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Mapping caribou habitat north of the 51st parallel in Québec using Landsat imagery

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Abstract: A methodology using Landsat Thematic Mapper (TM) images and vegetation typology, based on lichens as the principal component of caribou winter diet, was developed to map caribou habitat over a large and diversified area of Northern Québec. This approach includes field validation by aerial surveys (helicopter), classification of vegetation types, image enhancement, visual interpretation and computer assisted mapping. Measurements from more than 1500 field sites collected over six field campaigns from 1989 to 1996 represented the data analysed in this study. As the study progressed, 14 vegetation classes were defined and retained for analyses. Vegetation classes denoting important caribou habitat included six classes of upland lichen communities (Lichen, Lichen-Shrub, Shrub-Lichen, Lichen-Graminoid-Shrub, Lichen-Woodland, Lichen-Shrub-Woodland). Two classes (Burnt-over area, Regenerating burnt-over area) are related to forest fire, and as they develop towards lichen communities, will become important for caribou. The last six classes are retained to depict remaining vegetation cover types. A total of 37 Landsat TM scenes were geocoded and enhanced using two methods: the Taylor method and the false colour composite method (bands combination and stretching). Visual interpretation was chosen as the most efficient and reliable method to map vegetation types related to caribou habitat. The 43 maps produced at the scale of 1:250 000 and the synthesis map (1:2 000 000) provide a regional perspective of caribou habitat over 1200 000 km^2 covering the entire range of the George river herd. The numerical nature of the data allows rapid spatial analysis and map updating.

Key words: forest fire, lichen, northern Québec, *Rangifer tarandus*, remote sensing, vegetation, visual interpretation.

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Introduction

From estimates in the order of 50 000 animals in the 1950s, the total number of caribou (*Rangifer tarandus*) in Québec/Labrador possibly approached 1 000 000 animals in the mid 90s. In the past two decades the sizes and dynamics of the Québec/Labrador caribou herds have attracted attention on several fronts including: population management, native and recreational harvest, low flying jet aircraft, hydroelectric developments, airport safety and finally a concern for habitat deterioration caused by the animals themselves. In order to address some of these management issues, a baseline set of mapped information was needed to serve as a unifying tool for the various interests in the area. Satellite imagery was chosen as a time-saving and cost-effective means for synoptic habitat mapping for very large areas. Habitat mapping has been derived from optical satellite imagery mostly in the 80s and early 90s. The inherent assumption is that wildlife habitat is related to vegetation cover and ecological characteristics visible on satellite images.

In the early 1980s, several studies evaluated the potential of Landsat MSS imagery in wildlife habitat mapping for birds and mammals (Epp, 1985). Habitats were mapped for white-tailed deer (*Odocoileus virginianus*) (Dixon et al., 1982), moose (*Alces alces*) (Laperrière et al., 1980; Dixon et al.; 1984; Bowles, 1985) and caribou (Thompson & Klassen, 1979; Polson & Campbell, 1987). Habitat

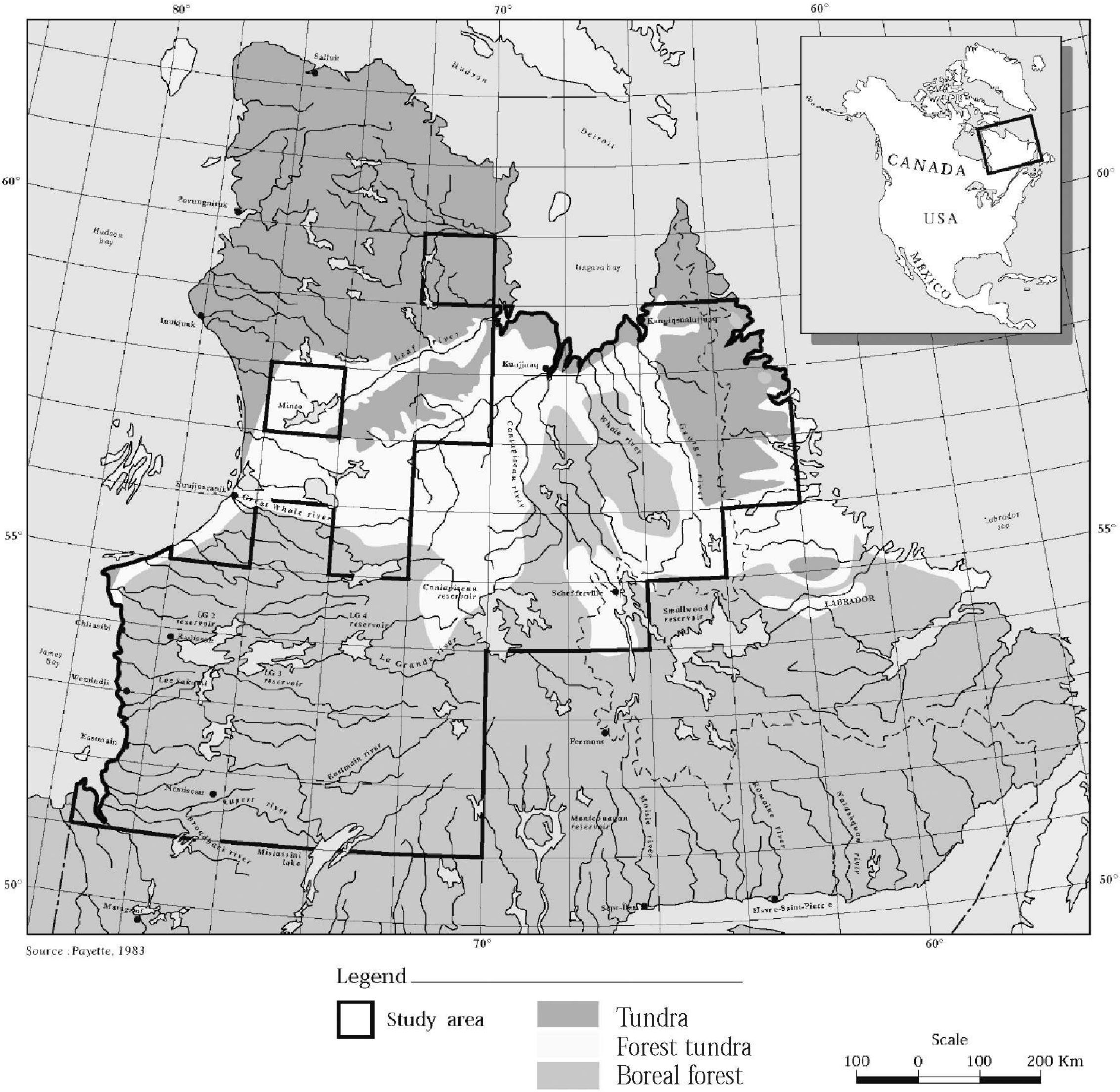

Fig. 1. Study area in northern Québec, Canada.

potential for wildlife in the Boreal Forest was also assessed by mapping vegetation types using MSS data (Grondin et al., 1983; Henderson, 1984; Talbot & Markom, 1986). The coarse resolution (80 m x 80 m) and the limited number of spectral bands (four visible and near infrared bands) of the MSS sensor limit its applications to general purposes: to provide a regional view, to delineate broad vegetation patterns or to be used as a first stratificator for field studies. In those studies, confusion between classes was frequent and the sensor was not adapted for systems with high vegetation heterogeneity. Visual interpretation seems to allow a more precise recognition of vegetation types (Grondin et al., 1983).

The increased spatial resolution (30 m x 30 m) of the Landsat TM sensor, in operation in the mid 80s, combined with additional spectral information (six visible and infrared bands) offered new possibilities in thematic mapping and map scale precision. Numerous studies, using Thematic Mapper data to map wildlife habitat in large remote areas, have been reported for caribou in Norway (Tømmervik & Lauknes, 1987), for moose in Ontario and Newfoundland (Oosenbrug et al., 1988; Ellis et al., 1990), for white-tailed deer in Michigan and southern Québec (Sirois & Bonn, 1984; Ormsby & Lunetta, 1987), for wood bison (*Bison bison athabascae*) and muskox (*Ovibos moschatus*) in the Northwest Territories (Matthews, 1991; Ferguson, 1991) and waterfowl in western Canada and the United States

(Jacobson, 1991). The extent of mapped areas in these studies varies from 200 to 10 000 km^2, with an average of 3300 km^2. The waterfowl habitat inventory stands apart with its 900 000 km^2 in the prairie region (Jacobson, 1991). In these studies, the number of vegetation or habitat classes always varies between 7 to 15.

The objectives of the study were threefold: 1) to develop an operational methodology to map caribou habitat north of the 51st parallel in Québec using Landsat TM imagery, 2) to develop a simple classification of vegetation types, accounting for the wide biogeographic variability, while linking it to lichens and 3) to produce digital maps of caribou winter habitat. A fundamental underlying principle was that these maps would be easy to update over time with a minimal commitment of resources. Final maps sought were to serve as a basic management tool to assist the decision-making process of different interests groups in northern Québec in relation to northern development and caribou population management.

In a project of this scope, many constraints challenge the cartographer. The remoteness of northern Québec, along with the vast areas to survey (over 1 200 000 km^2 north of the 51st parallel) were major difficulties. The long distance movements of herds from calving to wintering grounds covered a wide biogeographical variation (three biomes) difficult to classify in a reasonable number of vegetation classes. The predominance of terrestrial lichens in the caribou winter diet (Gauthier et al., 1989; Crête et al., 1990), of graminoids (mostly Cyperaceae) in spring, and of dwarf birch leaves (Betula glandulosa) and other shrubs in summer (Crête & Doucet, 1998) had to be integrated in the definition of vegetation classes because of the the critical importance of the calving grounds. Moreover, disturbance by forest fires that affects lichen regeneration, and lichens abundance which can influence caribou winter distribution (Couturier & St-Martin, 1990) add a temporal dimension to mapping. Finally, the method had to deal with mosaics of habitat types, which were difficult to map without multiplying the number of vegetation classes.

Study area and data sets

Study area

The study aimed to cover the entire annual range of the George river caribou herd from wintering habitats in the James Bay region northeastwards to the calving grounds of the George river Plateau covering more than one million km^2. The study area also overlaps with the wintering range of the Leaf river caribou herd. Extending from 51st to 60th parallels between James Bay and the Labrador Sea, the actual mapped area covers 536 000 km^2 and exhibits a wide range of biophysical characteristics.

The study area extends over three biomes (Payette, 1983; Fig. 1). The Boreal Forest covers about 61% of the mapped area, the Forest Tundra 26%, and the Shrub Tundra 13%. Black spruce (Picea mariana (Mill.) BSP.) is by far the dominant tree-species throughout the area. Tree cover is continuous in the Boreal Forest (except in peatlands) and is decreasing while lichens cover increases progressing north in the forest tundra, where lichen-heath-dwarf birch (Betula glandulosa Michx.) communities cover extensive areas. In the true tundra biome, the communities without trees are dominated by arctic floristic elements.

The long-term repeated influence of natural fires, in conjunction with climate, is responsible for this vegetation zonation (Payette et al., 1989). Forest fires remain the most important disturbance controlling vegetation diversity and lichens composition (Morneau & Payette, 1989; Arseneault et al., 1997). The natural fire rotation period dictates the spread of lichens regeneration, community composition, biomass and spatial extension (Morneau & Payette, 1989). The fire rotation period is estimated at 100 years in the Boreal Forest, 180 years in the southern Forest Tundra and about 1460 years in the northern Forest Tundra (Payette et al., 1989).

Satellite imagery data

To cover the study area, 37 Landsat TM scenes were needed, ranging from 1985 to 1994 to produce a single mosaic. We tried to use images from the latter part of the growing season because the spectral discrimination of vegetation, at this time of the year, is at its best. Among the six visible and infrared bands of the TM sensor (TM1 blue band, TM2 green band, TM3 red band, TM4 near infrared band, TM5 and TM7 middle infrared bands), only three bands (TM3, TM4 and TM5) were selected because they enable to distinguish and discriminate several vegetation types.

Topographic map data

Forty-three numerical topographic maps at the scale of 1:250 000 (National Topographic System of Canada) were used as base map. Topographic map at the scale of 1:50 000 (paper copy) were used for the geometric correction and as a guide for wetland delimitation. Finally, to produce a synthesis vegetation map for the entire study area, we used a numerical base map at the scale of 1:2 000 000.

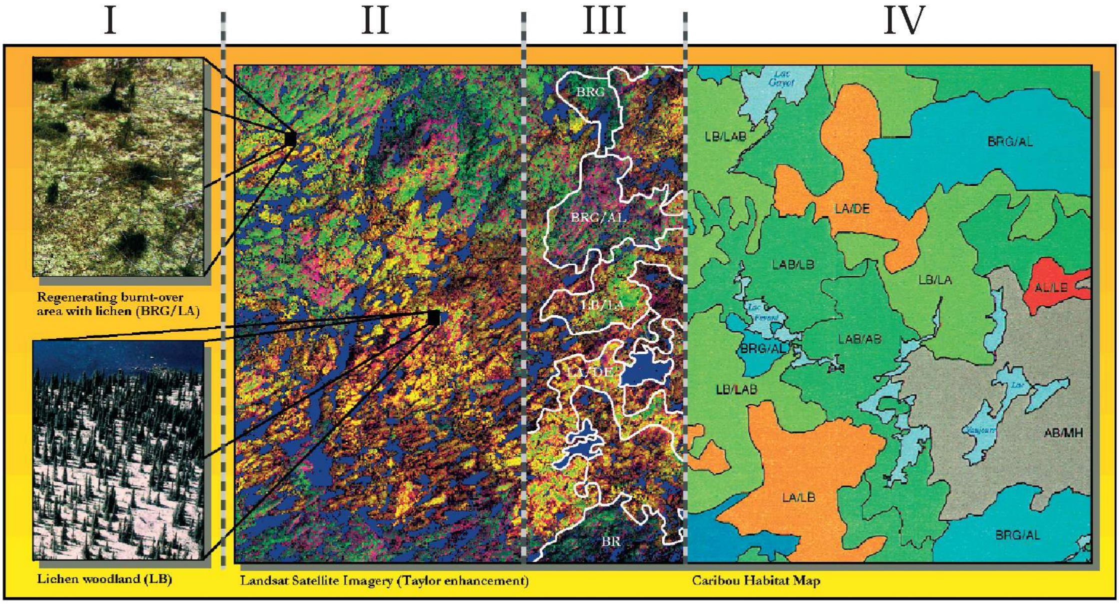

Fig. 2. Caribou habitat mapping method: I) Field survey of pre-selected control points; II) Landsat image with a Taylor enhancement to highlight lichens; III) Visual interpretation, delimitation of polygons and assignment of an attribute; IV) Map edition.

Method

The overall method of digital mapping including field survey, visual interpretation of the geocoded and enhanced images, polygons delimitation, assignment of a label and production of a thematic map, is illustrated in Fig. 2.

Field surveys

Reference data were gathered during summer and autumn. The objectives of the field surveys were to 1) analyze the colours and texture represented on the preliminary image enhancement 2) refine the image enhancement 3) understand the landscape from the visual interpretation 4) obtain data on specific classes, and 5) describe vegetation classes.

The field surveys were conducted by helicopter to verify predetermined control points located on Landsat subscene photographic prints at the scale of 1:100 000. Selection and number of control points enabled to cover the variability of each colour on each image, and the patterns of colours or landscape types. Ground control points were also sampled to have a more precise description or a better understanding of the vegetation cover, in particular lichen abundance and type. To obtain precise geographic coordinates, a Global Positioning System on board the helicopter was used during field survey in 1994 and afterwards. For each control point, panoramic (oblique) and vertical colour slides were taken for visual reference during the interpretation process.

Digital image processing

Before enhancement, each satellite image was geometrically corrected and geocoded to the Universal Transverse Mercator cartographic projection system with a 25 meters re-sampling spatial resolution. The geocoded images were merged to produced mosaics corresponding to the 1:250 000 topographic maps. To minimise the radiometric variability between images acquired at different dates, they were calibrated on the most recent image.

The enhancement process produces an image with optimum colour contrasts that facilitate visual interpretation. Two enhancement methods were employed, the Taylor enhancement method (Beaubien, 1984) and the false colour composite method (bands combination and stretching). The Taylor method consists in the production of three component channels, by using original bands, and interpreted them as intensity, red-green and blue-yellow.

Vegetation classification

After reviewing the literature on caribou and habitat mapping, vegetation cover, especially lichens, was selected as the main variable reflecting caribou habitat quality for map production. We then proceeded with the definition of 9 classes, knowing that number of classes would probably evolved over time. This

Table 1. Vegetation classification.

Sites	Preliminary classes	Final classes	Symbol[1]	Vegetation and spectral characteristics
WELL-DRAINED WITH LICHEN	Lichen with <10-15% of tree or shrub cover	1. Lichen	**LI**	True dominance of the lichen stratum with very sparse shrub layer. Spectral dominance of the lichen stratum.
	Lichen with >15% of shrub cover	2. Lichen-Shrub	**LA**	Lichen stratum with spectrally significant shrub layer. No trees.
	Lichen with >25% of shrub cover	3. Shrub-Lichen	**AL**	Abundant shrub layer with presence of lichen. Spectral dominance of shrubs.
	Lichen, sedges-grasses and low shrubs in various proportions	4. Lichen-Graminoid-Shrub	**LAH**	Lichen stratum with abundant dwarf shrubs and the presence of sedges and grasses.
	Lichen with 15-25% of tree cover	5. Lichen-Woodland	**LB**	Lichen-covered floor with open coniferous tree layer. Sparse layer of shrubs. Combination of spectral response of conifers and lichens.
	Trees with shrubs and lichen (approx. 30% of trees, shrubs and lichen cover)	6. Lichen-Shrub-Woodland	**LAB**	Lichen, shrub and tree layers in similar proportions giving a mixed spectral response. Shrub layer usually more abundant than trees.
DISTURBED	Recent burnt-over area (<30 years-old on average)	7. Burnt-over area	**BR**	Stage 1 of post-fire succession: spectral dominance of bare ground, dead trees with pioneer species of lichen. Sharp boundaries.
	Regenerating lichens (*Cladina mitis*) and shrubs	8. Regenerating burnt-over area	**BRG**	Stage 2 of post-fire succession: combined reflectance of little bare ground and pioneer lichens with regenerating lichens and shrubs. Mosaic of colors with clear boundaries.
POORLY-DRAINED, WITHOUT LICHEN	Spruce-moss forest	9. Shrub-Woodland	**AB**	Coniferous forest, more or less open, with abundant shrub layer and feather mosses. May include treed bog. Combination of spectral response of conifers and shrubs (and mosses) with dominance of one or the other.
	Wetland (including bog and fen)	10. Wetland	**MH**	Include all types of wetlands from herbaceous fens to open bogs. Variable spectral and spatial response on the image. Mapped with the help of topographic maps (1 : 50 000) and color composite type of enhancement.
OTHERS WITHOUT LICHEN	Shrubs (or deciduous trees)	11. Shrub	**AR**	True dominance of deciduous plants (trees or shrubs).
	Dwarf shrubs with sedges and grasses in variable proportions	12. Graminoid-Shrub	**HA**	Combined presence of dwarf shrubs and of sedges and grasses in variable proportions.
	Moss with dwarf shrubs	13. Moss-dominated tundra	**M**	Moss-dominated strata with dwarf shrubs.
	Bare area	14. Bare area: outcrops/granular deposits	**DE**	Without vegetation cover or with poor vegetation cover masked by spectral dominance of rocks.

[1] derived after the French denomination. For example: LA = Lichenaie Arbustive.

preliminary classification provided a broad overview of vegetation types over a large area, with refined divisions and more precise definitions of lichen classes. The final classification of 14 classes (Table 1) was determined by successive refinements over the first three years of the project. As the surface area mapped increased, knowledge of the vegetation evolved. With a better understanding of the images and the enhancement process, new classes were added and the definitions of existing ones refined.

Visual interpretation and cartography

The interpretation process consisted in the visual recognition of vegetation classes based on colour tints, texture and context observed on the enhanced images (false colour and Taylor compositions) displayed at the scale of 1:70 000 approximately on the monitor (Thibault et al., 1990). Ancillary data (topographic maps, thematic maps of physical units, biomes or fire dating) and field survey results provided the context information clarifying the interpretation.

The interpretation usually consists of successive refinements. First, broad vegetation units were outlined. These units were then subdivided while isolating the lichen component. If necessary, the lichen-rich areas were subdivided once more, to reflect structural variations in the lichen cover as defined by the classification (e.g. Lichen-Shrub or Shrub-Lichen, Lichen Woodland with openings of Lichen-Shrub). Remaining areas without lichen were then subdivided to reflect landscape reality and yield significant polygons without excessive intra-variability.

For a homogeneous group of colours forming a specific vegetation type (for example Lichen Woodland), a single attribute was given. More complex areas, with many vegetation cover types, received a complex attribute with a dominant and a sub (indicated with /) or co-dominant (indicated with -) vegetation class (Shrub Woodland co-dominant Lichen Woodland).

The 1:250 000 scale was chosen for map production because of the need to cover large areas with limited number of homogeneous regions or polygons, each larger than 5 km^2.

GIS integration and map production

The polygon boundaries and attributes were integrated in a GIS software and a colour thematic map was produced. The colour of each polygon was assigned by the dominant class. Statistics of the classes, spatial coverage with or without sub-dominant, were generated for each 1:250 000 map, or for a target region.

Results

Method development

This study allowed the development of an operational method for mapping caribou habitat. Visual interpretation of enhanced images that uses field knowledge by the interpreter was chosen over other methods of per-pixel automatic classification. Two different types of enhancement were needed to visually interpret correctly all the vegetation cover types defined in the classification. To extract lichen cover types, the Taylor enhancement method was used. This method requires a field survey and a good knowledge of the spectral reflectance for the vegetation cover types observed within the study area. The Taylor method displays three band combinations produced with the original TM3, TM4 and TM5 bands in different colour axes (first axis is dark to bright, second axis is red to green and third axis is blue to yellow). White lichens (Cladina mitis, Cladina stellaris) possess very high reflectance values in each of the three band combinations. The first band combination displays lichens in bright colour, the second one displays shrubs in red, lichens and bare areas in green. The third one displays burnt and bare areas in blue and lichens in yellow. This enhancement method allows the production of a contrast image facilitating visual interpretation and distinction between lichen cover types. A second enhancement was made for a better discrimination of the remaining cover types (free of lichens) that are sources of confusion in the Taylor enhancement. It consists in displaying TM4, TM5 and TM3 spectral bands in red, green and blue respectively and to apply linear stretching to all bands. This false colour composite helps to visualise general patterns and broad vegetation classes (e.g. wetlands, burns, lichen dominated areas, coniferous forest dominated areas) and allows a better discrimination of specific classes: wetlands, deciduous cover types, bare hilltops and anthropical elements.

Vegetation classification

The final classification (Table 1), that takes into account the possibilities of images in terms of visual distinctiveness, is based on the physionomic structure of vegetation. Classes (or cover types) are defined using a binomial denomination based on the two spectrally dominant strata: coniferous trees, deciduous shrubs (or trees), graminoids (grasses or sedges) and lichens or mosses. A trinomial denomination is possible (e.g. Lichen-Shrub-Woodland) when the overall reflectance of a vegetation type is a mixture of 3 different strata. A single designation is also possible (e.g. Lichen) when the reflectance is strongly dominated by one stratum.

The final classification of 14 classes (Table 1) includes six classes of upland sites with lichens, two fire-related classes with pioneer lichens and with regenerating lichens and six classes for other land cover types, including one class representing spring habitat (Graminoid-Shrub). The detailed description of vegetation classes is presented below.

1) Lichen: The lichen class corresponds to a very open mature lichen woodland with tree cover not exceeding 10-15% dominated by Cladina stellaris with sparse layer of shrubs. Its occurrence, in the Boreal Forest, is restricted mainly to sandy deposits along rivers and often associated with Lichen-Woodland (LI/LB). In the Tundra biome, this class occurs on well-drained sites, often associated with granular deposits (LI/DE). Lichens, with arctic taxa such as Alectoria, Cetraria or Cornicularia dominate the ground cover with sparse or intermixed dwarf shrubs, such as Ledum decumbens, Salix uva-ursi, Arctostaphylos alpina, etc. It may include more exposed arctic land with lichens and graminoids (such as Deschampsia cespitosa, Carex bigelowii, Luzula confusa, Hierochloa alpina), almost without shrubs. Associated with the bare areas class, it covers significant areas in the Minto lake region.

2) Lichen-Shrub: The heath community without trees is characterized by a continuous lichen floor covering sprinkled with low ericaceous shrubs, including dwarf birch and willows and possibly sparse stunted spruces. In the Boreal Forest, the Lichen-Shrub class occurs mainly as a sub-dominant class in regenerating burnt-over areas (BRG/LA) and indicates an advanced stage of regeneration where the lichen stratum dominates in patches. It is limited to exposed summits of lichen heath and bedrock (LA/DE). In the northern part of the Forest Tundra biome, the Lichen-Shrub class is ubiquitous, in association with granular deposits (LA/DE, DE/LA), with strips of Shrub-Woodland (LA/AB), with increased presence of shrubs (LA/AL; AL/LA) or with Lichen-Woodland, generally in young regenerated areas (LA/LB, LB/LA). In the Tundra biome, this class is similar to the preceding Lichen class but with an important coverage of low arctic shrubs. Boulders or rocks represent about 15% of ground cover. With a higher coverage of rock, LA is in mosaic with DE. The sparse lichen heath community is not visible on the image when the rocks cover reaches 30% or less of the ground cover.

3) Shrub-Lichen: It corresponds to a variant of the Lichen-Shrub class, where shrubs have a greater importance. Spatial coverage of the shrub stratum exceeds that of the lichen stratum. This class rarely occurs as the dominant and with no significant spatial extent. It is often associated with the post-fire regeneration mosaics in the Boreal Forest biome (BRG/AL, AL/LAB or else).

4) Lichen-Graminoid-Shrub: It is characterized by the presence of lichens, sedges-grasses or herbs and low shrubs in different cover percentages and various spatial arrangement in response to the variations in the micro-topography and in the moisture regime. This class was retained to depict complex vegetation types where periglacial processes are very active, usually in mesic to humid sites. It includes dry, earth hummocks, cryoturbated surfaces with polygons, and moist depression areas or furrows. It corresponds approximately to the "hummocky tundra" of Ferguson (1991). This class includes also mosaics of intermixed Lichen/Shrub with sedges-dominated arctic fens. When the mosses and graminoid components are more important in poorly-drained sites, the Lichen-Graminoid-Shrub class is associated with the Wetland class (LAH/MH, MH/LAH, LAH-MH). When the dwarf shrubs are predominant, the Lichen-Graminoid-Shrub class is combined with the Shrub class in the attribute of the mapped polygons (LAH/AR, AR/LAH).

5) Lichen-Woodland: It represents the mature and open black spruce lichen forest, occurring between 50 to 100 years after fire on well-drained sites. A few ericaceous shrubs, usually Vaccinium spp., occur in the dwarf shrub layer. The forest floor is characterized by a thick carpet of lichens (Cladina stellaris, Cladina rangiferina, Cladina mitis). These stands contain the highest values of lichen biomass (Arseneault et al., 1997). This class may also include open jack pine lichen stands. This is the typical and dominant forest type of the southern part of the Forest Tundra biome and the dominant class over the entire mapped area.

6) Lichen-Shrub-Woodland: This class represents a closer form of Lichen-Woodland where the mature coniferous stratum is more dense (around 30% of ground cover) and where the shrub layer takes expansion over the lichen stratum. It appears usually in mosaic with closed coniferous moss forest (Shrub-Woodland). It also represents

a post-fire regenerating stage with young shrubby spruces and important shrub cover occurring before the mature lichen woodland (stage 3).

7) Burnt-over area: The burnt-over area is characterized by the dark burned ground, bare rocks, the presence of dead trees and a regeneration by ericaceous (Vaccinium spp., Ledum groenlandicum, etc.), deciduous (Salix spp., Alnus) shrubs and dark species of lichen.

8) Regenerating burnt-over area: This class corresponds typically to a Shrub-Lichen structure of vegetation, where the yellowish Cladina mitis is the dominant species. It consists generally of a mosaic of regeneration types including bare ground, shrub-dominated areas, young jack pine stands, lichen-dominated parts with or without young black spruce regeneration. The overall mosaic still stands easily apart from mature portions of the territory.

9) Shrub-Woodland: It is typically a mature black spruce forest with mosses and ericaceous shrubs. The density of the tree cover varies depending on latitude and soil conditions. Ericaceous species typically dominate the understory, often with an abundance of Ledum groenlandicum. Alnus rugosa may provide tall shrub cover. Continuous ground cover by Sphagnum and feathermoss is characteristic of this class. The Shrub-Woodland occurs mainly on poorly drained sites in association with wetlands, on moist to wet lowland or lower slope sites and in mountainous areas. This class comprises mature jack pine or jack pine – black spruce stands. Some wetland black spruce stands with stunted trees and sphagnum-dominated on wet, organic sites (treed bogs) are also included. Prostrate forms of black spruce stands (krummholz) with an abundant shrub layer is represented by the Shrub-Woodland class. This class is more abundant in the southern part of the Boreal Forest region and occurs sporadically as a sub-dominant towards its northern limit.

10) Wetland: This class include all types of wetlands from herbaceous fens to shrub-Sphagnum bogs or associations of the two types, palsa bogs occurring in the Forest Tundra biome, and coastal marshes. Forested portions of bogs with significant covering of black spruce could be confused with the Shrub-Woodland class. In the Tundra, the wetland class corresponds to arctic fen, a wet sedge meadow with mosses and water. It should be noted that, if these arctic fens do not cover large enough areas, they may be included in the Graminoid-Shrub class. Wetlands occupy extensive areas on the marine deposits of the James Bay lowlands. Usually, it occurs mainly as a subdominant class.

11) Shrub: The shrub class is characterized by the dominance of deciduous species, mainly shrubs. It consists typically of slopes dominated by white birch (Boreal Forest), dwarf birch, alders and willows, with Ledum groenlandicum. The shrub class may be used to note shrubby openings in the coniferous forest or to specify the dominance of shrubs in a post-fire regenerating area. Riparian thickets of alders and willows are also part of this class. In the Tundra, it is often associated with the Bare Area class and represents the dwarf shrub tundra without lichen or appears as linear entities corresponding to rivers or slopes.

12) Graminoid-Shrub: This class brings together mesic to humid vegetation types characterized by the importance of the herbaceous and/or shrub stratum. It was first created to depict the "green valleys" standing out the rocky plateaux of the George River region and representing a significant habitat for caribou in summer (Crête et al., 1990). It includes also cryoturbate areas without lichens where variations in the microtopography lead to a mixed presence of shrubs and herbs and mosaics of sedge meadows (fens) and shrub-dominated rocky tundra.

13) Moss-dominated Tundra: It corresponds to a tundra community where the moss stratum is dominated by Rhacomitrium lanuginosum, with dwarf shrubs such as Ledum decumbens, Diapensia lapponica, Loiseleuria procumbens, and Salix uva-ursi. This class is confined to the vegetation of the plateaux surrounding the George River and is usually combined with the Bare Area class.

14) Bare Area (outcrops and granular deposits): This class is defined by the spectral dominance of the "bare" component. It includes all kinds of substrates devoid of vegetation, such as rock outcrops, blocks, sand, gravel, anthropic features (quarry, mine), etc. Interspersed vegetation may be present up to 50-60% of spatial cover, but it is completely masked by the strong spectral dominance of rock.

Map production

An area of 536 000 km^2 was mapped from 37 enhanced Landsat TM images, representing 43 caribou habitat maps at a scale of 1:250 000. Between 120 and 300 thematic polygons were delineated and identified for each 1:250 000 map. Maps were generally composed of three to four dominating classes, accounting for more than 80% of spatial cover. Maps located within the limit of 2 biomes, or with high physical variability are more diversified and 6 to 7 dominating classes are needed to map these regions. Occurrence and spatial covering of each class is highly variable. Three classes (Lichen-Shrub-Graminoid, Graminoid-Shrub, Moss-dominated Tundra) were used exclusively for mapping complex areas (mosaics of cover types) specific to the Tundra biome.

A synthesis colour vegetation map of northern Québec at a scale of 1:2 000 000 was also derived from the 1:250 000 maps. A simplified classification of seven classes was first elaborated, by merging similar classes (two lichen classes, one post-fire class, and four other classes). The minimal area of a polygon was fixed at 10 km^2. New and larger polygons were delineated by merging the existing polygons of similar dominance to adapt them to the smaller scale. The synthesis map provides a rapid overview of broad vegetation types relevant for caribou in northern Québec.

Discussion and conclusion

The development of a suitable vegetation classification representative of caribou habitat was the major concern. Exploration of the possibilities of image enhancements together with field assessment of vegetation cover types leads to the development of a classification of 14 vegetation classes, six of them related to lichen. Vegetation classes are superimposed against the backdrop of the three biomes, and bring out the important features of caribou habitat. The high number of classes was necessary to cover the variability of the vegetation cover throughout the entire range of caribou in northern Québec. The classification is a physiognomic one, based on vegetation structure. Unlike aerial photographs, the coarse resolution of Landsat data does not allow the recognition of species, thus classes cannot be defined by their floristic composition. However, the numerous field surveys allowed grafting onto the structural classes the description of a typical floristic composition by biomes and the association with biophysical characteristics. The database, consisting of 1164 sampling sites with associated colour slides, is a valuable source of data for more in-depth exploring of the maps.

The basic premise of the method developed was the use of visually-based image interpretation to derive caribou habitat maps. This classical approach, even subjective and time-consuming, was more accurate than computer-assisted classification to assess complex vegetation cover types over large areas with high biophysical variability. Visual interpretation on a paper colour map was used in other studies to allow for a preliminary analysis of very broad vegetation cover types and the selection of a sub-area for detailed investigation (Matthews, 1991). However, most habitat mapping studies with satellite imagery are based on a pixel-by-pixel automatic classification. These computer-assisted methods are using the spectral signature of vegetation types for the classification step. Often, as for caribou habitat, the identification unit is not the individual pixel but more a group of pixels forming an entire vegetation type, with no sharp spectral limits. Visual image interpretation relies on criteria of tone, brightness, shape, texture, pattern, size, shadow, height and context. As predicted by Ryerson (1989), these criteria are still difficult to quantify and entirely automatic methods (artificial intelligence) to integrate them are not yet developed. To map caribou habitat, visual interpretation provided a very accurate recognition of vegetation classes. It proved to be the best method to outline large units consisting of vegetation complexes.

The success of habitat mapping using satellite imagery is also linked to the spectral distinctiveness of the vegetation cover relevant for the species studied. The effective discrimination of wet graminoid communities permits a successful mapping of muskox habitat (Ferguson, 1991). The non-discrimination of tolerant vs. intolerant deciduous stands, an important characteristic of winter habitat for white-tailed deer (Sirois & Bonn, 1984), or the difficulty to distinguish balsam fir (*Abies balsamea* (L.) Mill.) from black spruce (*Picea mariana* (Mill.) BSP.) in coniferous stands for moose habitat (Oosenbrug et al., 1988), limits the application of satellite data to the regional level. On the other hand, the high spectral reflectance of lichens (white colour) in the visible electromagnetic spectrum makes it highly discernible on Landsat TM imagery. The six lichen classes, where lichens occur in various combination with other strata (herb, shrub or tree), were easily enhanced, identified by visual interpretation and mapped. A high degree of confidence is associated with them.

Burnt areas are among the more outstanding features when looking at images of the boreal region. Sharp limits, large areas and uniformity of colour in recent burns, contribute to their easy mapping. These characteristics offer a good potential for an automated update of recent burnt-over areas. Interpretation should be necessary however to map the evolution of older burns (Class: Regenerating

Burnt-over Area) and their progressive replacement by a mosaic of lichen classes.

The use of GIS technology for database integration provides a powerful tool for data management (sorting, modelling, etc.), statistical analysis for any targeted region, easy map updating and spatial analysis. Overlaying other data sources on caribou habitat map, like telemetric data on caribou movements, will offer new types of analysis and insights for caribou management.

Because of the long distance migrations, caribou management requires the knowledge of habitat characteristics in a very large area. The information needed for wildlife biologists to formulate conservation strategies or to direct future research is current habitat availability and changes in land cover types over time. The maps produced in this study provide a good source of reliable information about lichens, vegetation and fire regeneration. Future development is oriented toward the systematic update of maps, every 10 years for example, to monitor changes related to fire disturbance.

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