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Mapping lichen changes in the summer range of the George River Caribou Herd (Québec-Labrador, Canada) using Landsat imagery (1976-1998)

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Abstract: Habitat studies are essential in order to understand the dynamics of migratory caribou herds and to better define management strategies. In this paper, multi-date Landsat images are used to map lichen in the summer range of the George River Caribou Herd (GRCH), Québec-Labrador (Canada), over the period from 1976 to 1998. Multi-Spectral Scanner scenes from the seventies and Thematic Mapper scenes from the eighties and nineties were radiometrically normalized and processed using spectral mixture analysis to produce lichen fraction maps and lichen change maps. Field sites, surveyed during summer campaigns in 2000 and 2001, are used to validate the lichen maps. Results show a good agreement between field data and the lichen results obtained from image analysis. Maps are then interpreted in the context of previous caribou dynamics and habitat studies conducted in the study area over the last three decades. The remote-sensing results confirm the habitat degradation and herd distribution patterns described by other investigators. The period between 1976-1979 and 1985-1986 is characterized by a localized decrease in lichen cover in the southern part of the study area, whereas from 1985-1986 to 1998 the decrease in lichen cover extends northward and westward. This period coincides with the widest extent of the GRCH summer range and activity. The approach presented in this paper provides a valuable means for better understanding the spatio-temporal relation between herd dynamics and distribution, as well as habitat use. Satellite remote sensing imagery is a useful data source, providing timely information over vast and remote territories where caribou populations cannot be surveyed and managed on a frequent basis.

Key words: change detection, lichen, overgrazing, overtrampling, remote sensing, spectral mixture analysis.

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Introduction

Migratory caribou (*Rangifer tarandus*) herds are vastly distributed across circumpolar regions and can total a few hundred thousands of heads (Banfield, 1961; Williams & Heard, 1986). The herds represent a vital food and cultural resource for native communities, and are also an important economic resource. In northern Québec, for example, around 15 000 caribou hunting licenses were sold in 2001 (FAPAQ, 2003). This has significant economic repercussions for local communities, government, and outfitters. Predation, climate, human activities, and food availability are known to influence caribou population dynamics (Bergerud, 1980; Skogland, 1986; Messier *et al.*, 1988; Wolfe *et al.*, 2000; Dyer *et al.*, 2002), but the impact of each of these factors is not well understood. Monitoring populations and habitats is therefore essential to ascertain the sustainable management of caribou herds.

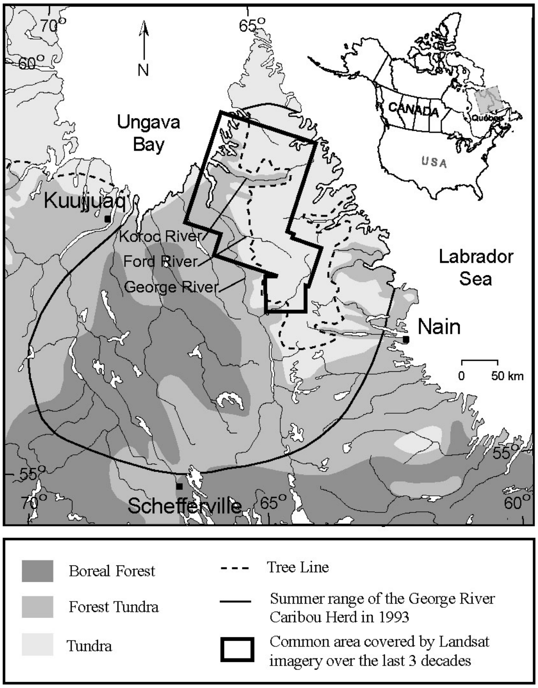

Fig. 1. Study location and area covered by the Landsat scenes. The summer range of the George River Caribou Herd (Russell *et al.*, 1996) as well as the biomes and tree line (Payette, 1983) are also indicated.

The George River Caribou (*Rangifer tarandus caribou*) Herd (GRCH) is located in the north-eastern Québec-Labrador peninsula (Fig. 1). Historically, after a population peak observed during the second part of the 19th century (Low, 1896), the herd declined and stayed at a low level until the 1950s (Elton, 1942; Banfield & Tener, 1958; Bergerud, 1967). Then, the GRCH increased from about 5000 to approximately 800 000 heads at the end of the 1980s (Couturier *et al.*, 1996). Since then, the herd has experienced a decline and the last survey, conducted in 2000-2001, indicates a population decrease to about 440 000 heads (Gouvernement du Québec, 2002). Decreases in pregnancy rates, calf survival and female health, as well as body composition anomalies and calving delays, have been observed since the 1980s and have raised questions regarding the factors affecting the GRCH (Couturier *et al.*, 1988; Messier *et al.*, 1988; Huot, 1989). Usually, winter factors such as predation, climatic conditions or winter habitat overuse are considered as dominant in explaining fluctuations in caribou populations (Bergerud, 1980; Skogland, 1986). However, these factors seem to affect the GRCH demography in a limited way and, therefore, raise the interest of examining more closely the summer habitat.

The GRCH makes annual migrations. In spring, gravid females migrate to the calving area located on high plateaus, east of the George River, and give birth at the beginning of June. Then, the females migrate to the summer habitats located between the George River and the Labrador Sea. In autumn, the herd leaves the Labrador coast and moves inland towards the west and north-west, a time which coincides with the rut season in October (Juniper, 1979; Messier & Huot, 1985; Couturier *et al.*, 1988; Vandal *et al.*, 1989). Large inter-annual variability occurs in these migration patterns, except for the calving area which remains the same year after year. The location of the GRCH calving grounds is relatively well known since the 1970s. Fidelity to these sites can be explained by their exposed location on high plateaus, which limits insect harassment and predation, as well as by food abundance (Messier *et al.*, 1988). This area has undergone significant changes over the years, which has played an important role in the herd demography. With a caribou density increase from 4.1 to 33.2 heads/km^2 between 1974 and 1984 (MLCP, 1987), calving grounds have been overused. In summer, the caribou diet is mostly composed of shrub leaves and twigs, and occasionally of lichen (Gauthier *et al.*, 1989). Trampling is the major source of lichen mat degradation in summer, especially during dry weather conditions when lichen is easily breakable (Pegau, 1970). Demographic changes encountered by the herd are also linked to the expansion of the calving area, as illustrated in Fig. 2 (from 2750 km^2 to 20 250 km^2 between 1981 and 1987). Increased energetic cost associated with larger movements could have directly affected reproduction and calf survival (Messier *et al.*, 1988).

The high latitude distribution of caribou makes their habitat very sensitive to perturbations because of slow vegetation growth. Previous studies on damages to lichen pastures in relation to atmospheric pollution (Rees & Williams, 1997; Virtanen *et al.*, 2002), wildfires (Klein, 1982; Morneau & Payette, 1989; Arsenault *et al.*, 1997), overgrazing and overtrampling (Moser *et al.*, 1979; Klein, 1987; Henry & Gunn, 1991; Käyhkö & Pellika, 1994; Rees *et al.*, 2003) show that vegetation and lichens can take more than 20 years to recover after a perturbation. On St. Matthew Island in the Bering Sea, for example, Klein (1987) estimated that only 10% of the lichen was regenerated after 22 years of overexploitation by the caribou. In a similar study, conducted on Rideout Island in the Northwest Territories (NWT), Canada, Henry & Gunn (1991) estimated that a 20-year regeneration period is necessary for initial lichen mats to recover following degradation by the caribou. Caribou herds are generally distributed over large territories which are not easily accessible.

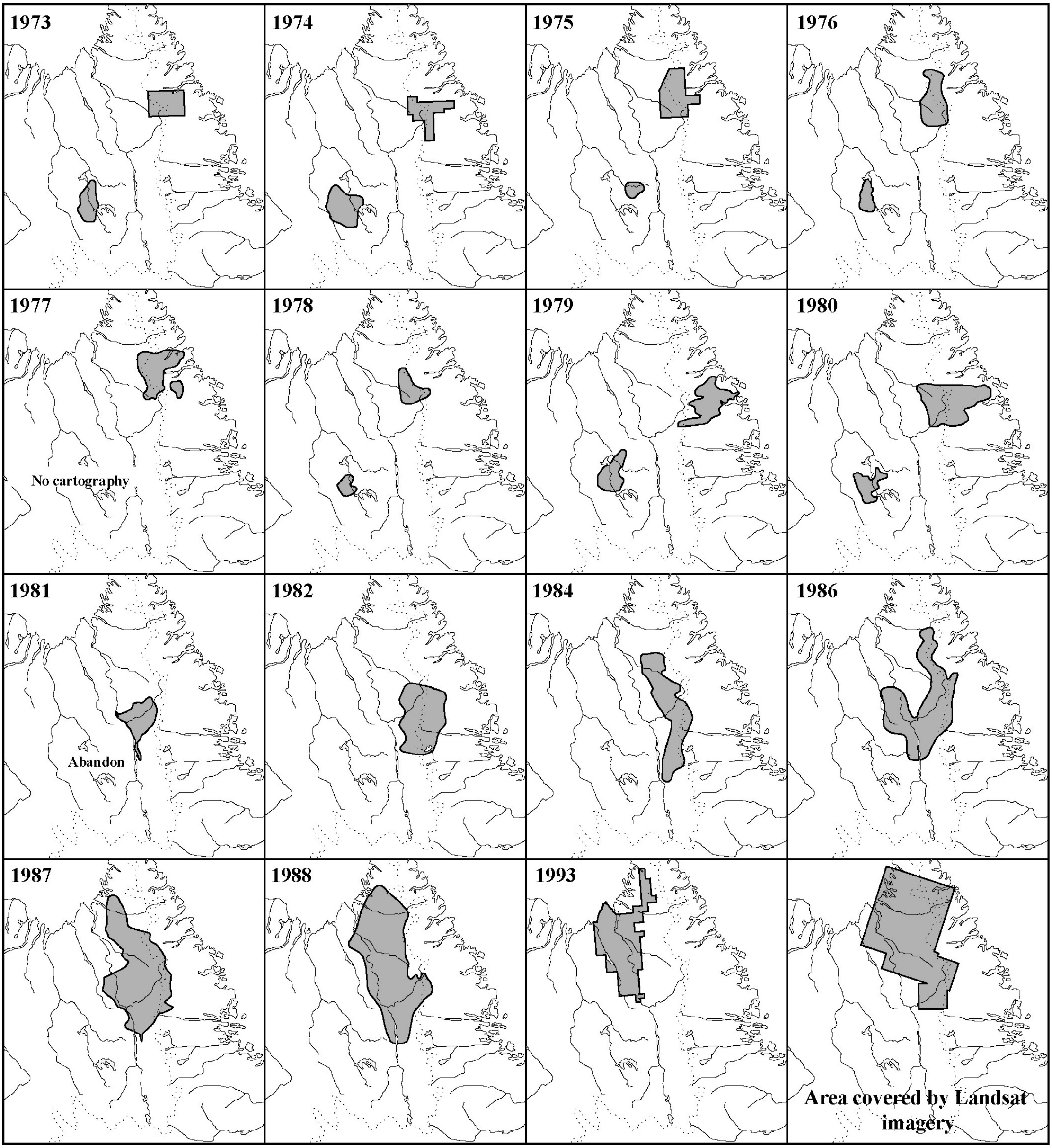

Fig. 2. Calving area maps (grey areas) of the George River Caribou Herd between 1973 and 1993 (Source: Morneau, 1999). The area covered by the Landsat images between 1976-79 and 1998 is also shown.

Field studies are limited and aerial surveys cannot be conducted frequently, providing only fragmented information on the demography and health of herds. Satellite remote sensing offers the synoptic view and temporal resolution compatible with habitat studies and is a good complementary data source to traditional information.

Satellite imagery has been used successfully in caribou habitat studies, especially in Scandinavia for reindeer pasture management. Nordberg & Allard (2002) used Landsat Thematic Mapper (TM) imagery to detect lichen cover degradation by correlating differences in the normalized difference vegetation index (NDVI) between two dates with changes in lichen cover. However, their methodology was restricted to habitats above treeline. Käyhkö & Pellika (1994) studied reindeer habitats for herd and pasture management and found that, although SPOT XS imagery was not entirely suitable due to spectral confusion between vegetation and lichen in the near infrared band, distinct vegetation patterns on both sides of the Finland-Norway border caused by differ-

Table 1. Landsat images used and their characteristics. TM refers to the Thematic Mapper sensor and MSS to the Multi Spectral Scanner.

Acquisition Date	Path/Row	Landsat (L-) Sensor	Center Coordinates	Root Mean Square Error (pixel) - Geometric Correction
1998-08-20	13/19	L-5 TM	58°41'N, 65°22'W	0.87
1998-08-20	13/20	L-5 TM	57°18'N, 66°11'W	0.90
1998-08-29	12/20	L-5 TM	57°18'N, 64°40'W	0.70
1996-07-11	15/20	L-5 TM	57°17'N, 69°09'W	0.97
1995-08-19	14/20	L-5 TM	57°20'N, 67°57'W	0.99
1986-07-18	13/19	L-5 TM	58°41'N, 65°33'W	0.30
1985-07-08	12/20	L-5 TM	57°19'N, 64°43'W	0.33
1979-08-25	14/19	L-2 MSS	58°23'N, 64°51'W	0.50
1976-09-08	13/20	L-2 MSS	57°15'N, 64°30'W	0.25

ent grazing pressures and pasture management practices in the two countries could be mapped. Colpaert *et al.* (1995) used vegetation survey data associated with Landsat TM images to assess the quality and area of caribou habitats in Finland. Rees *et al.* (2003) also used Landsat in the Russian arctic to map land cover change in a reindeer herding area. However, their interpretation was limited by the availability of accurate land cover data. In North America, a limited number of studies have been conducted on caribou using remote sensing data. Thompson *et al.* (1980) performed a classification of caribou habitat in the NWT, Canada, using Landsat Multi-Spectral Scanner (MSS). They accurately mapped vegetation complexes related to seasonal use by caribou. However, the study only covered open areas used during the summer and part of winter. Traditional winter habitats located in woodlands were not included in the study. In northern Québec, Saucier & Godard (1992a; 1992b) mapped vegetation based on caribou habitats using Landsat TM imagery. They produced vegetation maps with 14 classes, six of them representing lichen pastures, using a methodology based on image enhancement. Théau & Duguay (2004) successfully mapped lichen in the summer range of the GRCH using spectral mixture analysis applied to Landsat TM imagery. A map based on lichen fraction for each pixel was produced for the period 1995-1998.

Most of the studies described above have given site specific information on caribou habitats. However, habitat degradation is a dynamic process in which both the spatial and temporal scales must be examined in order to gain an improved understanding of the phenomenon. With their synoptic and repetitive data acquisition, and now longer historical records, satellite sensors offer a great potential for monitoring habitat change over time. The Landsat program, which started in 1972, is still active following the launch of Landsat-7 in 1999. This ensures continuity in data acquisition over a 30–year period. In this paper, the spatio-temporal evolution of lichen pastures inside the summer range of the George River caribou herd is mapped using Landsat MSS and TM imagery acquired between 1976 and 1998.

Material and methods

Study area

The study area considered herein is located in the north-eastern Québec-Labrador peninsula and encompasses an area of about 29 000 km^2 (Fig. 1). From west to east, the area is characterized by a vegetation gradient between forest tundra and tundra. This west-east gradient is induced by the climatic influence of Ungava Bay. Black spruce (*Picea mariana*) is the dominant tree specie. Tamarack (*Larix laricina*) and white spruce (*Picea glauca*) are also common, especially along coastal areas. *Cladina stellaris* is the dominant lichen species on well-drained sites not affected by caribou, and the shrub layer is dominated by dwarf birch (*Betula glandulosa*). The study area belongs mostly to the George plateau which is inclined east to west and dominated by glacial and fluvioglacial deposits. The George plateau is bordered to the west by the Whale River Plateau and to the east by the Torngat Mountains (Gouvernement du Québec, 1983). The climatic conditions are harsh and responsible for very slow vegetation dynamics. The mean annual air temperature is -7.5 °C, with approximately 50 frost-free days and a mean annual growing season of 90 days (Gouvernement du Québec, 1983).

The area of interest has undergone severe degradation by caribou (Morneau, 1999). It encompasses the calving grounds occupied by the GRCH for several decades (Fig. 2). Excessive grazing and trampling by the caribou population have caused a complete or partial (depending on location) destruction of the lichen mat in mature lichen stands and a degradation of superficial organic horizons with subsequent exposition of mineral soils at heavily-used sites (Morneau, 1999).

Landsat imagery

Landsat scenes were selected to cover the study area at three different time periods over the last three decades. The scenes were selected at a 10-year interval to ensure characterization of distinct periods in the herd history and to maximize the potential for change detection. The image selection was targeted on years 1998, 1988 and 1978. 1998 corresponds to a potential decline period for the GRCH and a likely recovery period for vegetation due to a limited caribou activity (Boudreau *et al.*, 2003). 1988 coincides to a population peak for the GRCH associated with severe habitat degradation (Morneau & Payette,

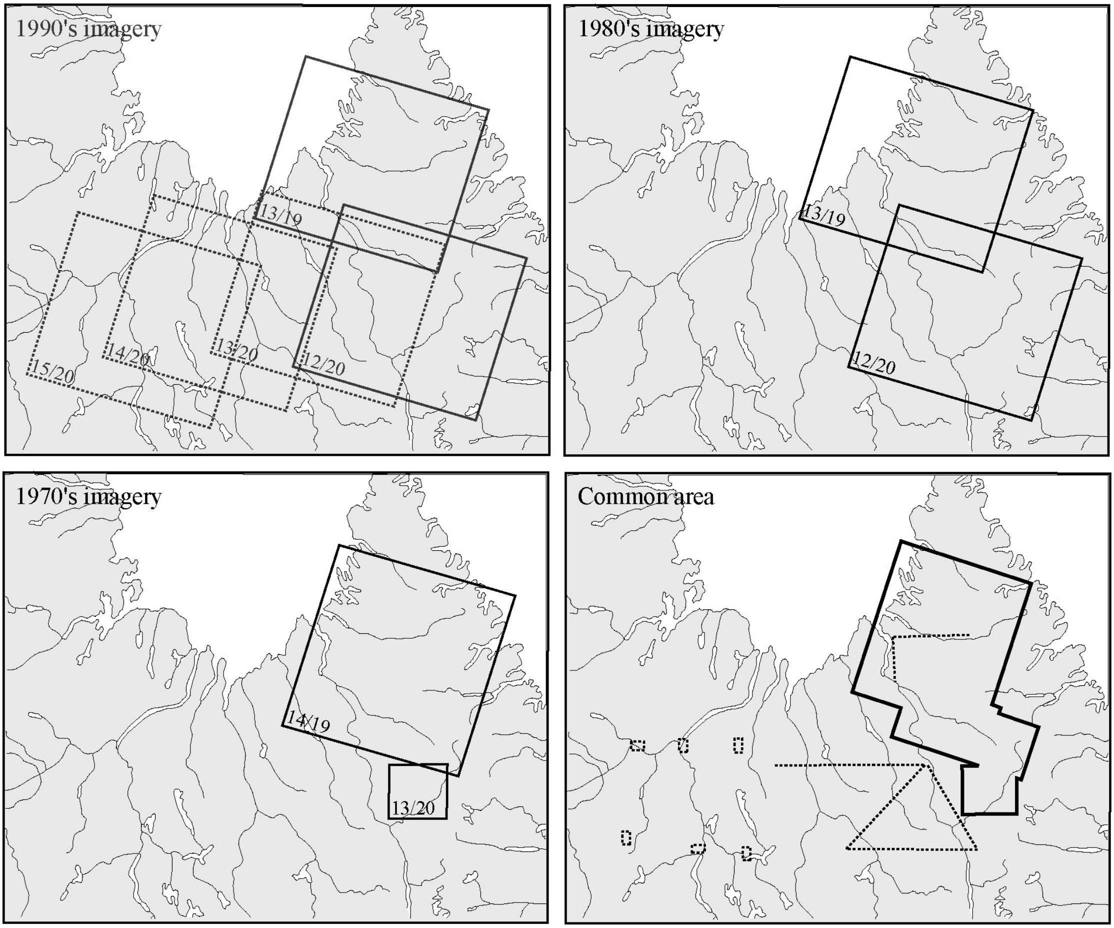

Fig. 3. Historical time series of Landsat images used to cover the calving area of the George River Caribou Herd for each decade and the common area of these three periods used for analyses. Path/Row for each scene is indicated in the lower left corner. The dotted line images (1990s imagery) were used for the selection of end-members and complementary field sites (validation). The dotted lines of the Common Area delineate the transects and areas surveyed during 2000 and 2001 campaigns, and used to validate the lichen map from the nineties.

2000). 1978 corresponds to the beginning of severe habitat degradation (Boudreau *et. al.*, 2003) and, according to Juniper (1977), a relative low population level (*e.g.* 170 000 heads in 1976).

Scenes were preferentially selected at the end of August to limit spectral reflectance differences due to vegetation phenology and to maximize the number of snow-free scenes. An effort was also made to choose scenes with low cloud amounts and other atmospheric perturbations. As a result, some scenes were selected outside our target years to ensure high data quality (Table 1). In addition, image selection was limited by the availability of images around the 1978 period. Unfortunately, images from this period are not as widely available due to the relatively low demand. Therefore, the reduced choice of images for the seventies period allowed only partial coverage of the calving grounds. Nonetheless, the information provided by this imagery is still useful since it covers the expansion of calving areas during the eighties. The spatio-temporal evolution of degradation in the most affected area over the last three decades was then mapped.

Two Landsat-2 MSS scenes and two Landsat-5 TM scenes were selected to cover the calving area for the seventies and eighties, respectively (Fig. 3). For the nineties period, two Landsat-5 TM scenes were chosen to cover the calving area and three other scenes were also used for image processing and validation. Details about the use of these additional scenes are provided in the next section. TM bands 3 and 4 were used for the eighties and nineties imagery because of their demonstrated suitability for vegetation and lichen studies (Petzold & Goward, 1988; Beaubien *et al.*, 1999; Nordberg & Allard, 2002; Théau *et al.*, 2003). The selection was also limited to these two bands due to the absence of a mid-infrared band for the MSS sensor. For imagery from the seventies, MSS bands were selected to correspond as closely as possible to the spectral bands available from Landsat TM: band MSS5 (0.60-0.70 µm), corresponding to band TM3 (0.63-0.69 µm), and band MSS7 (0.80-1.1 µm), corresponding to band TM4 (0.76-0.90 µm). Munyati (2000) successfully used this selection of bands to normalize multi-date MSS and TM images in a change detection investigation. Royer *et al.* (1987) also demonstrated comparable efficiency between the MSS and TM bands in gathering information on various land cover types.

All Landsat scenes were geometrically corrected and georeferenced to the Universal Transverse Mercator map projection (North American Datum 1983). Ground control points extracted from 1:50 000 topographic maps were used to correct images from the nineties. The images from the eighties and seventies were then registered onto the nineties images. Image resampling was performed using bilinear interpolation within the OrthoEngine V8.1.0 image analysis software available from PCI Geomatics™. The spatial resolution of the Landsat TM scenes was degraded to 80 meters to correspond to the nominal resolution of Landsat MSS.

Radiometric normalization

Change detection techniques have been used successfully to monitor land use/land cover, deforestation, vegetation phenology, and other environmental changes (Singh, 1989). However, these techniques must be applied carefully because of limitations due to image acquisition parameters and field characteristics. Changes in surface reflectance recorded by a sensor can be attributed to various factors such as changes in sensor calibration over time, illumination and observation angles, atmospheric conditions or surface conditions (Du *et al.*, 2002). Compensation for the first three factors can be made on multi-date images using radiometric corrections. For change detection, most of the radiometric correction methods are based on the use of pseudo-invariant features (PIF) on images. Reflectance values of these PIF are considered to be constant over time and variations observed are attributed to the first three factors. Correction parameters are computed by assuming a linear relation between the PIF values at different dates (Hall *et al.*, 1991; Hill & Sturm, 1991; Munyati, 2000). The key point of these methods is the selection of the PIF. Results can be subjective when the selection is made manually. However, an objective selection of these elements using principal component analysis and quality control has been proposed by Du *et al.* (2001), and successfully applied to normalize mosaics of Landsat TM images (Du *et al.*, 2001; Théau & Duguay, 2004) and for change detection purposes (Du *et al.*, 2002). When radiometric corrections are accurately applied on multi-date imagery, observed changes can be attributed directly to changes in target reflectance.

The Radiometric Normalization for Image Mosaics (RNIM) method described by Du *et al.* (2002), which is based on the statistical selection of pixel pairs in overlapping satellite scenes, was therefore adopted in the present study. Scene 13/19 (Fig. 3) from 1998 was chosen as the reference (or master image) for radiometric corrections since it was acquired at the end of August and relatively unaffected by atmospheric perturbations. Overlap areas with other scenes (or slave images) were used to perform the corrections.

All corrections followed the same procedure. First, pixels covered by clouds, shadow of clouds and water were masked as to avoid any spectral instability.

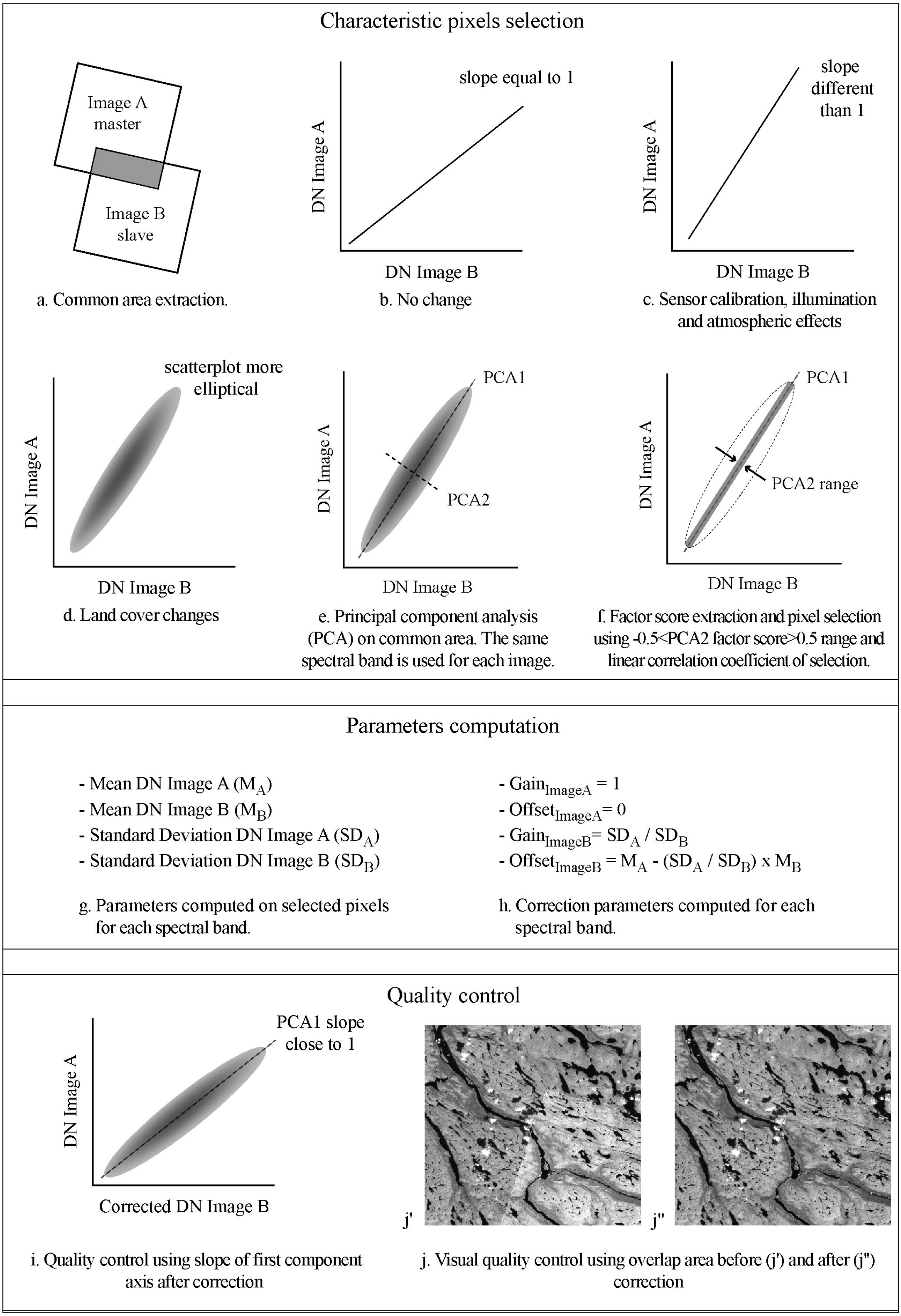

Fig. 4. Radiometric correction procedure.

Then, the common area between the master and the slave scene was extracted (Fig. 4a). Theoretically, if no changes occur in atmospheric and illumination conditions, sensor calibration, and land cover, a scatter plot between pixel values (Digital Number) from two dates will be a straight line with a slope equal to 1 (Fig. 4b). In practice, however, the slope of the relation is different than 1 due to sensor calibration, illumination and atmospheric changes between acquisition dates (Fig. 4c). Land cover changes also occur between dates (whether related to phenological or cover type changes) and, as a result, the scatter plot is more elliptical than linear (Fig. 4d). These effects were assumed to be linear and spatially homogeneous over the images, a reasonable assumption according to Du *et al.* (2002). The purpose of radiometric normalization was to recover a slope close to 1 in the relation between multi-date images (Fig. 4i). We assume that the pseudo-invariant features are distributed along the major axis of the elliptical scatter plot (no land cover changes) and their selection was made using numerical criteria with principal component analysis. Pixels close to the major axis of the first component (PCA1) where selected as PIF (Fig. 4f). A PCA2 range and a linear correlation coefficient was used to limit the selection of PIF pixels. As suggested by Du *et al.* (2002), a minimum coefficient of 0.9 was chosen to ensure that the pixels selected were linearly related and the PCA2 range was fixed at [-0.5 ; 0.5] to ensure sufficient PIF pixels selection (Fig. 4f). The mean and standard deviation of the selected pixels was then computed and used for the calculation of corrected gains and offsets (Fig. 4g and 4h). In order to avoid loss of information due to computed gains <1 and offsets <0, a normalization was performed. Gains were divided by the lowest gain <1 and the absolute value of the lowest offset <0 was added to all offsets. This normalization can be problematic when digital numbers of the satellite images are close to 255. Adding an offset can saturate high values. However, most digital numbers do not exceed 150 and cloudy pixels, which could have created problems, had already been masked. As a result, the saturation effect does not affect the information content of the images used in this study. For radiometric normalization, a combination of the ENVI software package (Research Systems Inc.) and STATISTICA (StatSoft Inc.) was used for the extraction of common areas, as well as the computation of PCA and correction parameters.

A quality control of the corrections was made using the slope of PCA1, after application of the new gains and offsets on the slave images. The best correction is obtained when the slope is closest to 1 (Fig. 4i). The quality of the corrections was also evaluated visually by examining the edges (overlapping areas) between the images. Disappearance of the edges and homogenization of the pixels values between the multi-date images allowed a supplementary verification of the quality of the radiometric normalization procedure (Fig. 4j).

Spectral mixture analysis

Since lichen pastures are used almost exclusively by caribou in northern Québec, evidences of overgrazing and overtrampling are accepted as being good indicators of caribou activity and habitat health (Moser *et al.*, 1979; Klein, 1987; Henry & Gunn, 1991; Morneau & Payette, 1998; 2000; Boudreau *et al.*, 2003). The very slow recovery of lichen pastures offers a relatively large time lag for change detection. Moreover, spectral patterns of lichen species are very distinct from vegetation and exposed soil, including at TM3 and TM4 wavelengths (Gauslaa, 1984; Petzold & Goward, 1988). Thus, lichen pastures were selected as an indicator of caribou habitat degradation and the image processing focused on the dominant lichen species (*C. stellaris*) and the dominant tree species (*P. mariana*). Spectral Mixture Analysis (SMA) was used for this purpose. This method is based on the fact that a pixel is rarely pure but made of a mixture of various surface elements. The reflectance of each individual element (or end-member) contributes to the overall reflectance of the pixel. Using pixel reflectance and spectral knowledge of the end-members, SMA involves retrieving their proportion (or fraction) inside the pixel. The critical step of this procedure consists of selecting the end-members. Fig. 5a presents a typical lichen pasture with a well developed lichen mat dominated by *C. stellaris* and a tree layer dominated by black spruce. As shown in this illustration, tree shadows can occupy a significant proportion of a pixel. Three end-members were selected to represent the composition of a typical lichen pasture covered by a Landsat pixel: lichen (*C. stellaris*), black spruce, and shadow. Assuming that linear spectral mixing occurs inside pixels, the total reflectance can be expressed as the sum of the product between end-members proportion and their respective reflectance (Fig. 5a). End-members were characterized spectrally using values of the purest pixels in open areas for lichen and dense forest areas for black spruce. The shadow end-member was characterized using pixels from a deep clear lake (Fig. 5b). The selection of end-members was based on the combined use of field observations and spectral properties of each element in TM bands 3 and 4. Imagery from the nineties was used for this purpose because precise field data were only available near this period. The advanced level of degradation observed in the study area made the

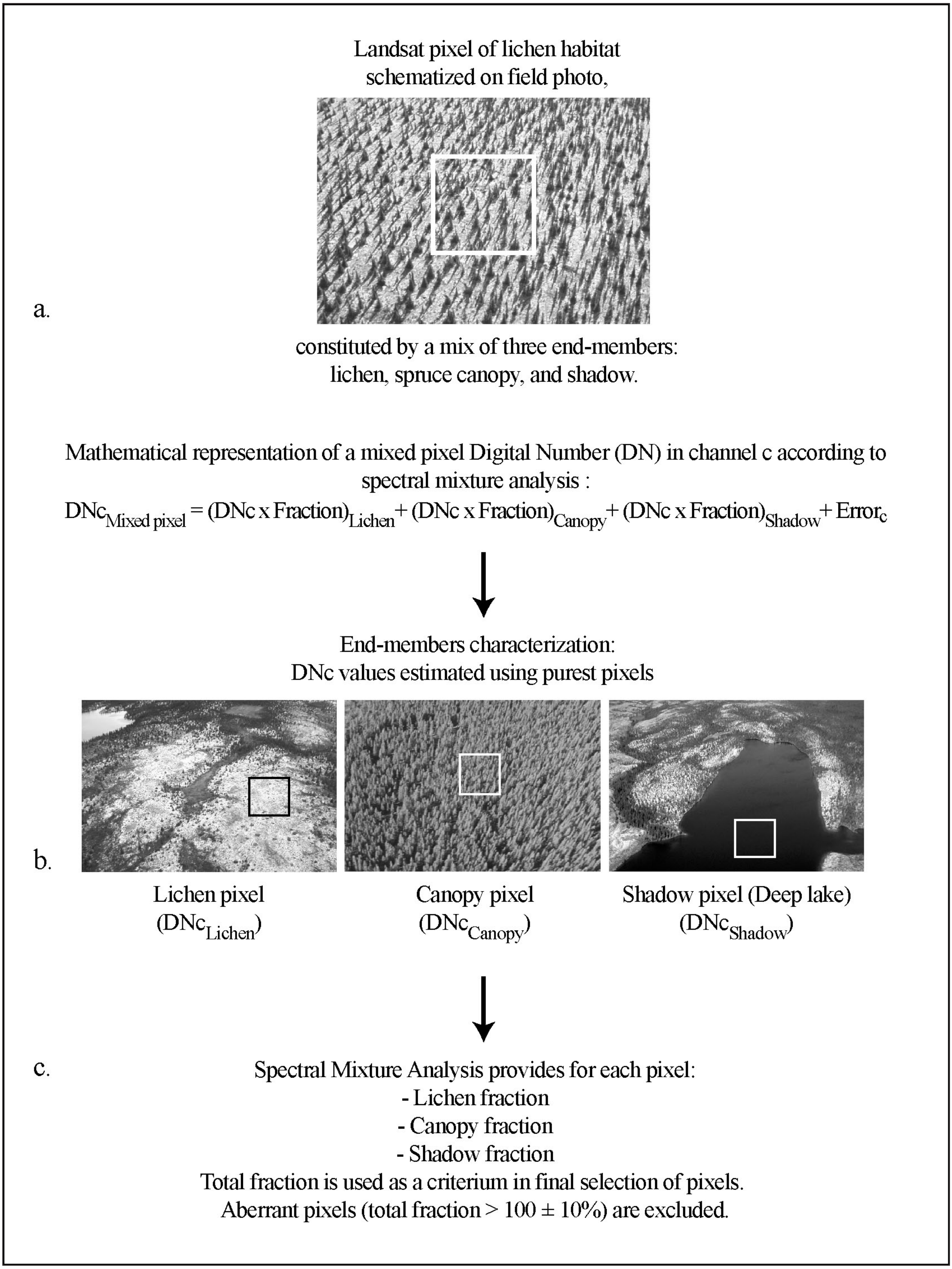

Fig. 5. Schema of spectral mixture analysis.

selection of a pure lichen pixel a challenging task. Scene 15/20 (Fig. 3) was used for this purpose because this area was not intensively occupied by caribou in the last decade (Morneau, 1999). Different biomes, including open lichen areas and dense spruce forests, are also represented in that scene. This scene was also relatively well covered and characterized in the field during summer 2001 (Fig. 3). As indicated in the previous section, this scene was radiometrically corrected against scene 13/19 using 13/20 and 14/20. The set of end-members selected on this scene was then used for all SMA on the normalized multi-date scenes. The SMA analysis was performed using an unconstrained algorithm provided in the ENVI software package (Boardman, 1989; 1992) which produced fraction maps for each end-member (Fig. 5c). Theoretically, for an appropriate end-member model, the sum of the fractions of each end-member should equal to one (or 100%). However, if end-members are not exactly representative of a pixel's content, the total fraction will not equal to 100%. The total fraction was thus used as a criterion to select or reject pixels. A deviation of up to 10% was tolerated in cases where the fractions did not sum to unity. This is the error range usually accepted in the application of SMA. Pixels outside this range were excluded and considered as non-lichen pastures according to our end-member selection. The procedure was applied to each scene and lichen fractions were used to produce final maps for each decade with respect to their common area.

Field data

Ideally, field data should be collected near the time of the satellite overpasses. Unfortunately, this is rarely possible particularly when using historical time series of satellite images (Munyati, 2000). In general, field observations are collected for the most recent image acquisition dates and used directly or indirectly to process older images (Rees & Williams, 1997; Yang & Prince, 2000). Historic data from various sources (e.g. indigenous knowledge, aerial photos) can also be used to complete the lack of information (Almeida-Filho & Shimabukuro, 2002; Rees *et al.*, 2003).

In this study, field data were acquired in the common area of Fig. 3 during summer 2000 to validate the lichen map produced with SMA using images from the 1995-1998 time period. As mentioned earlier, lichen pastures were severely damaged in this area. Intact lichen stands represented only a very low proportion of the area. To overcome this problem, field observations made at several sites during summers 2000 and 2001 were added. The sites all fell in scenes 15/20, 14/20, and 13/20, which were less affected by caribou degradation. Landsat images and field measurements were not acquired simultaneously due to the lack of cloud-free images and the lead time required between field planning and field work in such remote regions. Caribou grazing and trampling, as well as fires constitute the major source of perturbation for vegetation in the study area. These events cause dramatic changes in vegetation in a short lapse of time and could have caused changes between image acquisition dates and the field measurement periods. However, if these events occurred in some of the field sites, they would affect the quality of the image analysis results in a limited way. Radical vegetation changes caused by fires are easily detectable on visible/infrared imagery. Burned areas observed in the field, but not in the scenes, were excluded from the analysis. Habitat degradation by caribou is less obvious and cannot be identified directly on satellite imagery.

Surveys were conducted along transects during the 2000 field campaign and in specific, local areas in 2001 (see Fig. 3). Changes in the sampling strategy were made due to logistical constraints. However, they did not affect field data acquisitions because the sites were characterized in the same way along the transects and inside the specific areas. Field sites consisted of homogeneous groups of pixels selected on enlarged Landsat color prints before aerial surveys so as to define precise flight plans and ensure sufficient characterization of habitat diversity. Navigation, precise site location, and characterization were ensured by the complementary use of topographic maps and enlarged Landsat color prints. Sites were surveyed and photographed by the same observer from a helicopter at a mean altitude of 200 m, looking trough a window and flying around. Observations were made as close as possible to the nadir angle. Sites were visited at low altitude or on the ground in the case of ambiguous observations from the air. For each site, the type and percent coverage of the canopy layer, as well as the type and percent coverage of the soil layer were estimated and recorded. Mean coverage estimations were made at the site-level because individual pixel characterization was less appropriate for this very large area. Particular efforts were made on lichen pastures. In total, 69 sites with a mean area of 0.19 km^2 (min=0.02 ; max=1.54 km^2) were characterized and used for validation of the lichen map.

Results

Radiometric normalization

An average of about 1 190 000 pixel pairs, with linear correlation coefficients ¶ 0.90, was selected on each overlap area used to perform the radiometric corrections (Table 2). The PCA2 range selection was reduced from [-0.5 ; 0.5] to [-0.4 ; 0.4] for three series of pixels to conserve a linear correlation coefficient ≥ 0.90. The comparison of slopes from the first principal component axis (PCA1), before and after radiometric corrections, indicates that the statistical similarity between image pairs was greatly improved

Table 2. Computational details of overlap areas, including the linear correlation coefficient (*r*) of the selected pixels and validation of the efficiency of the procedure with slopes of the first principal component axis before (PCA1a) and after (PCA1b) radiometric correction.

Overlap area (year/path/row)	TM3/MSS5				TM4/MSS7			
	Pixels selected	*r*	PCA1a slope	PCA1b slope	Pixels selected	*r*	PCA1a slope	PCA1b slope
1998/13/19-1998/12/20	2 084 775	0.91	0.818	1.004	2 012 965	0.93	1.091	1.002
1998/13/20-1995/14/20	895 885	0.92*	1.182	1.006	959 244	0.90*	1.269	0.995
Corr1995/14/20-1996/15/20	1 3493 35	0.96	0.942	0.994	1 375 820	0.95	1.040	0.989
1998/13/19-1986/13/19	1 808 283	0.93	0.900	1.001	1 619 999	0.91	1.118	0.996
1998/13/19-1985/12/20	1 088 939	0.93	0.882	1.000	1 034 113	0.91	0.895	1.006
1998/13/19-1979/14/19	900 794	0.91	1.368	1.004	952 276	0.94	0.806	1.004
Corr1998/12/20-1976/13/20	228 742	0.91*	0.786	0.994	317 694	0.93	0.913	0.998

* indicates a range selection -0.4 < 2[nd] Principal Component axis > 0.4, and Corr. indicates a scene corrected in a previous step.

by the radiometric normalization procedure since the slopes are closer to 1 (Table 2).

A visual inspection was also performed as a complement to the numeric quality control. The inspection was preferentially made along the edges between the normalized scenes, as illustrated in Figure 4. Following the application of the radiometric normalization procedure, the edges became virtually invisible (except for cloudy areas) and the mosaic of scenes more homogeneous.

Spectral mixture analysis

Validation was accomplished by plotting the lichen

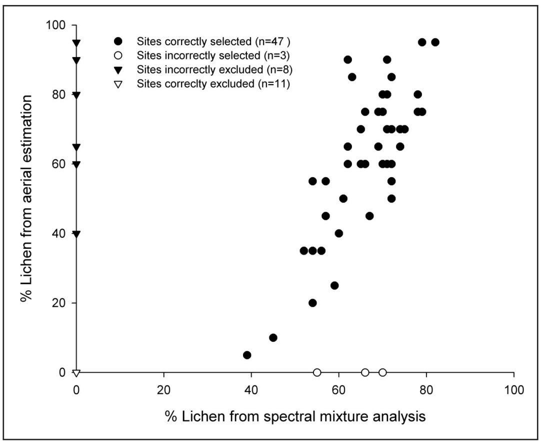

Fig. 6. Scatter plot between mean percent lichen vertical coverage estimated in test sites during aerial surveys and values obtained from the spectral mixture analysis. Each symbol represents the mean percentage observed and computed at each site.

fraction results obtained with SMA against the lichen aerial estimate from above the ground at each site (Fig. 6). The scatter plot shows a significant correlation (r=0.90; P<0.05) between the SMA and field estimates. Fraction discernment is lower for the SMA than from field observations. Lichen fractions estimated in the field vary from 5% to 95% while they vary between 40% and 82% for SMA results. It should be noted, however, that obtaining absolute values was not the goal of the SMA. Relative values between sites are of interest in our study and were accurately determined by the procedure. Lichen sites were well discriminated from the non lichen sites by SMA with accuracies of 86% and 79%, for correctly selected (47 out of 55) and correctly excluded (11 out of 14) sites, respectively (see Fig. 6). Eight lichen sites, identified in the field, were excluded by the SMA procedure. At all sites, occurrences of mineral soil and rock exposed naturally or by moderate caribou activity were noted during field observations. End-members selected for the SMA (lichen/canopy/shadow) were probably not totally representative of the pixel content for these sites, even if they contained lichen. Three non-lichen sites, surveyed in the field, were selected by the SMA procedure as if they contained lichen. One of these was characterized in the field as moss woodland. These sites often contain small lichen spots in dryer areas which are not clearly visible from the air. These occurrences could explain the detection of lichen by SMA. Also, two sites were characterized in the field as degraded lichen woodlands but selected by the SMA. Typically, these sites are severely damaged by caribou and lichen is absent. The detection of lichen in these sites could be explained by degradation events in the interval between image acquisition and field characterization. For example, a damaged site observed in 2000-2001 could have been intact in the satellite image acquired a few years before.

Lichen maps

Lichen maps of the common area for each decade are presented in Figs. 7, 8, and 9. In the grey level maps, dark pixels correspond to low lichen fractions whereas white pixels correspond to high lichen fractions. Black pixels are those that were excluded by the SMA procedure. The change maps between each decade were produced by performing image differencing between each period. They are presented in two versions: lichen fraction increase maps and lichen fraction decrease maps. Lichen fraction increase maps are represented using a yellow scale. White represents pixels with low levels of change while yellow represents pixels with increasing levels of change. Black pixels are those which experienced no increase in lichen fraction. Lichen fraction decrease maps are represented with a red scale and can be interpreted in a similar manner as the increase fraction maps. Extreme changes in both types of maps must be interpreted with some caution since the absolute values are not in a 1:1 correspondence with field reality, as explained in the last section. For example, a lichen increase of 80% does not mean a regeneration of 80% inside the pixel between two dates. A pixel with 80% of lichen can be excluded by the SMA if mineral soil exposed by moderate caribou activity is present, because end-members are not totally representative of overall pixel reflectance. After a few years, if lichen regeneration occurred and mineral soil is less significant, this pixel could be selected by the procedure. The lichen fraction maps and change maps should therefore be interpreted more through their representation of the general geographic patterns they provide than as indicators of absolute quantitative information. In the following section, results are described chronologically with reference to the location of the George, Ford and Koroc rivers.

Discussion and conclusion

The purpose of this paper was to map changes in lichen cover in the summer range of the GRCH over the period from 1976 to 1998, and to study the spatio-temporal evolution of the lichen pastures in relation to their degradation by caribou. The radiometric normalization procedure applied to multi-date and multi-sensor Landsat imagery gave generally good results based on the visual and numerical quality control. However, some radiometric effects still persisted after normalization, especially noticeable between pairs of MSS images (*e.g.* linear demarcation in the southern part of Fig. 7). SMA was used to map lichen at the sub-pixel scale and also gave satisfying results when compared to field validation data. Lichen sites were well discriminated from non lichen sites and the relative variations of lichen cover in the field were well conserved by the procedure, based on the validation data.

The area covered by the historical time series of Landsat images corresponds to the summer range of the GRCH, and more precisely to the calving grounds mapped in the late 1980s (Fig. 2). Calving grounds are known to undergo severe disturbances by caribou because in this period of the year, the herd, especially females, are regrouped. These high densities make lichen pastures vulnerable to overtrampling and overgrazing. Assuming that vegetation dynamic is very slow in northern environment, we hypothesized that dramatic changes in lichen cover were linked to caribou activity. Fires also constitute a major source of vegetation disturbance but they had a limited impact during the study period of this investigation. The fire rotation period near the tree line in Northern Quebec is estimated to be >7800 years, with average surface areas of 6.75 km^2 in northern forest tundra and 0.81 km^2 in tundra biome being affected (Payette *et al.*, 1989). Moreover, fire scars are easily detectable on visible/infrared imagery and none were detected in our study area. Lichen maps produced for the 23-year period were interpreted in relation with lichen degradation and regeneration, caribou population dynamics and distribution.

Period (1976-1979) - (1985-1986)

During this period, decreases in lichen fractions are observed mainly in the eastern and southern part of the study area (Fig. 7). Changes are evident on both sides of the Koroc River, especially along the southern banks of the Koroc River. High values observed in this area are related to the low number of pixels selected by the SMA for the period (1985-1986), as shown by the lichen map for these years. After examination of these images using the original visible/infrared bands, significant amounts of snow were observed in this region but not present for the other periods. The presence of snow can be explained by the early summer acquisition of the 1985-1986 imagery. Lichen map results for this region must then be interpreted carefully because lichen could have been under-evaluated by SMA. The absence of a general pattern in this region for the lichen change maps of the 1976-1979 and 1998 periods (Fig. 9), confirms potential biases in the 1985-1986 images.

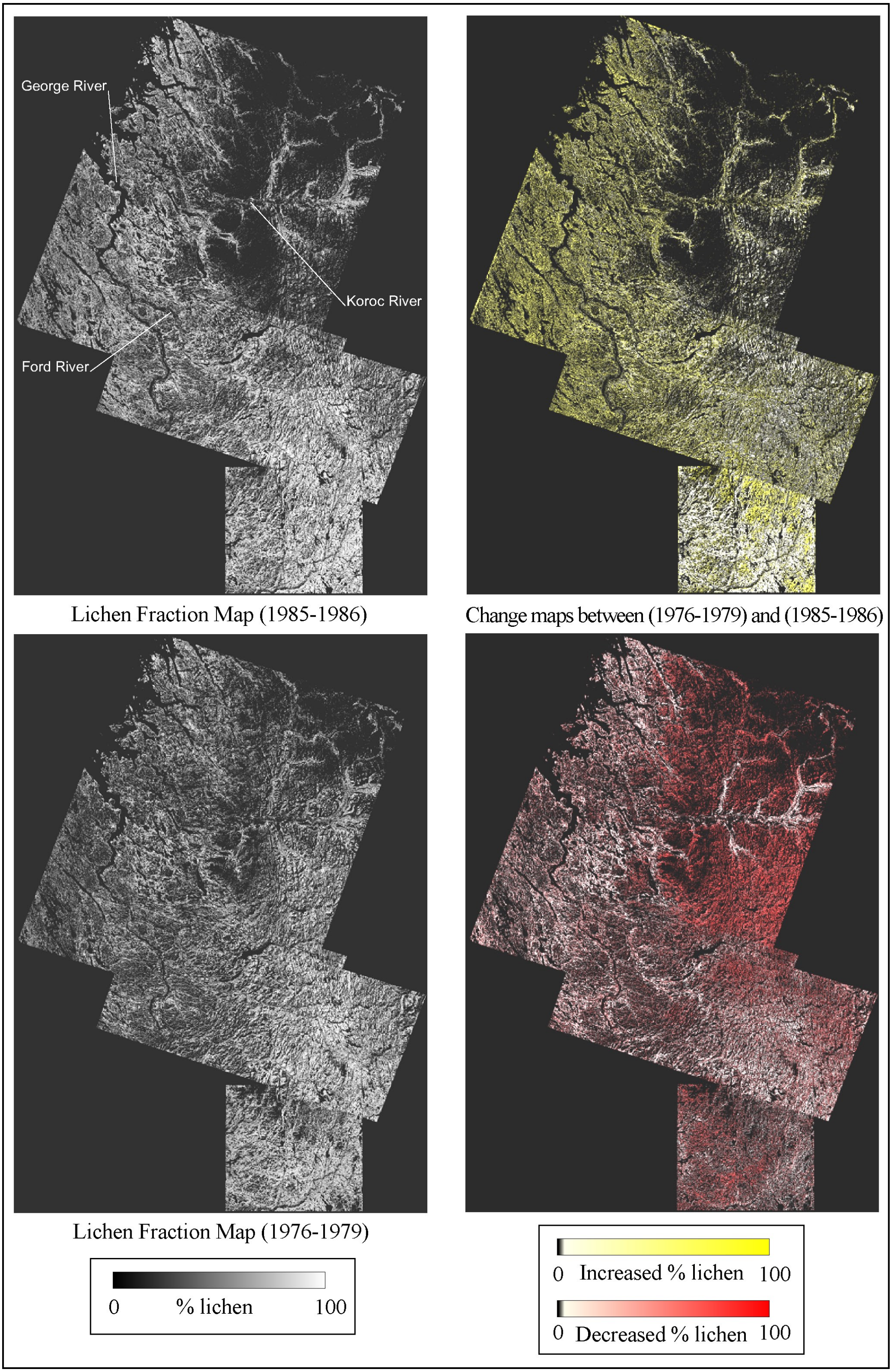

Fig. 7. Lichen fraction maps and change maps between 1976-1979 and 1985-1986.

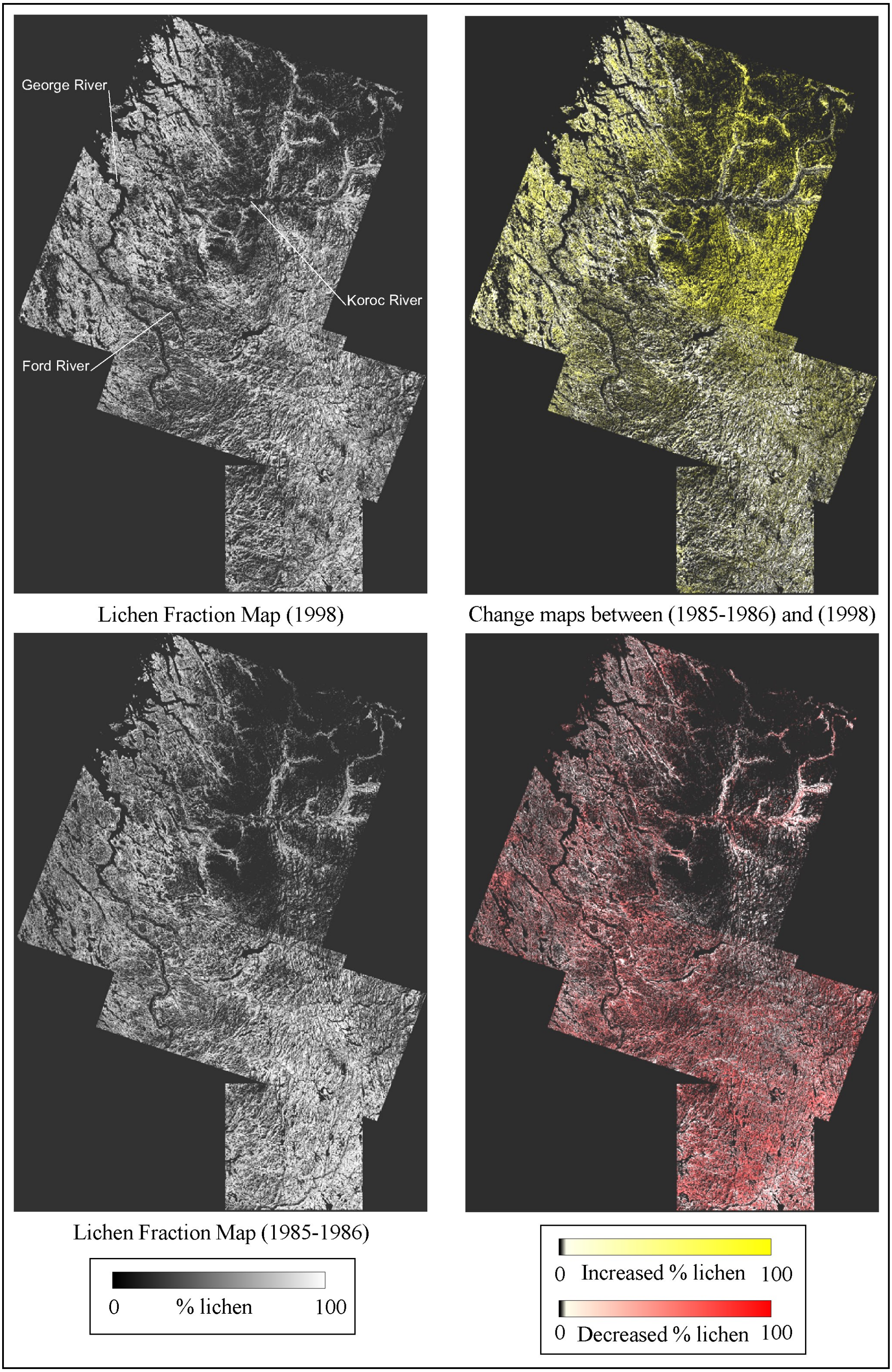

Fig. 8. Lichen fraction maps and change maps between 1985-1986 and 1998.

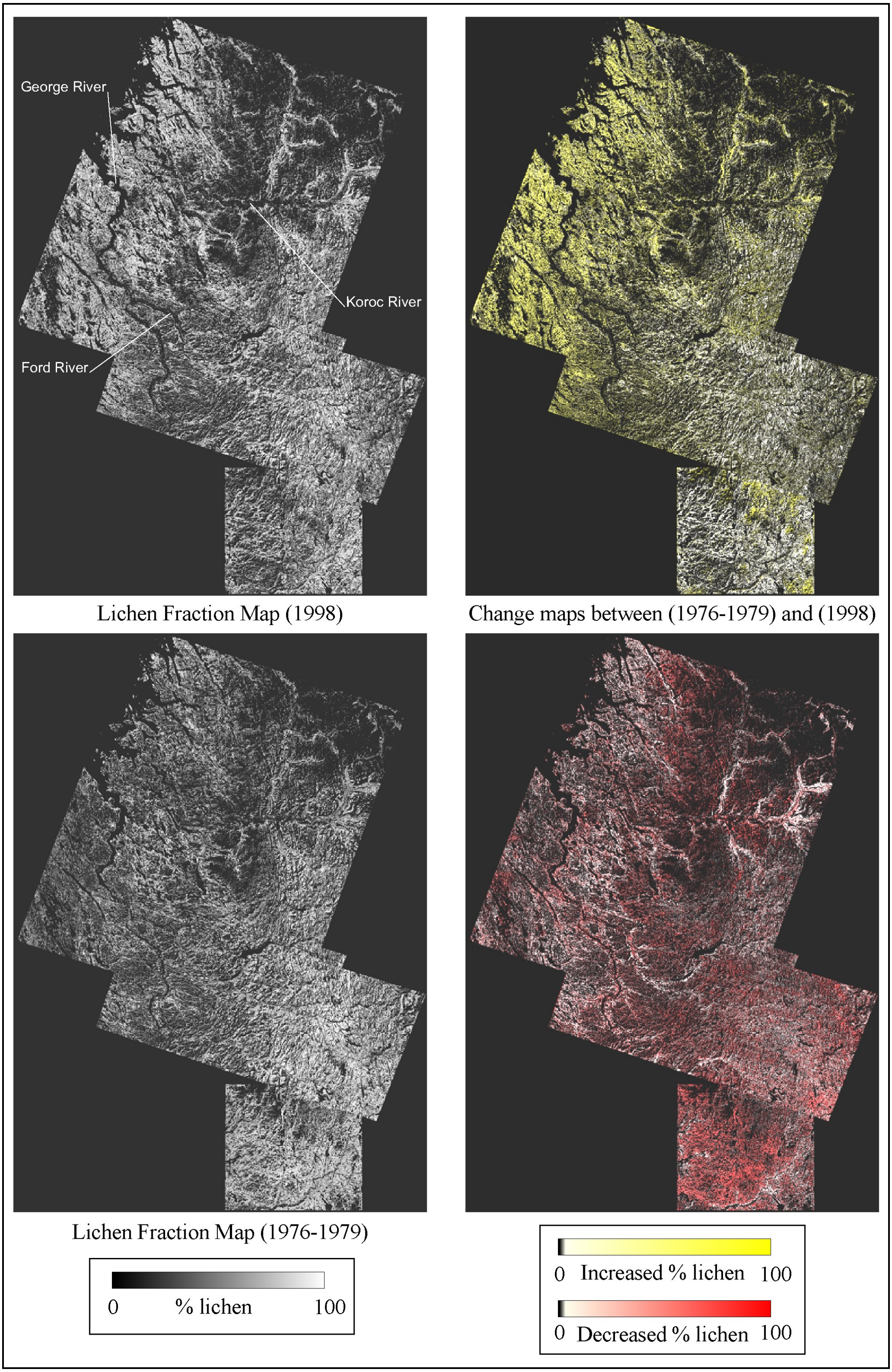

Fig. 9. Lichen fraction maps and change maps between 1976-1979 and 1998.

The extreme north-eastern section of the area belongs to the Torngat Mountains. The few pixels selected in this region for all decades can be attributed to topographic effects and will therefore not be interpreted in relation to caribou activity. Increases are noticeable in the valley in association with slight decreases. In the western region, the opposite process and general increase in lichen cover can be observed. Along the western bank of the George River and along the coast of Ungava Bay changes are dominated by increases in lichen cover, even if small occurrences of decreases can be depicted near the mouth of the George River. In the southern part, patterns are not as clear. This region is characterized by a mixed mosaic of decreases and increases in lichen cover. However, the extreme southern part is characterized by a local concentration of red pixels which suggests a general decrease in lichen cover for this region. Between (1976-1979) and (1985-1986), calving grounds were localized in the eastern and southern part of the study area (Fig. 2), which coincides with lichen cover decreases observed for this period (Fig. 7). Herd population census performed in 1976-77 and 1984-85 indicate an increase from around 170 000 to 643 600 (± 25%) heads, respectively (Juniper 1977; Crête *et al.*, 1991). However, albeit this exponential growth, calving grounds were still localized in the southern and eastern parts of the study area. The western part of the area was not used as calving grounds in this period and could explain the increase pattern observed in lichen change maps. Even if these areas were used by the herd in its annual migration (Messier & Huot, 1985), the impacts were probably not as concentrated as in the calving grounds and did not induce severe degradation.

(1985-1986) - (1998) period

During this period, the Koroc River valley is dominated by decreases in lichen cover, in a similar fashion to the George and Ford rivers (Fig. 8). This pattern can also be observed in other valleys and around lakes between the Koroc and Ford rivers. The western part is not characterized by any general pattern. A mosaic of decreases and increases in lichen cover is observed along the Ungava Bay coast and near the mouth of the George River. The southern part is dominated by a decrease in lichen cover. From the mouth of the Ford River to the extreme south, red pixels dominate and thus indicate that a general decrease in lichen cover has occurred in this region. Pixels showing increases are also present but only the light yellow ones are visible.

Between 1985-1986 and 1993, calving grounds underwent an expansion westward and northward associated with the population increase and its 776 000 (±13.4%) heads level observed in 1993 (Couturier *et al.*, 1996). Unfortunately, no published maps are available after this period but recent observations have shown a reduction in the annual range of the herd (FAPAQ, unpubl. data), which is associated with the population decrease observed in the 2000-2001 census (Gouvernement du Québec, 2002). Using dendrochronology on trampling scars produced by caribou hooves, Boudreau *et al.* (2003) also found that the general activity of the GRCH has decreased since the early nineties. Therefore, the calving grounds probably did not exceed the largest range observed in 1988, but possibly underwent a decrease since 1993. However, the expansion observed between 1985-1986 and 1993 coincides with an expansion of lichen decrease pixels northward and westward observed in the change maps of the 1985-1986 to 1998 period. This pattern corresponds to the degradation of lichen pastures observed since the eighties in various studies (Saucier & Godard, 1992a; Manseau *et al.*, 1996; Morneau & Payette, 2000). The Koroc River valley was snow-free in the 1985-1986 imagery and underwent decreases in lichen cover. This pattern suggests that a similar pattern probably occurred along the river, including in the southern bank. A decrease in lichen cover is not as clear near at the mouth of the George River and along the coast of Ungava Bay. Utilization of these areas as calving grounds began after 1988 and was possibly abandoned after 1993. These regions were likely less intensively occupied and damaged by the herd. The lichen change map derived for the 1976-1979 to 1998 period (Fig. 9) confirm this pattern because a general increase in lichen cover was observed in these areas, except for the George River valley. The most affected areas in the 23-year period are located in the southern part of the study area, which were used as calving grounds almost exclusively as early as 1973. Calving grounds were identified in the eastern part of the Koroc River and associated with a herd distinct from the George River herd (MLCP, 1987). Local degradation patterns observed in change maps between 1976-1979 and 1998 in the eastern Koroc River coincide with the maps produced by MLCP (1987). However, the existence of this herd is not unanimously accepted and few data are available because this herd is generally considered as belonging to the GRCH.

Overall, the results obtained from the analysis of Landsat images show the same general demographic and habitat patterns of the GRCH as described in other studies. However, one should be aware of some of the limitations due to the use of multi-date and multi-sensor imagery (*e.g.* radiometric effects), and the use of SMA to generalize lichen pasture results. Even if accurate radiometric normalization is performed, the heterogeneity between scenes caused by variations in the phenological state of vegetation, climatic conditions or radiometric resolution between sensors cannot always be totally eliminated. Ideally, this methodology should be applied to another set of multi-date Landsat images to corroborate the results obtained here. The availability of MSS imagery constitutes the principal impediment at the moment. However, the Canada Centre for Remote Sensing and the United States Geological Survey are working on increasing public access to MSS image archives. With the increased availability of MSS images, a study over the whole summer range would also be useful for obtaining more complete results on the spatio-temporal evolution of lichen pastures over the last three decades. Mapping of lichen cover fraction was recently successfully performed on late 1990s imagery (Théau & Duguay, 2004) and could be applied on imagery from the eighties and seventies. The selection of end-members can also be a source of uncertainty. The variability associated with end-members series selected at different locations over a very large area can be significant. In the case of this study, the absence of historical field data constrained the choice of end-members to the nineties imagery. Ideally, one set of end-members should be chosen for each decade.

Despite some of the limitations inherent to the imagery and to the generalization process, lichen fraction maps and change maps over a 23-year period in the summer range of the GRCH were produced. The maps enabled to better understand the spatio-temporal interactions between the herd distribution and the over-utilization of lichen pastures. No previous remote sensing studies of the type described in this paper have ever been performed in this area to characterise habitat degradation by caribou. The summer habitat of the GRCH is known to act as a limiting factor that greatly affects herd demography. Knowledge of this ecological component of the herd is then essential for an improved management of the caribou resource. The results obtained herein confirm observations made during past herd census and vegetation studies and illustrate, visually, the impact of the herd on its habitat.

However, the maps produced raise questions about impacts of this degradation on herd demography and about habitat selection. We have shown evidences of degradation over the last 23 years but also evidences of lichen cover increase, especially near the mouth and the western bank of George River. Moreover, Théau & Duguay (2004) have shown lichen-rich areas distributed all over the summer range, outside calving grounds, in lichen maps produced for the 1995-1998 time period. These results do not fully support the hypothesis that the recent decline of the herd was caused primarily by resource degradation in the summer range. Special attention should also be placed on the impact of winter factors such as habitat use, hunting, predation and climate harshness, especially in the actual context of climate change.

This study also illustrates the need to use data from a variety of sources, ideally integrated into a geographic information system (GIS), in such remote and vast environments. In the absence of census surveys, which are costly and not frequent in northern regions, satellite remote sensing offers a useful means for mapping and monitoring lichen pastures on a regular basis and inferring herd habitat use.

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