence classes as sample A. It should be noted that (as with samples A and B), classes 6 and 18 did not have strong greater or lesser occurrence.

Although the results demonstrate correlations between Woodland Caribou locations and spectral characteristics, they do not indicate the physiography or vegetation type of the greater and lesser occurrence classes. Therefore, three distinct groups of spectral classes were qualitatively mapped as Woodland Caribou habitat (table 3-5). The first, and most dominant group was the "black spruce group", which is characterized by black spruce peatlands, but with varying levels of canopy closure. This group includes six spectral classes and comprises 31.6% of the study area. However, it accounted for 49.7% (sample A), 52.9% (sample B), and 46.3% (VHF dataset) of the Woodland Caribou locations. The second group was labeled "shrubby fen" and it includes three spectral classes characterized by low vegetation growth such as shrubs or stunted trees. Its usage was higher in sample A (17.2%) and the VHF dataset (15.0%) than was available in the landscape (13.0%), but was lower in sample B (12.4%). The final group, called "open fen", includes two spectral classes and forms distinct patches in the scene. It was distinguished from shrubby fen by its extremely high DN values in a Landsat TM 4,3, and 2 band combination. It has little or no growth of trees or shrubs, but the exact vegetation types have not yet been determined. It occupied only 3.7% of the study area, but accounted for 6.0 - 8.3% of the caribou locations for each of the three datasets. The final classification (figure 3-1) shows the distribution of the three greater occurrence classes within the entire minimum convex polygon subset.

The result of the supervised classification performed on the Landsat 5 TM scene (path 43 row 21) is, essentially, a predictive Woodland Caribou habitat classification. Spectral signatures from areas of caribou occurence were used to detect similar areas outside of the study area (minimum convex polygon). The black spruce group occupied a lower percentage in the overall Landsat scene (24.9%) than it did within the study area (31.6%). Conversely, the shrubby fen area occupied a larger percentage in the Landsat scene (20.2%) than it did within the study area (13.0%). Our results also indicate that there is also a slightly higher percentage of open fen in the Landsat scene (6.0%) than there was within the study area (3.7%).

3.7 Discussion and Conclusion

While previous studies in Alberta have correlated Woodland Caribou use to existing vegetation or peatland maps and have provided useful preliminary information about the extent of Woodland Caribou habitat (Bradshaw et al. 1995; Stuart-Smith et al. 1997; Schneider et al. 2000), the results are based on maps that were never designed for classifying Woodland Caribou habitat. The correlation between Woodland Caribou location and spectral signatures is an attempt to develop more precise caribou habitat mapping. This method identifies the spectral similarity of the landscape classes that Woodland Caribou tend to occur within, and does not use *a priori* ecological information or interpretations. As a result, areas that are important to Woodland Caribou can be identified and mapped over large regions in a relatively short time. This is not to say that the greater occurrence spectral classes are the only classes or features that are necessary to maintain a viable Woodland Caribou population. Limiting factors such as predation, habitat alteration, linear corridors, human activity, and weather and climate (Dzus 2001) all influence Woodland Caribou populations and were not taken into consideration during the generation of this remote sensing classification technique.

While the relationship found in this study between spectral signatures and Woodland Caribou locations is a strong one, successful wildlife management requires input from a variety of sources. The prediction of habitat suitability by any single factor will have low probabilities of success (Thomas et al. 1996) and therefore should be an accumulation of data from multiple sources. As a result, satellite and GPS interpretation should be used in combination with other baseline habitat knowledge in order to produce an effective habitat map for Woodland Caribou.

Testing for independence of observations showed very little variation in percent occurrence results and no variation in the greater versus lesser occurrence rules. This is likely due to the fact that because the location dataset is so large, the removal of auto-correlated data was not needed. Also, the fact that the VHF dataset, which has lower positional accuracy and fewer recorded locations, produces identical results shows that accounting for auto-correlation within the GPS dataset is successfully addressed.

The comparison of Woodland Caribou locations during different seasons showed that caribou in the Wabasca region did not greatly alter their choice of spectral class selection. There was some variation within the greater occurrence classes, but lesser occurence classes were equally low during all times of the year.

Although the VHF dataset was used for validation purposes, the classification results were significant. First of all, the VHF dataset was a completely independent source of Woodland Caribou location data, thus allowing validation of the habitat classification technique. Secondly, because the correlation between VHF locations and the Woodland Caribou habitat classification was strong, similar habitat classification studies could be performed where GPS locations are unavailable. While GPS collar technology is superior in location accuracy, it is considerably more expensive and does not allow for historical temporal studies to be completed, as VHF technology dates back much farther than GPS technology.

Although the correlation between DN and Woodland Caribou locations is strong, almost 30% of all locations fell within lesser occurence classes (figure 3-4). Some of this is expected from normal Woodland Caribou behavior, including animals traveling from one habitat type to another (and traversing poor areas). However, there are also several possible sources of measurement error. These include physical errors involving satellite image georeferencing and atmospheric interference. Atmospheric correction of the satellite data (conversion of raw DN into values of reflectance) was not performed in this study, as the spectral signatures used were never compared to actual ground reflectance signatures. As a result, conversion into reflectance was unnecessary. Also included are the effects of topography, which will cause misclassification of some pixels within the image. However, due to the extremely flat terrain within the study area, this likely had a minimal influence. The positional inaccuracy involved in both the GPS and the VHF datasets will also result in some locations to be erroneously placed into neighboring pixels that are not representative of their actual location.

It is also important to note that although the greater/lesser occurrence rules were determined by the average of occurrence, particular animals occupied classes in percentages that were highly variable. To illustrate this point, the individual animal that was responsible for the high variance in sample B (described in results) occupied class 6, a lesser occurence class overall, 23.1% of the time. Additionally, this same individual occupied classes 7 and 8, which were greater occurrence classes, a total of

14.7% and 16.1% of the time respectively, which is much higher than the sample's mean usage (6.9% and 8.7% respectively). The result is that this particular individual occupies three of the possible twenty-five classes 53.9% of the time. This individual's behavior deviates from the average use of habitat by Woodland Caribou in this study. Classes 7 and 8 were determined to be black spruce complexes and showed greater occurrence by all animals in the study. However, class 6 had generally lesser occurence, but was used by this animal almost one quarter of the time. Close examination of the Landsat image revealed that pixels from class 6 tend to be located near pixels from classes 7 and 8. In fact, there is a possibility that class 6 also represents a black spruce complex, but with a greater degree of canopy closure than the other black spruce types.

While the unsupervised classification appeared to consistently isolate only related vegetation cover types, the supervised classification had some errors in the identification of particular greater occurrence classes (i.e. some areas were erroneously included in spectral classes which were clearly not physiographically or biologically similar). Such errors may not have as much to do with habitat suitability as it does with misclassification of pixels. For example, closer observation of the shrubby fen group revealed that there was a significant amount of previously burned area that was classified as shrubby fen, a situation that was not relevant within the study area and was thus not addressed during the unsupervised classification. The spectral signature of low growing shrubs within the fen may have similar spectral signatures to the regenerating growth within the burned areas. The supervised classification was not always able to distinguish between the two signatures. One option to overcome this problem would be to remove or mask out all known burns within the area; however, this would alter the classification process. Also, the point at which a burn is considered burned area and when it is again considered suitable Woodland Caribou habitat has not yet been established within this region.

Other minor misclassifications of pixels occurred within the Landsat TM Scene. Recent clear-cuts and industrial impacts (e.g. pipelines, roads, wellsites, etc.) were occasionally classified as open fen. Again, the level of regenerative growth on these disturbances appears to be confused with the low vegetative growth of the open fen complexes. We must stress that this interpretation is tentative, however, since the initial unsupervised classes are arbitrary, and unknown with respect to what they represent on the ground. Additional information (e.g. aerial photographs, ground truthing, vegetation mapping, etc.) can be used to support habitat mapping beyond the range of radio-collared animals, in order to avoid significant mapping errors. These possible misclassifications highlight the errors that can occur from this habitat classification approach, and demonstrates the need to continue to rely on human judgement and interpretation to avoid such errors.

This study showed how spectral signature characteristics extracted from Landsat 5 TM imagery can be related to Woodland Caribou occurrence and, as such, can be used as a basis for habitat mapping. The overall approach combined satellite imagery, radiotelemetry locations, field work and Geographic Information Systems techniques. This technique can refine our understanding of habitat use for local groups of radio-collared animals. More importantly, it creates the potential for extending habitat mapping to areas where satellite imagery is the primary or only practical source of information. A significant feature of this approach is that it does not require interpretation of land cover mapping (e.g. vegetation inventories). It is therefore not affected by the limitations inherent in interpreting habitat from land cover mapping that was created and optimized for other purposes.

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Figure 3-1: Unsupervised classification of the study area located in the Wabasca area in northeastern Alberta, Canada. Greater occurrence classes have been joined into three broad categories (black spruce group, open fen, and shrubby fen). Spectral class 1 of the unsupervised classification isolates water bodies and is labeled as "water" to allow easier reference to the area. Class 1 occupies 3.0% of the entire scene and accounts for 0.1 - 0.4% of the caribou locations.

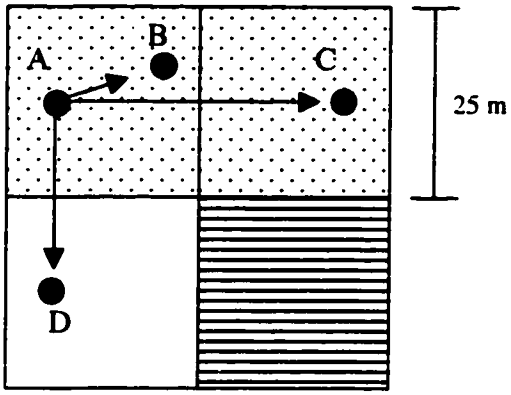

Figure 3-2: Example showing the removal of spatially correlated data. If location A is followed by location B (which is within the same pixel), then location B is removed from the dataset. If location A is followed by location C (which is a different pixel, but with the same spectral class description), then location C is removed from the dataset. If location A is followed by location D (which is a different pixel and a different spectral class description), then location D remains in the dataset.

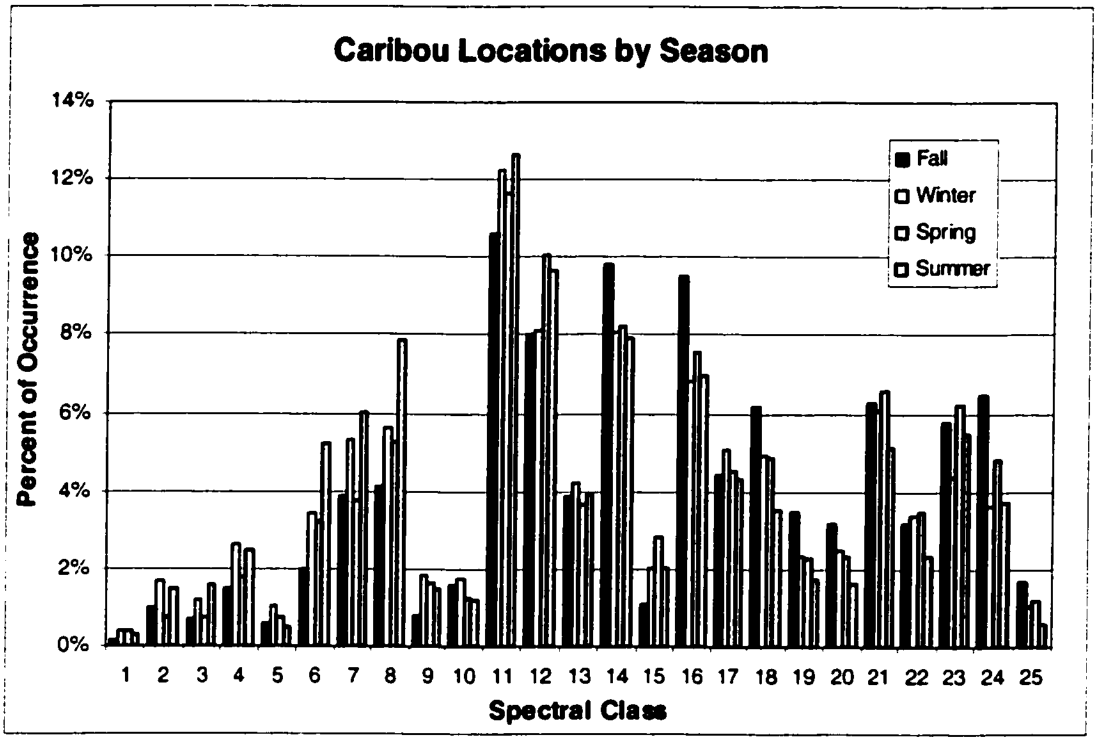

Figure 3-3: Caribou locations divided by season; fall (Sept. 16–Nov. 15), winter (Nov. 16 Apr. 15), spring (Apr. 16–June 30), and summer (July 1–Sept. 15).

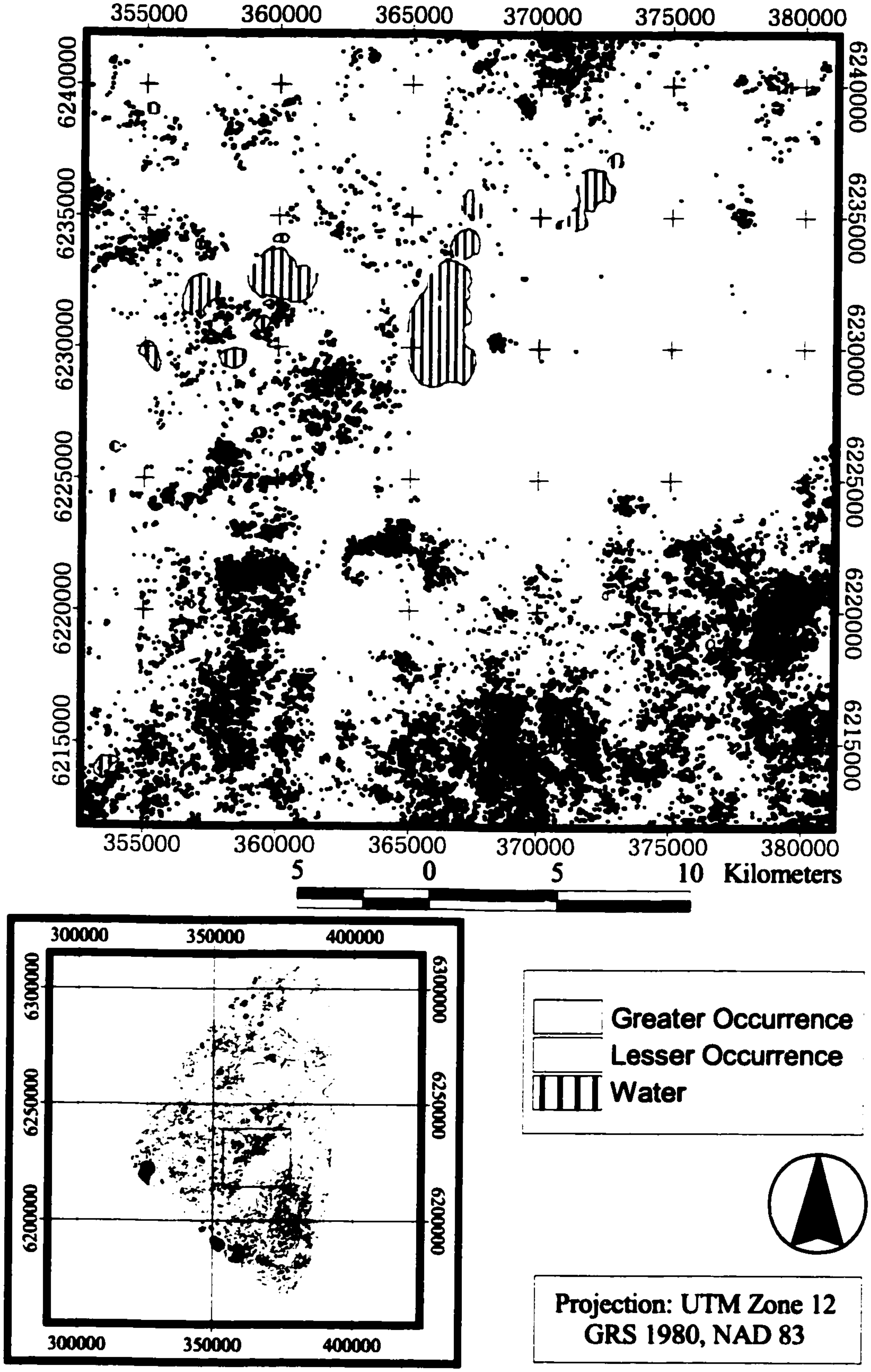
355000
360000
365000
370000
375000
380000
6240000
6235000
6230000
6225000
6220000
6215000
5
0
5
10 Kilometers
300000
350000
400000
6300000
6250000
6200000
Greater Occurrence
Lesser Occurrence
Water
Projection: UTM Zone 12
GRS 1980, NAD 83

Figure 3-4: Subset of Woodland Caribou habitat classification showing the relationship between caribou locations (black circles) and greater occurrence spectral classes. All preferred spectralgreater occurrence classes have been amalgamated (grey polygons), as have all lesser occurence classes (white polygons). Spectral class 1 (water bodies) is labeled as "water" to allow easier reference to the area and is also a lesser occurrence class. For display purposes, a minimum mapping unit of three hectares was applied to the classification shown.

Spectral Class	**Study Area Available (%)**	**Sample A Used (%)**	**Sample A Used (%) (Revised)**	**Sample B Used (%)**	**Sample B Used (%) (Revised)**	**Entire GPS Dataset Used (%)**	**VHF Dataset Used (%)**
Class1	3.0	0.1	0.1	0.2	0.2	0.2	0.4
Class2	3.0	0.9	0.9	1.3	1.3	1.1	1.7
Class3	3.7	1.0	1.1	2.0	1.8	1.5	1.3
Class4	4.1	2.0	2.2	3.0	3.2	2.5	3.1
Class5	2.1	0.5	0.6	0.6	0.8	0.6	0.8
Class6	5.7	4.2	4.1	6.9	6.0	5.6	5.6
Class7	5.3	6.3	5.9	6.9	6.7	6.6	6.4
Class8	5.2	5.9	5.5	8.7	8.3	7.3	7.2
Class9	3.3	1.4	1.7	1.3	1.6	1.3	1.2
Class10	3.0	1.4	1.6	1.1	1.4	1.3	1.3
Class11	6.9	14.3	11.4	13.6	11.4	13.9	11.2
Class12	5.4	8.4	8.0	9.8	9.0	9.1	7.4
Class13	4.7	5.0	4.8	3.8	4.3	4.4	3.0
Class14	4.8	8.1	7.9	8.3	7.9	8.2	7.3
Class15	1.3	1.4	1.7	1.7	1.9	1.6	2.8
Class16	4.1	6.8	7.3	5.7	6.3	6.2	6.8
Class17	3.7	5.1	5.7	3.8	4.1	4.5	4.4
Class18	4.3	5.0	5.3	3.8	4.0	4.4	4.4
Class19	3.9	1.9	2.0	1.5	1.7	1.7	2.1
Class20	4.1	2.0	2.2	1.5	1.7	1.7	2.6
Class21	4.9	7.0	6.7	4.7	5.2	5.9	6.2
Class22	4.8	2.8	3.4	2.0	2.3	2.4	3.1
Class23	2.4	4.8	5.3	4.3	4.9	4.6	5.5
Class24	4.6	2.8	3.3	2.6	2.9	2.7	3.2
Class25	1.8	0.8	1.0	1.0	1.3	0.9	1.0

Table 3-1: 'Availability' versus 'use' datasets. "Used (%)" indicates the percentage of use by Woodland Caribou for each spectral class. "Revised" datasets have undergone spatial auto-correlation analysis. "Entire GPS dataset" is combination of sample A and sample B (36 animals in total). VHF dataset is independent from the GPS dataset.

Spectral Class	Area (ha)	Available (%)	Used (%)	σ	Occurrence
Class 1	25870.4	3.0	0.1	0.3	Lesser
Class 2	25612.4	3.0	0.9	0.9	Lesser
Class 3	31297.9	3.7	1.0	0.9	Lesser
Class 4	35271.3	4.1	2.0	1.8	Lesser
Class 5	17772.3	2.1	0.5	0.4	Lesser
Class 6	48429.5	5.7	4.2	2.5	Lesser
Class 7	44982.6	5.3	6.3	3.3	Greater
Class 8	44252.6	5.2	5.9	3.3	Greater
Class 9	28450.3	3.3	1.4	1.0	Lesser
Class 10	25617.8	3.0	1.4	1.2	Lesser
Class 11	58429.3	6.9	14.3	7.7	Greater
Class 12	45822.3	5.4	8.4	5.1	Greater
Class 13	39700.4	4.7	5.0	3.3	Lesser *
Class 14	41130.5	4.8	8.1	3.0	Greater
Class 15	10711.5	1.3	1.4	1.9	Greater
Class 16	34933.1	4.1	6.8	3.5	Greater
Class 17	31473.4	3.7	5.1	2.3	Greater
Class 18	37085.0	4.3	5.0	3.0	Greater
Class 19	32965.5	3.9	1.9	2.4	Lesser
Class 20	34785.0	4.1	2.0	2.0	Lesser
Class 21	41900.8	4.9	7.0	5.7	Greater
Class 22	40906.4	4.8	2.8	1.5	Lesser
Class 23	20549.2	2.4	4.8	3.1	Greater
Class 24	39208.5	4.6	2.8	2.0	Lesser
Class 25	15429.8	1.8	0.8	0.8	Lesser

Table 3-2: Sample A result from unsupervised classification of Wabasca study area by spectral class. ‘Available’ is the portion of the study area made up by a class. ‘Used’ is the percent of only those pixels that contain caribou locations. Standard deviation (σ) is of Used (%) data. * Class 13 selected as lesser due to higher variance than Sample B.

Spectral Class	Area (ha)	% Available	% Used	σ	Occurrence
Class 1	25870.4	3.0	0.2	0.3	Lesser
Class 2	25612.4	3.0	1.3	1.5	Lesser
Class 3	31297.9	3.7	2.0	2.3	Lesser
Class 4	35271.3	4.1	3.0	2.0	Lesser
Class 5	17772.3	2.1	0.6	0.6	Lesser
Class 6	48429.5	5.7	6.9	8.5	Lesser *
Class 7	44982.6	5.3	6.9	3.8	Greater
Class 8	44252.6	5.2	8.7	3.6	Greater
Class 9	28450.3	3.3	1.3	0.7	Lesser
Class 10	25617.8	3.0	1.1	0.5	Lesser
Class 11	58429.3	6.9	13.6	6.5	Greater
Class 12	45822.3	5.4	9.8	6.6	Greater
Class 13	39700.4	4.7	3.8	1.1	Lesser
Class 14	41130.5	4.8	8.3	4.4	Greater
Class 15	10711.5	1.3	1.7	1.6	Greater
Class 16	34933.1	4.1	5.7	2.8	Greater
Class 17	31473.4	3.7	3.8	2.7	Greater
Class 18	37085.0	4.3	3.8	2.1	Greater *
Class 19	32965.5	3.9	1.5	0.9	Lesser
Class 20	34785.0	4.1	1.5	0.9	Lesser
Class 21	41900.8	4.9	4.7	2.6	Greater *
Class 22	40906.4	4.8	2.0	1.3	Lesser
Class 23	20549.2	2.4	4.3	2.1	Greater
Class 24	39208.5	4.6	2.6	2.0	Lesser
Class 25	15429.8	1.8	1.0	0.8	Lesser

Table 3-3: Sample B result from unsupervised classification of Wabasca study area by spectral class. 'Available' is the portion of the study area made up by a class. 'Used' is the percent of only those pixels that contain caribou locations. Standard deviation (σ) is of Used (%) data. * Denotes different result than from sample A.

Spectral Class	Area (ha)	Available (%)	Used (%)	Occurrence
Class 1	25870.4	3.0	0.4	Lesser
Class 2	25612.4	3.0	1.7	Lesser
Class 3	31297.9	3.7	1.3	Lesser
Class 4	35271.3	4.1	3.1	Lesser
Class 5	17772.3	2.1	0.8	Lesser
Class 6	48429.5	5.7	5.6	Lesser
Class 7	44982.6	5.3	6.4	Greater
Class 8	44252.6	5.2	7.2	Greater
Class 9	28450.3	3.3	1.2	Lesser
Class 10	25617.8	3.0	1.3	Lesser
Class 11	58429.3	6.9	11.2	Greater
Class 12	45822.3	5.4	7.4	Greater
Class 13	39700.4	4.7	3.0	Lesser
Class 14	41130.5	4.8	7.3	Greater
Class 15	10711.5	1.3	2.8	Greater
Class 16	34933.1	4.1	6.8	Greater
Class 17	31473.4	3.7	4.4	Greater
Class 18	37085.0	4.3	4.4	Greater
Class 19	32965.5	3.9	2.1	Lesser
Class 20	34785.0	4.1	2.6	Lesser
Class 21	41900.8	4.9	6.2	Greater
Class 22	40906.4	4.8	3.1	Lesser
Class 23	20549.2	2.4	5.5	Greater
Class 24	39208.5	4.6	3.2	Lesser
Class 25	15429.8	1.8	1.0	Lesser

Table 3-4: VHF data result from unsupervised classification of Wabasca study area by spectral class. 'Available' is the portion of the study area made up by a class. 'Used' is the percent of only those pixels that contain caribou locations.

Group Name	**Spectral Classes Included**	**Available (%)**	**Sample A Used (%)**	**Sample B Used (%)**	**VHF Dataset Used (%)**
Black Spruce Grp.	7, 8, 11, 12, 14, 16	31.6	49.7	52.9	46.3
Shrubby Fen	17, 18, 21	13.0	17.2	12.4	15.0
Open Fen	15, 23	3.7	6.2	6.0	8.3
Water	1	3.0	0.1	0.2	0.4
Lesser Occurrence	2,3,4,5,6,9,10,13,19,20, 22,24,25	48.7	26.8	28.6	30.0

Table 3-5: Grouping of Unsupervised Classes.

CHAPTER FOUR

4.0Conclusions

4.1 Remote Sensing Conclusions

This thesis shows the usefulness of remote sensing in two extremely different environments for two different purposes. Chapter two is an in depth investigation into the spectral characteristics of rock encrusting lichens for the purpose of geological mapping and mineral exploration (Staenz et al., 1998; Kruse, 1999). Chapter three correlates Woodland Caribou telemetry data and satellite imagery to contribute to habitat maping for the purpose of wildlife management (Dzus 2001).

While the objectives differ, the usefulness of remote sensing as an effective tool for boreal and subarctic observations becomes evident. Scientific research in Canada's vast wilderness provides the perfect environment for the use of remote sensing. For geological mapping and mineral exploration, remote sensing offers a means by which large areas can be mapped without having to perform expensive, time consuming, and possibly dangerous, ground surveys. Such is the case in Canada's lichen-dominated subarctic regions. For wildlife mapping, remote sensing provides an opportunity to map extremely large areas that can normally be difficult to access. Woodland Caribou tend to inhabit large tracts of mature to old growth forests (Dzus 2001) and a variety of peatland coverages that are difficult to observe and monitor. Furthermore, remote sensing also allows for unobtrusive observations without disrupting the species being studied (Jensen 2000).

4.2 Lichen Conclusions

Although the biophysical and physiological characteristics of leafy vegetation are extremely well documented (see Treitz and Howarth (1999) for a comprehensive review), lichens have received far less attention. Lichens contain both a fungal component and an alga component (Hale 1983) and are, therefore, unique in the plant Kingdom. However, they still contain many of the same biophysical properties as seen in leafy vegetation. For example, the alga contains chlorophyll while the fungus does not. Therefore, the chlorophyll is screened by the fungus, resulting in a more subtle or absent reflection peak at 550 nm, a characteristic of green vegetation (Gates 1980).

It is these biophysical parameters that provide an opportunity to identify unique spectral characteristics of lichens. With a better understanding of the spectral properties of lichens comes the ability to better map geological targets that can contain varying levels of lichen cover. Remotely sensed observations of lichen-dominated environments will result in a linear combination of spectral endmembers (Singer and McCord 1979). In this case, the endmembers are either rock (quartzite) or lichens. Spectral mixture analysis (SMA) (Smith et al. 1990; Mustard and Sunshine 1999) addresses the complexity of target identification within mixed pixels and can allow detection of substances exposed at sub pixel resolution. Therefore, an understanding of the spectral characteristics of pure lichen endmembers is required.

This thesis provides support that transmittance of light through lichen is less than 3% in the 350-2500 nm range. Also, a spectral index is provided that allows for the discrimination of lichen species. Finally, a spectral index is provided that allows for the spectral unmixing of rock and crutose/foliose lichens using a single lichen endmember.

4.3 Woodland Caribou Habitat Mapping Conclusions

This thesis takes a unique approach to wildlife habitat mapping in that we allow the animal to identify its preferred and avoided habitat types. By correlating telemetry locations to spectral signatures obtained from Landsat TM satellite data, we can effectively map a Woodland Caribou habitat over an entire caribou range. Furthermore, we can take spectral signatures that represent important Woodland Caribou habitats, and use them to locate possible caribou habitat in areas where no telemetry data exists.

However, it is important to emphasize that the spectral signatures that represent Woodland Caribou habitat in this study might or might not represent Woodland Caribou habitats that are not distinguished by peatland complexes dominated by black spruce. For example, the mountain ecotypes (Edmonds 1991) of Woodland Caribou occupy very different habitat types and also migrate seasonally. As a result, identification of habitat using the technique described here would require reproduction of the above methods using independent satellite imagery and telemetry location data.

An important outcome of this study is one that was not foreseen during the planning stages of this project. While we intended to only use GPS location data for our study, the use of the VHF data was invaluable. First of all, it allowed us to verify the technique with a truly independent dataset. More importantly, its effectiveness allows similar studies to be performed in areas where no GPS location datasets are available. VHF location data is a fraction of the cost of GPS location data, and VHF has a much longer historical record. This opens the door to temporal studies of Woodland Caribou habitats, as older VHF telemetry data could be used in coordination with historical Landsat imagery.

4.4 Woodland Caribou and Lichens

While this thesis does not relate Woodland Caribou and lichen within the same study, it is important to recognize that there is an extremely important relationship between the two. Lichens are an extremely important food source for Woodland Caribou and can influence habitat use and distribution (Dzus 2001). Therefore, detection of lichen is important for determining important foraging areas for caribou (Arsenault et al. 1997). The spectral characteristics of lichens could again be utilized for remote sensing observations, but for the purpose of detecting lichen-rich habitats. Detection of lichen may be performed in boreal ecosystems as well, as the physical parameters of lichens remain the same. The difficulty lies in the sub-pixel mixing of a forest or woodland area. In subarctic environments, the mixture tends to primarily be a combination of rock and lichens. In the boreal forest, the mixture would be of lichens and a multitude of green plants and soil or rock exposures. Furthermore, rock and lichen spectra are far more distinct from one another than are lichen and green plants.

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