

A Multisensor Multiresolution Method for Mapping Vegetation Status, Surficial Deposits, and Historical Fires Over Very Large Areas in Northern Boreal Forests of Quebec, Canada

Antoine Leboeuf and Richard A. Fournier

Abstract—Boreal forests have a significant impact on the Earth's climate and on global warming. In this context, a mapping method was developed and was capable of dealing with very large areas with a lack of support datasets, which could characterize the current forest, surficial deposits, and forest disturbance history. The method based on remote sensing data, images processing techniques, and images interpretation was applied over a very large area (680 000 km²) in Québec, QC, Canada that was dominated by black spruce (*Picea mariana* [Miller] BSP). It involved five steps: 1) mapping the vegetation based on unsupervised classification, imputation, and segmentation methods; 2) mapping the history of fires that occurred over the mapping area based on archives Landsat images; 3) determining the dominant species characterizing forest stands; 4) mapping surficial deposits; and 5) accuracy assessment of map attributes based on video dataset. Kappa values ranged from 72.5% to 96.3%, indicating substantial agreement when compared with validation dataset. The results demonstrated that our method is a convenient and inexpensive way of mapping forest ecosystems over large areas of northern boreal forest.

Index Terms—Boreal, fire history, forest attributes, Landsat, RapidEye, surficial deposits.

I. INTRODUCTION

BOREAL forest represents 38% of global forest area [1]. These forests have a significant effect on the radiative balance of the Earth [2]. Because of their rough texture and low reflectance, boreal forests absorb a high proportion of incoming solar radiation, subsequently converting it to heat [3]. The likely future expansion of boreal forests toward current tundra regions could amplify global warming. Also, boreal forests that are located within the tundra region contain 40% of the soil carbon that could be potentially transferred to the atmosphere, mainly

due to forest fires. This corresponds to the current amount of carbon that is held in the atmosphere [4]. Boreal forests are characterized by a small number of tree species and are primarily driven by disturbance in the form of catastrophic wildfires at the landscape scale. Depending upon site conditions, the fire interval ranges from 50 to 500 years [5], [6]. Major insect outbreaks are chronic in the boreal forest and also represent an important disturbance factor that contributes to modifying the landscape [7], [8]. Using a global climate change scenario for the boreal forest, Soja *et al.* [8] predicted increased wildfire and insect infestations, northward forest expansion, and substantial alterations to stand composition and structure.

The importance of boreal forest ecosystems to planetary dynamics justifies efforts to monitor forest coverage and to assess its resilience, i.e., its ability to recover after a disturbance [9]. A reliable assessment of current stand conditions is the basis for predicting the evolution of forest coverage and health under the changing climate. Boreal forest ecosystem conditions are generally estimated by forest inventory data comprising sample plots and forest map. These forest maps are usually produced through interpretation of aerial photography to describe stand characteristics and forest attributes, such as species, tree height, stand cover, age, and surficial deposits [10]–[12], typically with a minimum polygon unit area of 2 ha. These maps, however, are mainly produced for managed areas in the southern boreal forest. For northern regions, most projects that have undertaken large-area mapping of the boreal forest generally have used coarse resolution images with few field samples, given the poor road conditions that limit access to training or validation sites. For example, Viereck *et al.* [13] in Alaska, Wulder *et al.* [14], Beaudoin *et al.* [15] in Canada, and Berner *et al.* [16] in Russia mapped very large areas but these contained only a few general classes. These mapping exercises were developed for a general assessment of landscape-level variables, which consequently could not provide the level of detail that is required for operational forest inventories [17], [18]. Other research that was conducted by Despons and Payette [19] and Arsenault *et al.* [20] proposed mapping methods at finer scales and for specific issues. These methods have only been applied to relatively small areas and their subsequent extrapolation to large areas is difficult.

In recent years, improvements to satellite sensor capabilities, image availability, and progress in mapping methods

Manuscript received May 11, 2015; revised July 22, 2015; accepted August 31, 2015. Date of publication October 06, 2015; date of current version January 18, 2016.

A. Leboeuf is with the Direction des Inventaires Forestiers, Ministère des Forêts, de la Faune et des Parcs, Québec City, QC G1H 6R1, Canada, and also with the Centre d'Applications et de Recherches en Télédétection (CARTEL), Université de Sherbrooke, Sherbrooke, QC J1K 2R1, Canada (e-mail: Antoine.Leboeuf@mffp.gouv.qc.ca).

R. A. Fournier is with the Centre d'Applications et de Recherches en Télédétection (CARTEL), Université de Sherbrooke, Sherbrooke, QC J1K 2R1, Canada.

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/JSTARS.2015.2477780

have provided a wide array of options for large-area mapping. The way has been opened for exploring new methods to map boreal ecosystems at a level of detail compatible with operational inventories, such as those performed in southern forest regions. Medium-resolution satellite images, such as those obtained from Landsat 5, have demonstrated their usefulness for natural resource management and monitoring [21], [14]. Such images (Landsat 5, 7, and 8), with a spatial resolution of 30 m, have been made easily available since 1984 at low or no cost, thereby enabling continual forest monitoring for a period of more than 30 years. Comparable platforms provide a considerable number of sensors that now offer images at finer spatial resolutions (e.g., SPOT-5 and RapidEye), with the potential to cover large areas of boreal forest [22]–[24]. Forest ecosystems can be characterized with satellite images that are based on what features are immediately visible when observed from above, thereby placing more importance on tree or canopy attributes while excluding most of the understory, ground cover, and underground characteristics. Yet, surficial deposits can be mapped from interpretation of aerial photography. The surficial deposit maps describe the surface sediments overlying the bedrock, their morphology, their material composition, their sedimentation processes, etc. Surficial deposits can be deposited through a number of processes including glacial, glaciofluvial, fluvial, lacustrine, aeolian, colluvial, and marine. These maps are used to evaluate the site productivity for vegetation growth, in mineral exploration, to assess environmental impacts of disturbances, and to support forest management and road infrastructure. Apart from standard photo-interpretation directives [12], few studies have proposed methods for mapping surficial deposits [25], [26]. Other surficial deposit maps that are available for these areas are generally produced either at large scales [27] or only cover local areas [28]. Furthermore, they are not compatible with the scale of forest maps. In boreal ecosystems, surficial deposits are correlated with the growth of vegetation and its resilience following disturbance. Known methods of mapping surficial deposits have required extensive resources and, thus, are difficult to apply to large areas.

The long recovery times for boreal ecosystems following disturbance are indicative of their vulnerability to change climate conditions. Catastrophic wildfire is the main disturbance affecting boreal ecosystems [5], [29]. Maps providing polygons that include the date and extent of past forest fires, such as those made by Payette *et al.* [30], are essential for assessing current recovery times of disturbed forest stands. Recovery time is strongly influenced by ecophysiological and physioclimatic factors, such as species, surficial deposits, precipitation, and among others [31]. Many studies propose maps of forest areas, but the results are usually coarse and not suitable for forest management [32]–[34]. Describing fine spatial distribution of forest fire perimeters and evaluating their dates precisely over a large boreal area require extensive field work [35]. Regardless of the efforts required, a fire history map is an essential tool for defining fire recurrence, assessing the role of fire in forest cycles, establishing stand resilience, determining the impact of fire on biodiversity and, ultimately, proposing effective strategies for ecosystem management [31].

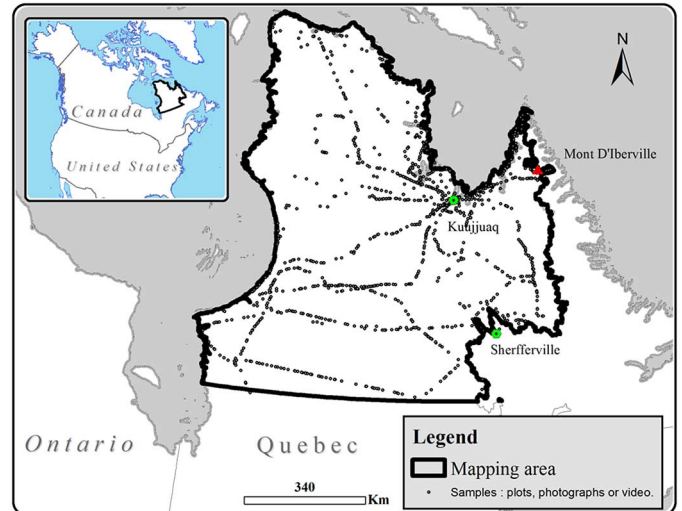


Fig. 1. Location and extent of the mapped area in northern Quebec, Canada.

An important challenge presents itself when estimating map accuracy in a context where ground databases are limited, as is the case of many boreal regions. Estimating the accuracy of polygonal maps usually involves the comparison of map layers with data that are obtained from field sample plots or transects [36], [37]. This resource-consuming approach is difficult to apply over large areas and may incur substantial bias since the scales of comparison are quite different. Another alternative involves the use of a second set of satellite images of finer spatial resolution [38]. In all cases, the technique that is adopted needs to take into consideration both the availability of data and accuracy requirements.

In support of northern boreal ecosystem requirements, the first goal of this project was to develop a mapping method to report on forest stand status, site productivity, and resilience for a vast area of northern Quebec (680 000 km²). Reporting the forest stand status of the northern lands involves assessing the dominant tree species, forest cover type, understory type, stand cover, tree height and age, and the open land type (i.e., nonforest land cover). The method aimed at providing the same level of information that is available for southern forests in Canada. Site resilience of the northern ecosystems depends largely upon site productivity, which is linked with surficial deposits, and forest fires that occurred in the last century. Three scientific challenges were met during this project: 1) developing new methods for mapping vegetation and surficial deposit at the stand level, in methods that could be adapted for large areas without relying on spatial and field datasets; 2) developing a method to map wild fires for large areas that describes all perimeters and dates of fire events that occurred in the last century; and 3) adopting a validation approach of the map attributes that can be adapted to a large and remote area.

II. METHODS

A. Mapped Area

The mapping area is located in the boreal Canadian Shield Ecozone (Fig. 1) of northeastern Canada. It covers

680 000 km², between the 53rd and 63rd parallels, which is an area more than twice the size of Finland. Forest tree species dominant in the mapping area consisted mainly of black spruce [*Picea mariana* (Mill.) BSP]. Other conifer species were encountered in the forest canopy in decreasing abundance. Jack pine (*Pinus banksiana* Lamb.) was found in the landscape within stands that were affected by recurrent fire, followed by balsam fir [*Abies balsamea* (L.) Mill.] and white spruce [*Picea glauca* (Moench) Voss]. The latter two species were found in stands that were located on specific sites that had been preserved from fire events (coastal or mountain sites). Other species that were present, but more sparsely distributed, included tamarack or eastern larch [*Larix laricina* (Du Roi) K. Koch.], trembling aspen (*Populus tremuloides* Michx.), and white birch (*Betula papyrifera* Marsh.). In most stands, the ground cover and understory, respectively, consisted of lichen and moss, and shrubs in varying proportions. Wildfire occurs recurrently over most forested lands, with the exception of high elevation and coastal areas. The landscape is mainly flat, with some hills reaching a maximum elevation of 1622 m, i.e., Mont D'Iberville. Mean annual temperature varies from -1.1°C to -10.8°C , resulting in a short growing season across the region (between 78 and 155 days); mean precipitation varies from 201 to 1200 mm per year. For most of the mapped area (see below), surficial deposits are dominated by glacial till and thin till (till with frequent rocky outcrop). Wood harvesting is very limited and the main ecosystem disturbance is fire.

B. Data

Two seasonal mosaics, composed of Landsat-TM and -ETM+ images, were superimposed on to the mapped area. Only the central strip of the Landsat-ETM+ images acquired was clipped for the mosaic since the borders were affected with scan line corrector failure. The 90 images of the summer mosaic were acquired during the growing seasons (mid-July to end of August), between 2003 and 2010. The 78 images of the winter mosaic were acquired during the period when the ground was covered with snow (March, April, and May), between 2005 and 2013. These 3 months were selected for the winter mosaic to ensure that snow covered all of the mapped area, while also maximizing solar elevation to reduce shadow effects on north-facing hills as much as possible. All images were in raw digital number with a dynamic range of 8 bits and were resampled for a spatial resolution of 30 m. It was decided to leave the Landsat images in 8-bit format to avoid the excessive space that the 680 000 km² area would have required. Our preliminary tests demonstrated satisfactory results using images with raw digital numbers. These images were already ortho-rectified by USGS (Level-1T). The image mosaic was assembled using a histogram-matching technique to minimize spectral differences between images [39]; the method was available in PCI Geomatics software [40]. The histogram-matching method aims to adjust the color of one image at a time to a reference image using both images' histograms. Clouds or hazy areas were masked. Three spectral bands were used: 1) red (0.63–0.69 μm); 2) near-infrared (0.76–0.90 μm); and 3) mid-infrared (1.55–1.75 μm). The choice of these three bands was

justified by band decorrelation (process to reduce the cross-correlation) and their potential to differentiate forest classes [41]. Finally, cloud-free Landsat image archives (from 1973 to 2013) were acquired during the growing season to map historic fire perimeters.

The mapped area was also covered by a mosaic that was composed of 163 RapidEye images, which had at a spatial resolution of 5 m and that were composed of five spectral bands: 1) blue (0.44–0.51 μm); 2) green (0.52–0.59 μm); 3) red (0.63–0.69 μm); 4) red-edge (0.69–0.73 μm); and 5) infrared (0.76–0.85 μm). These images were acquired during the growing season between May 2010 and October 2011. A mosaic of natural color bands (blue, green, and red) was generated to support the surficial deposit interpretation procedure. The method that followed the production of the RapidEye mosaic was similar to that was used for the Landsat mosaic described above. This RapidEye mosaic was used to produce a three-dimensional (3-D) anaglyph mosaic. An anaglyph is an encoding image build on filters of different colors, which were red and cyan in our case. This referenced encoding image can be displayed on simple GIS systems to digitalize polygons using only red and cyan glasses. This is an efficient alternative of costly 3-D stereo vector digitalizing systems based on either pair of aerial photography or satellite images. The 3-D anaglyph mosaic was produced using the STE algorithm in PCI Geomatics software [40], [42], together with the topographic map at a scale of 1:50 000.

A series of sample plots, aerial photographs, and aerial video was collected to support the validation of the resulting maps, including historic fires. A first database of 3419 sample plots, which were collected in the mapped area between 2010 and 2013, was amassed (Fig. 1). Measurements in these plots included tree species identifications, percent stand cover, tree height measurements (clinometer), understory species, surficial deposit types, wetland types, geomorphologic characteristics, and among others. A second database consisted of 306 sample plots that were distributed over the whole mapped area. It contained the measurements of fire scars on tree trunks. Plots were located on the boundary of the past fire perimeters. By counting the rings between the burned ring and the bark, the year of fire was determined. More than one scar per fire perimeter was usually measured to improve the estimates for the years since the fire. A third database consisted of 105 009 photographs that were taken during an aircraft survey, where GPS coordinates were linked to each photograph. Existing topographic and hydrographic maps at a scale of 1:50 000 were acquired from the CANVEC layers [43]. A final database was acquired along a 3500-km transect that was composed of a geo-referenced video taken from a plane. Flight altitude was generally around 700 m or a scale of 1:1500, which made interpretation possible of the dominant tree species, forest cover types, and stand cover and understory types, with a high degree of confidence.

C. Mapping Methods

The objectives of this study were met as follows. First, a general mapping method was adapted to the boreal ecosystem of

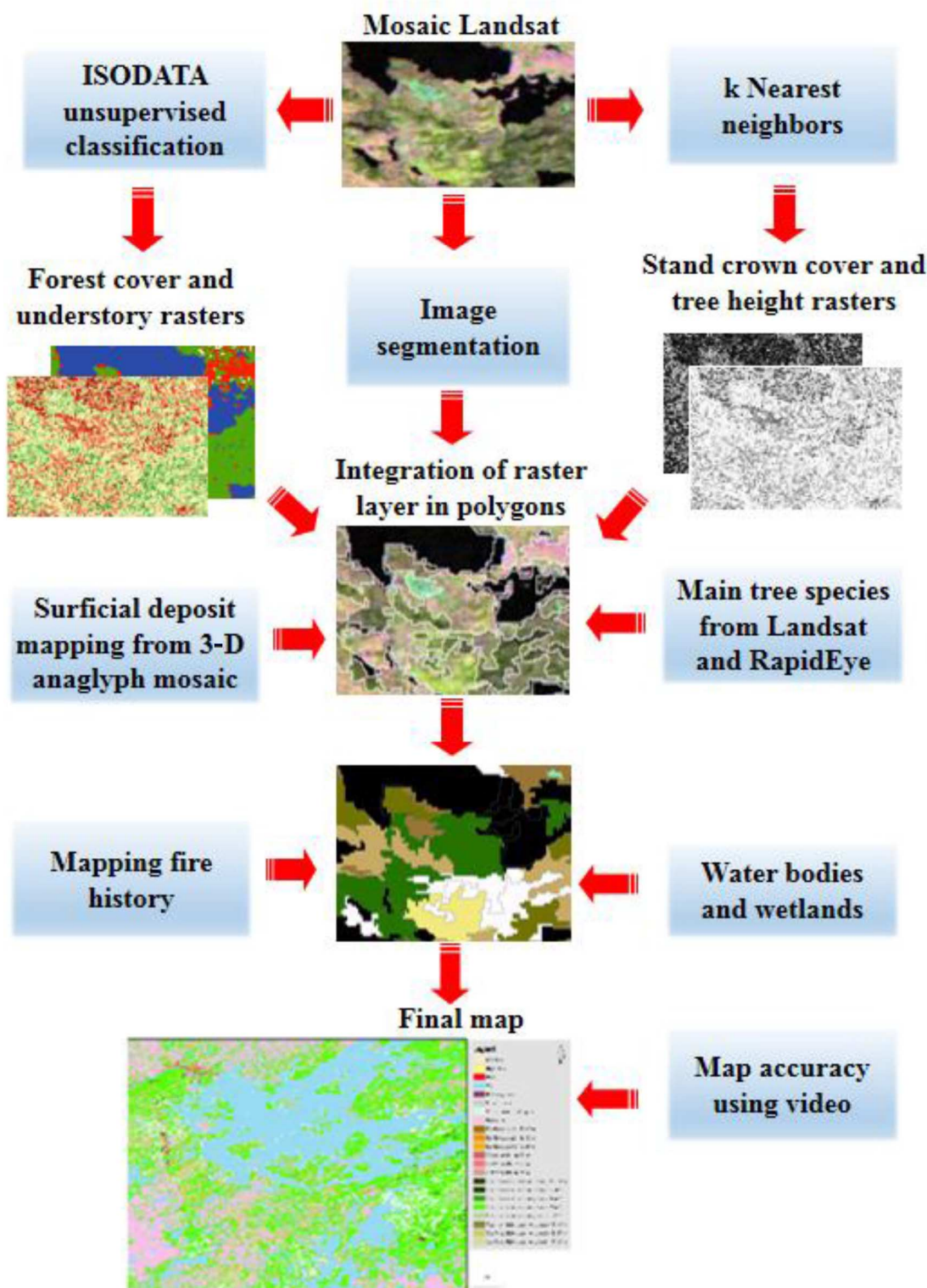


Fig. 2. Mapping scheme illustrating the main methodological steps.

Quebec: initial vegetation mapping was based on an object-based classification of the main forest types, followed by further image processing to generalize specific information of forest attributes, and finally, identification of wetland and dominant forest species. Second, two methods were developed to map surficial deposits and forest fire history. Last, a series of

procedures was established to validate the mapping methods, considering that independent spatial datasets for the northern area are few to none. These procedures, as shown in Fig. 2, resulted in polygonal maps with contextual map attributes: forest cover type, understory type, stand crown cover, tree height and age, open land cover, surficial deposit type, and

time-since-last fire. The maps were produced with a minimum mapping area of 100 ha for surficial deposits and 16 ha for all other attributes. Other mapping rules (e.g., avoidance of polygon overlap) were applied as defined by northern mapping standards [44]. A detailed description for each of these methodological steps follows.

1) *Mapping Vegetation and Forest Attributes:* Several mapping techniques were used to reduce human interpretation and to ensure consistent mapping of vegetation and forest structure over the entire mapped area. As the first step of the mapping method, two thematic raster layers were produced: forest cover type and understory type. The two thematic raster layers had pixels of 30 m × 30 m and described 1) three classes of forest cover (coniferous, deciduous, and mixed) and 2) four classes of understory (lichen, moss, shrub, and mixed). The classification procedure used the Landsat summer mosaic and employed the field samples and polygons that were interpreted from aerial photographs as training data. ISOCLUS from PCI Geomatics Inc. [40], a widely used clustering algorithm [45], [46] that is based on the ISODATA method [47], was selected to produce the two thematic raster layers. Several iterations were required to obtain the optimal classification parameters: number of clusters, maximum number of iterations, and the movement threshold. Each iteration allowed the comparison of mapped results for all selected parameters with those that were obtained from field samples, aerial photographs, and RapidEye mosaic interpretations.

The second step of mapping focused upon the production of two further thematic raster layers: 1) stand crown cover and 2) tree height. The Landsat summer mosaic was used as an input with an imputation method (k nearest-neighbors or k NN) to generate these two layers [48], [49]. This intuitive and versatile technique aims to estimate variables that are based on similarity of covariables between attributes to predict and observe samples. The Landsat summer mosaic is correlated to stand crown cover and tree height since Leboeuf *et al.* [50] demonstrated linear relationship between shadow fraction at a resolution of 30 m and those two forest attributes for similar northern areas. Both thematic layers were then produced with pixels of 30 m × 30 m. Stand crown cover represents the canopy closure percentage and tree height is the mean height in meters. Field sample plots were selected to ensure that stand crown cover and height values covered the whole range of values, i.e., 0%–100% for crown cover (10% class intervals) and 0–28 m for the height (1 m class intervals). The plot subset also had to be the representative of the proportion of stand crown cover and height values over the study area to avoid using nonrepresentative or exceptional values. Values of the forest attributes ($FAknn_i$), either stand crown cover or height, were calculated for each pixel using field sample and Landsat summer mosaic band data

$$FAknn_i = \frac{\sum_{k=1}^{k_{\max}} W_k FA_{GSP_k}}{\sum_{k=1}^{k_{\max}} W_k} \quad \text{for } k \neq 1, \quad \text{where } W_k = \frac{1}{d_k^j} \quad (1)$$

where i is the target pixel, k designates the nearest spectral neighbors, which can be found from 1 to a maximum of $k_{\max}$, FA_{GSP_k} is the forest attribute value from a selected sample plot of interpreted polygon, W_k is the weighting coefficient for this k th neighbor, and d_k^j is the Euclidean distance for this k th neighbor, the power j . The resulting $FAknn_i$ value is in fact a weighted value of the FA_{GSP_k} values, which have the nearest spectral value of the pixel being evaluated. The parameters (k and W_k) were established based on a sensitivity analysis that examined a reasonable range for these parameters. The results were evaluated using leave-one-out cross-validation [51] that was based on all available field samples. Three statistics were then calculated (as percentages): 1) R^2 ; 2) relative root-mean-square error (RMSE_r); and 3) relative bias (bias_r).

Each of the four thematic raster layers (forest cover type, understory type, stand crown cover, and tree height) provided separate vegetation and forest information for the mapped area. As a third step of the mapping method, this pixel-based information was regrouped spatially for the final map to form stand polygons. A stand polygon was represented as contiguous land cover characteristics that were sufficiently uniform in terms of species composition, forest attributes, and general condition, so as the polygon could be considered as a homogeneous and distinguishable unit. Stand polygons were generated by segmenting the Landsat summer mosaic with the segmentation tools that are available in eCognition software [52], [53]. The Landsat summer mosaic was selected because it discriminated accurately the main stand polygons present in the mapping area. This resulted in polygon boundaries that were based on three elements: surrounding pixel homogeneity, as determined from their spectral values; and two shape functions, which are referred to as the scale and shape factors. The image texture was not considered in the segmentation process since preliminary tests increased the processing time and did not improve the resulted polygons. Parameter values of the segmentation (band weights, scale, and shape) were determined through several iterations where an operator used patterns that had been previously interpreted and available in the forest inventory map, together with a mean area around 16 ha to guide polygon generation [54]. The segmentation procedure generated polygons that identified forest stands where further information was needed to be assessed from a classification procedure to produce the four available raster layers (forest cover type, understory type, stand crown, and tree height). For the two first raster layers, which consisted of 1) forest cover types (coniferous, deciduous, or mixed) and 2) understory type (lichen, moss, shrub, or mixed), the proportion of each pixel type was calculated for each polygon. The forest and understory covers were designated by association of corresponding proportion of pixel type in each polygon that met the mapping standard (e.g., a polygon had a class of lichen understory when more than 75% of the pixel underlain were identified as lichen). For the two other raster layers, mean crown closure with classes A (80%–100%), B (60%–80%), C (40%–60%), D (25%–40%), or L (10%–25%) and mean height value (0–28 m) were calculated for each polygon using the raster layer of the stand crown cover and mean height. Finally, open land cover was mapped following a definition of a land

that was covered with less than 10% of stand crown cover and understory type.

The fourth step of the mapping method was to integrate water bodies, wetlands, and main tree species into the stand polygon map that was previously established. First, the map was updated by water bodies and wetland polygons from the existing topographic map at scale of 1:50 000. Wetland polygons that were added to the map were classified into 10 categories (uniform fens, structured fens, uniform bog, etc.) based on satellite image interpretation, as described in a wetland classification guide [55]. For all forested stands, i.e., polygons with stand crown cover greater than 10%, the dominant tree species was determined by image interpretation resulting only one dominant tree species for each forested stands. From existing inventories, it was expected that the dominant species would be in descending order of abundance: black spruce (more than 98%), jack pine, balsam fir, white spruce, tamarack, birch, or poplar. To discriminate among tree species, several iterations were tested to establish the most favorable image bands and enhancement parameters. Landsat summer, Landsat winter, and RapidEye mosaics were tested to develop an interpretation guide. This interpretation guide was calibrated and validated with field data.

2) *Mapping Surficial Deposits:* A polygonal map of surficial deposits was produced in parallel with mapping vegetation and forest attributes by interpreting the 3-D anaglyph mosaic that was obtained from RapidEye images. Leboeuf *et al.* [44] and Robitaille and Allard [56] described 33 different surficial deposit classes that are applicable to northern Quebec and used them as a basis for identifying their characteristics. The polygons for surficial deposits are much coarser than those for the stand polygon leading to an area in average about 10 times larger. The 3-D anaglyph mosaic made three vital interpretation elements available from the same image for facilitating interpretation: 1) texture; 2) color; and 3) topography. Texture is related to some heterogeneous surficial deposit types, such as dead-ice moraines. For visual interpretation of images, color allows parent rock (blue on the image) to be differentiated from other deposits. Topography provided information on slope positions and shape patterns that were related to deposit thickness and elongated profiles such as drumlins. The interpreter was trained with the available field samples. Finally, the surficial deposit map was linked spatially to the vegetation map.

3) *Mapping Fire History:* At this stage, the polygons contained forest and surficial deposit information but nothing about stand age. Rather than interpreting the age of the forest based on their composition and structure, efforts were concentrated on mapping fire perimeters and detailing the year in which fire had occurred on the mapped area. At these latitudes, forest fires leave noticeable traces over a landscape that is perceptible on satellite images for more than 60 years, depending upon forest and vegetation resilience. Thus, Landsat images that were acquired from 1973 to the present were used to delineate fire perimeters over the entire region using a method inspired from Stocks *et al.* [32]. Following creation of the fire perimeters, reliable information of occurrence years available for some fires of the mapping area was collected [30], [32], [57]. The year of these fires was determined from these sources. For fires with no documented source, the year was determined in two ways,

depending upon their dates. For fires that occurred between 1973 and 2013, the fire year was determined using archived Landsat images that had been acquired at the time closest to fire occurrence. For older fires, from 1920 to 1973, the year of fire was determined from data collected in the field from fire plots. The date of fire was estimated from measurements in the fire plots: the time that elapsed since the last fire was estimated from fire rings on trees exhibiting scars. Fire perimeters for which no scars were found had to be interpreted by associating the patterns of Landsat images of fire perimeters where scar was measured to the pattern of this fire perimeter. Image color and context provided clues to fire, based upon similar fires for which scars were encountered. This process was applied to produce polygons that were associated with fires from 1920 to 2013 in the context of boreal ecosystems. Fires that occurred earlier than 1920 were not visible because their perimeters had gradually merged with the surrounding landscape. The fire history polygons were joined with the layers that had been created. The fire map provided the stand age simply by subtracting the year of image acquisition with the designated year of each burned area.

All layers, which were created at different scales from the methods that are described in Sections II-C1–II-C3, were joined to compose the final map with the following polygon attributes: forest cover type, main species, understory type, stand crown cover, tree height, disturbance, age, open land cover, and surficial deposits (Table I). A smoothing algorithm (the Peak algorithm from ESRI [58]) was applied, with a tolerance unit of 200 m. All map polygons were checked to ensure that the minimum distance between two nodes of an arc of polygons was greater than 10 m, to avoid polygon overlap. Also, water body polygons were added from existing topographic map at scale of 1:50 000. The final map was revised by an experienced interpreter to correct any minor errors, such as confusion between vegetation classes.

4) *Accuracy Assessment of the Map Products:* The use of sample plots for accuracy assessment was avoided primarily because of differences in scale: plot data would introduce substantial bias since it is typically collected on 400 m², whereas map polygons generally cover several hectares. As an alternative to using sample plots, map classes were compared with those estimated by the interpretation of a video transect that was acquired by an airborne video camera. The flight lines were first established by positioning 10 points randomly over the mapping area with a minimal distance of 100 km between them to avoid grouping and co-occurrence. All points were then linked by a series of flight lines. The resulting images were equivalent to photographs at a scale of 1:1500 with the inclusion of continuous frame displacement, which provided greater latitude for image interpretation. This scale is suitable for providing interpreters with sufficient visual detail for an accurate estimation of map attributes. The lines were then filmed with the video camera using *geovideo software* [59], which allowed the position to be recorded for all the video. When this video was used on a GIS system, the video was displaying on a first window and the geographic position of the record was displayed on a second window, both in coordination. The resulting videos provided fine details of the vegetation to facilitate interpretation.

TABLE I
CONTEXTUAL MAP ATTRIBUTES OF THE INTEGRATED MAP AND THEIR DESCRIPTION

Contextual map attributes	Map classes
(a) Forest cover type	R (coniferous), F (deciduous) or M (mixed)
(b) Main species	EN (black spruce), PG (jack pine), SB (balsam fir), EB (white spruce), ML (tamarack), BP (white birch) or PT (poplar)
(c) Understory type	m (moss), c (lichen), a (shrub), cm (lichen and moss)
(d) Stand crown cover	A (80% to 100%), B (60% to 80%), C (40% to 60%), D (25% to 40%), or L (10% to 25%)
(e) Tree height	1, 2, 3, ... 28 m.
(f) Disturbance	BR (burnt), BRP (partial burnt), ES (severe insect outbreak), EL (partial insect outbreak)
(j) Age	10 (1 to 14 years), 20 (15 to 24 years), 80 (75 to 84 years), mature (85 and more)
(k) Open land cover	20 classes : LL (lichen barrens), AH (high shrubs > 2 m), AB (low shrubs < 2 m), AR (bare rocks), LM (moss barrens), TOU (uniform bog), TOS (structured bog), TOR (wrinkled bog), TOM (pond bog), TMS (structured fens), TMU (uniform fens), TMP (feather fens), TMR (riparian fen), MS (salted marsh), LTE (electric lines), CB (boulder field), SD (bare soil with sand or loam), EAU (water), (IH) Anthropogenic buildings, ILE (island)
(l) Surficial deposits	33 classes : 1A (till thickness > 1 m), 1AR (thin till : 25 cm–1 m); 1BA (Ablation moraine), 1BD (drumlins), 1BC (Rogen moraine), 1BG (De Geer moraine), 1P (dead-ice moraine), 1AB (boulder field), 2 (fluvioglacial), 3 (fluviatil), 4 (lacustrine), 5 (marine), 6 (shoreline), 7 (organic), 8 (wind), R (rock with less than 25 cm of surficial deposit), AN (anthropogenic)

The vegetation and forest map attributes that were produced by the method in Section II-C1 were the first to be evaluated. To do so, 20% of the polygon were selected upon which the flight line was superimposed. Polygons that were covered by less than 10% by the video swath were eliminated from the evaluation, to ensure sufficient sampling for the evaluation. The random selection of polygons required that at least 30 polygons were selected from each forest class. An independent interpreter was provided with the polygon boundaries with no additional information, to assign a value for each of the five map attributes: 1) forest cover type; 2) understory type; 3) stand crown cover; 4) disturbance; and 5) open land cover. Six error matrices, one for each map attribute, were calculated by comparing the map that had been produced with the classes that were interpreted from the geo-referenced video. The year of fire occurrence was not assessed; only the presence or absence of a fire polygon between 1920 and 2013 was noted. For a global evaluation, an error matrix was also calculated for the merged classes of the five map attributes: 1) forest cover type; 2) understory type; 3) stand crown cover; 4) disturbance; and 5) open land cover.

Surficial deposits were evaluated independently of the five other map attributes, since the number of surficial deposit polygons was lower than the other map attributes. In that context, the evaluation was based on an interpretation of 50% of all terrestrial polygons on the map that overlaid the video. The random stratified approach led to a minimum of 30 polygons for all classes of surficial deposits. Classes that had less than 30 polygons were merged into a class referred to as “other.” One error matrix for surficial deposits was calculated by comparing the final map with the classes that were interpreted from the geo-referenced video. In all cases, the polygons’ perimeter

was not validated, given that they had been created through an automated process within the segmentation algorithm.

III. RESULTS

The final parameters of the ISODATA algorithm (initial number of clusters, the maximum number of iterations, and the movement threshold) were selected based on the classification results that had been obtained after several iterations. It resulted in two nominal raster layers: 1) forest cover type and 2) understory vegetation. The final parameters that were selected based on iterations were, respectively, 100, 22, and 0.01. In the case of the numeric raster layers (stand crown cover and tree height) that were generated from the kNN algorithm, the best estimates of the parameters (k and t) were 5 and 2, respectively. Based on these established parameters, the best estimates of statistical values (R^2 , RMSE, and bias) were 66.7%, 40.6%, and 0.5%, respectively, for stand crown closure, and of 63.0%, 27.6%, and 0.3% for tree height.

The integrated map was produced by merging 1) the map of vegetation and forest attributes that is described in Section II-C1; 2) the surficial deposit map that is described in Section II-C2; and 3) the fire history map that is described in Section II-C3. This integrated map had 337 631 polygons (293 546 terrestrial polygons) with a mean area of 33 ha and a minimal area of 16 ha. The segmentation parameters (described in Section II-C1) that were estimated following several iterations were set to 30 and 10 for scale and shape factors. The iterations that were performed on satellite images, together with knowledge acquired in the field, suggested a guide for the most favorable image combination and discrimination elements that could be used for differentiating tree species (Table II).

TABLE II
DOMINANT TREE SPECIES DISCRIMINATION PARAMETERS

Tree specie	Recommended images and band combinations	Discrimination elements
Black spruce	Landsat winter mosaic (MIR, IR, R) ¹ .	Grey to black ²
Jack pine		Green
Balsam fir	RapidEye mosaic (IR, G, B).	Dark blue
White spruce		Dark grey
Tamarack	Landsat winter mosaic (MIR, IR, R). RapidEye mosaic (IR, G, B) to discriminate the tamarack from deciduous (birch or poplar).	Red to orange on Landsat winter mosaic and green on RapidEye mosaic.
Birch		Red both on winter Landsat mosaic and on RapidEye mosaic
Poplar	Landsat winter mosaic (MIR, IR, R) to discriminate the deciduous versus coniferous. RapidEye mosaic (IR, G, B) to discriminate the birch from poplar.	Red on Landsat winter mosaic and Clear red on RapidEye mosaic

1) MIR, mean infrared; IR, infrared; R, red; G, green; B, blue.

2) All the images were enhanced with a linear regression. For the winter Landsat, the maximum values of the linear regression were established at the mid-band histogram.

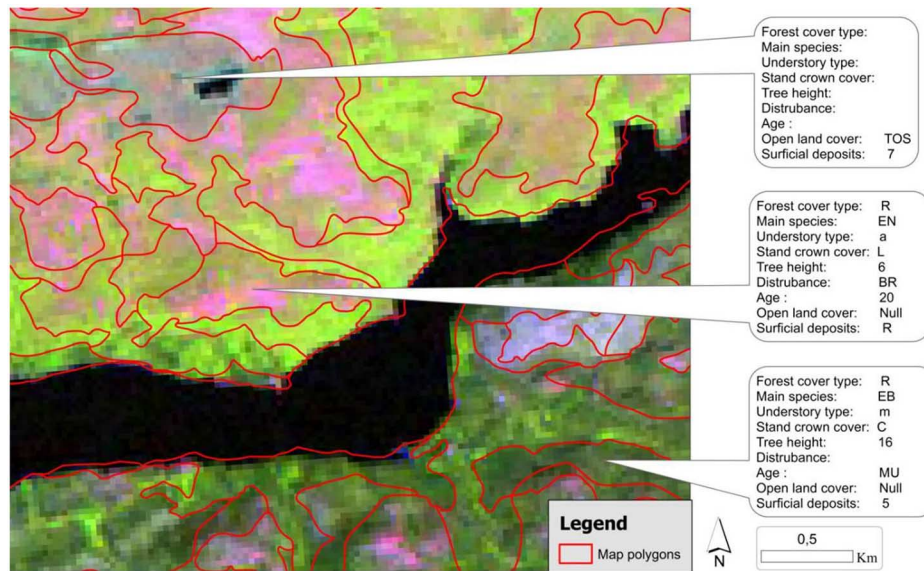


Fig. 3. Portion of the map illustrating map polygon's perimeters and three polygons database with associated stand attributes.

The integrated map consisted of eight contextual database attributes, as described in Table I. Only one of these attributes is numeric (tree height), while the others were classes. These map database attributes represent a rich source of information with respect to a stand that is being identified under a polygon. As an example, a stand could be characterized as having the following attributes: coniferous; dominated by black spruce and having a moss understory; crown closure class is B; mean tree height is 14 m; originated from 1940 fire, and stand age is 80 years; and the surficial deposit is till. Fig. 3 illustrates a portion of the map for La Grande River area with three polygons that were taken individually, with their associated databases, and using a Landsat summer mosaic as background. As an example, these three polygons show the combinations of forest cover type, understory type, crown cover, and land cover, where dense stands are darker than open stands. The information regarding vegetation and forest type that was produced from this work, however, had to be evaluated quantitatively to indicate the level

of confidence that users should have and to demonstrate the strength of the developed methods.

As a quantitative evaluation of map accuracy, an error matrix was first computed, as detailed in Table III, for the five map attributes: 1) forest cover type; 2) understory type; 3) stand crown cover; 4) disturbance; and 5) open land cover. The rows' values are the classes from the map and columns are the classes that were interpreted from the geo-referenced video. Table IV shows the global accuracy and Kappa values (κ) for the five-error matrix and for the statistics of the merged attribute matrices, which were not shown in this paper. Overall accuracy and the Kappa statistics explain the reliability and accuracy of the maps produced and are largely reported [60]. A total of 2910 polygons overlaid the flight lines and of these polygons, 843 were randomly selected. Global accuracy values ranged from 89.9% to 99%, while Kappa values ranged from 86.9% to 96.3%. Forest cover types, land cover, and disturbance had Kappa values greater than 93%. The greatest confusion or

TABLE III
FIRE ERROR MATRIX CALCULATED FOR THE MAP ATTRIBUTES

Forest cover type	Reference				Total
	F	M	R	Null	
F	31	3		3	37
M		23	10		33
R		4	482	5	491
Null			6	276	282
Total	31	30	498	284	843

Understory type	Reference					Total
	a	c	cm	m	Null	
a	28	1	1	1	1	32
c		123	8	3	3	137
cm		6	110	12		128
m		3	18	172	1	194
Null	2	3	4	7	337	353
Total	30	136	141	195	341	843

Stand crown cover	Reference					Total
	B	C	D	L	Null	
B	26	6	1			33
C	4	28	10	9	1	52
D			221	41	4	266
L			3	203	4	210
Null				6	276	282
Total	30	34	235	259	285	843

Disturbance	Reference		Total
	BR	Null	
BR	94	3	97
Null	3	743	746
Total	97	746	843

Open land cover	Reference						Total
	AB	LL	SD	TMS	TOR	Null	
AB	30					2	32
LL		31	2			1	34
SD			41				41
TMS				37		2	39
TOR					49		49
Null	3	2	0	0	1	642	648
Total	33	33	43	37	50	647	843

TABLE IV
STATISTICS FOR THE FIRE ERROR MATRIX CALCULATED FOR THE MAP ATTRIBUTES AND THE GLOBAL ACCURACY: 78.1% AND KAPPA: 72.5%

Map attributes	Global accuracy (%)	Kappa value (%)
Forest cover type	98.1	95.2
Understory type	89.9	86.7
Stand crown cover	91.2	86.9
Disturbance	99	96.3
Open land cover	98.5	96.0
Merged map attributes	81.8	79.3

misclassification for forest cover types was between the deciduous and mixed classes. In fact, almost half of the polygons that were evaluated within mixed classes were misclassified. For the coniferous class, only 3% of all polygons were misclassified. For land cover, only shrubs and lichen barrens exhibited misclassifications with forest stands (stand crown cover higher than 10%). Understory type and stand crown cover attained lower values of global accuracy (89.9% and 91.2%, respectively) and Kappa (86.7% and 86.9%, respectively). In the case of the understory type, 6% of “moss” polygons (m) and 4% of “lichen” polygons (c) were misclassified as the mixed class “lichen-moss.” For stand crown cover, the weaker results can

TABLE V
ERROR MATRIX CALCULATED FOR THE SURFICIAL DEPOSIT

	Reference							Total
	1A	1BC	1BD	5A	7	R	Other	
1A	171	3	4	1	2	1	2	184
1BC	5	19	1				0	25
1BD	34	8	74	1	1	0	1	119
5A	1	0	0	90	8	0	0	99
7	2		1		31		0	34
R	54	0	1	0	4	106	0	165
Other	7	0	0	0	3	2	33	45
Total	274	30	81	92	49	109	36	671

be explained by the fact that forest stands that were present in the area most had a cover around 25%, which is the boundary value for classes L (10%–25%) and D (25%–40%). Validation of the disturbance classes yielded the highest statistics, with a global accuracy of 99% and a Kappa of 96.3%. Finally, the map attributes merged gave strong agreement with a global accuracy of 81.8% and a Kappa value of 79.3%.

The specific error matrix produced for surficial deposits is detailed in Table V. A total of 1342 polygons overlaid the flight lines and 671 polygons were selected for the evaluation. The surficial deposits obtained the lowest statistics, with a global accuracy of 78.7% and a Kappa value of 72.5%. These low values could be attributed to 32% of till polygons (1A) being misclassified as till with either rock (R) or drumlins (1BD). Misclassification of surficial deposit classes mainly occurred between similar surficial deposit types: rock (R) instead of till (1A) in 20% of till classes and marine deposits (5A) instead of organic classes (7) in 16% of organic classes. Consequently, lower summary statistics were estimated for surficial deposits when these were compared to other map attributes, but the Kappa value of this map attribute indicated substantial agreement. This disparity can be explained by the fact that the window of evaluation, given by the geo-referenced video swath, was quite small relative to the mean area of surficial deposit polygons, which had a minimum area of 100 ha.

IV. DISCUSSION

Acquisition of accurate measurements and temporally continuous inventories of northern boreal forest ecosystems is challenging, given that they cover very large areas, which are not very accessible. The method proposed went beyond available studies using satellite remote sensing, which limited their developments by using either aerial photographs or pixel-based classification. In terms of a general strategy, our method enhanced the approach 1) by using a wider array of satellite images (Landsat summer mosaic, Landsat winter mosaic, and RapidEye); 2) by integrating several techniques according to their potential to discriminate the attributes being mapped (object-based classification, *knn* imputation, and image interpretation); and 3) by including the ability to represent raster data at different scales (pixel-based at 30 m, stand-level, and polygons representing the surficial deposits or fire extent). Combining methods and scales allowed us to maximize the results. The method proposed results in a series of useful

layers that are adapted for forest management while dealing with the limitations inherent to huge northern areas. Overall, it addressed important scientific challenges by creating a method that goes beyond those proposed in previous studies.

The first challenge was to propose a set of procedures that can be adapted to map a huge area of the boreal forest from satellite images. In Canada, traditional forest mapping exercises were either based on a combination of aerial photographs and field sample plots [10]–[12] to generate the polygonal map, or on the use of coarse- to medium-scale satellite images [13]–[16], [61] that generate a raster map. The effectiveness of land-cover mapping using semiautomated segmentation and object-based classification has been effectively demonstrated [62]–[64]. The present study used these methods to integrate pixel-based classification into polygons that were generated by segmentation. This method generalizes the information at the polygon level, yet it is adaptable to different guidelines according to forest practices or other issues. For example, specific attributes that are associated with each polygon, such as the percentage of lichen composition, stand crown cover, or the standard deviation of stand height, can be easily calculated and compared for all areas. Even though some research projects have tested the potential of applying remote sensing images to tree species classification [65], [66], this project introduces new options. It takes advantage of summer and winter conditions by using the summer and winter Landsat mosaics. It also takes advantage of multiresolution images by using Landsat, RapidEye, and aerial images for map production and validation. The method took advantage of low tree species diversity in northern boreal regions to improve the ability to map tree species composition over a huge area using the Landsat and RapidEye images. This innovative set of procedures that led to a map describing the vegetation, its detailed composition and main tree species is a step forward in dealing with huge and data-poor boreal contexts.

A second challenge was finding a way to use satellite images to map surficial deposits, which are usually mapped by photo-interpretation [10], [25], [26]. Traditional approaches for mapping surficial deposits require extensive resources and, therefore, are difficult to apply over large areas. Not only were the procedures based on 3-D RapidEye images, the accuracy of the resulting map of surficial deposits yields a significant improvement over earlier methods for effectively mapping large areas. The resulting map is adapted to support foresters who are assessing ecosystem resilience to natural or anthropogenic disturbance.

A third challenge was mapping stand age over the huge area while maintaining consistency and accuracy. Traditional inventories in Canada involve the interpretation of stand age from aerial photographs with the interpreter being trained from field samples [10]–[12]. This method is costly and can introduce heterogeneity to the map through subjective interpretations. Forest age in boreal regions is primarily driven by natural disturbances, generally by catastrophic wild fire. Therefore, an useful alternative for assessing forest age is mapping old fire perimeters. However, this approach requires extensive field work to define the date of a fire and its resulting perimeters, since evidence of these perimeters disappears within the landscape as

the forest recovers in the time following disturbance. This limitation has constrained its implementation over large and remote areas of boreal ecosystems [35]. The method proposed to determine stand age by measuring the year when the fires occurred over the landscape using easily available archived remote sensing images. Only a few fire scar samples have to be collected from the field to train the method. The procedures proposed were practical to implement and provided an objective, reliable map of uniform quality for stand fires, thereby providing stand ages over a very large area.

Interestingly, a fourth challenge arose when attempting to validate our results. Most mapping projects propose map validation using ground sample plots as a reference [67], [68], [33], [34]. This procedure involves inherent biases due to differences in scale between the plot and pixel/polygon that are to be evaluated [69]. Therefore, map validation of forest layers requires a large number of plots to calculate significant error statistics. The approach that has been proposed in this paper overcame this limitation by using a common imaging tool (the frame video camera) and an airborne platform. The very fine resolution images that were acquired by the airborne camera allow detailed interpretation of targeted areas and reliable validation. The potential bias of interpreters is offset by the very fine resolution of the images. Our experience with this approach to validation is convincing: planning data acquisition along the transect proved to be practical and estimating the appropriate classes for the targeted layers did not seem to cause much hesitation. Consistency was tested between interpreters; further most classes were relatively distinct from one another at the scale of the airborne images. This approach to map validation can easily be adapted in many other contexts.

Even though several aspects of our work demonstrated the potential of the proposed method, several limitations still remain. First, despite being applied to a huge area (44% of the Quebec Province), it is still unknown as to how well the method can be adapted to the rest of the boreal region, particularly where different inventory practices exist. Second, the proposed method requires *a priori* calibration data to obtain a suitable level of detail and accuracy: archived aerial photographs or maps, aircraft surveys, or field studies. Third, the surficial deposit maps that were produced from 3-D anaglyph mosaic were rendered at a coarser scale than the vegetation map, resulting in a much coarser minimal mapping unit. Consequently, local surficial deposits smaller than 100 ha were difficult to interpret from this mosaic and could not be discriminated. Fourth, the validation approach using an airborne camera is limited to the validation of all map attributes that do not require 3-D information. Tree heights that are calculated for each polygon were not evaluated by this approach but had been evaluated previously with the imputation process.

The proposed mapping method opens several new perspectives, either for improving the method or for the use of the map layers. First, the present method is mainly based on Landsat images with 30 m of spatial resolution. The new Landsat 8 images, with their 15 m spatial resolution and reflectance products, can improve the accuracy of the image processing results and facilitate interpretation. As second option, the present study was relied upon existing data that were available. In another

context, existing maps or datasets can be used. As an example, an archive of surficial deposit maps that were created by interpretation of aerial photography could be simply added to the vegetation map that was created with this proposed method. The use of existing data can be more productive and accurate than the approach proposed here. Third, the proposed method achieved a higher level of accuracy for the individual and merged map attributes when it was compared with other similar projects [70], [71]. This enlarges the possibilities for using this method for other areas of boreal ecosystems. For example, this map can produce reports on ecosystem sensitivity and temporal trends in a global warming context. In fact, forest attributes (crown cover or height) and characteristics (species or composition) can be reported for large areas. As another example, the method can be used to document faunal habitat richness, e.g., understory type (moss, shrub, or lichen), which is relevant to the diet of woodland caribou (*Rangifer tarandus caribou*). As a final example, the fire history map that was related to the present vegetation characteristics could be a valuable source of information regarding the resilience of these ecosystems after fire. This can be linked to the sensitivity of these ecosystems to global warming.

V. CONCLUSION

The methods that were developed in this project introduced several technological innovations. First, image classification using an object-based approach improved the ability for applying queries to extract spatial statistics on the mapped attributes, such as surface heterogeneity and horizontal structure of the vegetation. Second, species mapping that was based on multirate satellite images is flexible and, consequently, can be applied to other, similar ecosystems or it can be adapted to different ones. For example, the species identification guide can be applied to a large part of the boreal region of North America or even for other northern ecosystems in Scandinavia or Asia, where tree species are comparable to those that were covered by this study. Third, the study demonstrated the effectiveness of our method to map fire history based on archived images of satellite sensors covering very large areas. The proposed method for mapping fire perimeters and age is applicable over the circumboreal forest, which is composed of fire-driven ecosystems. Fourth, interpretation of surficial deposits from 3-D RapidEye images is novel and can also be applicable over large areas for which satellite images and topographic maps are available. Fifth, the use of geo-referenced video technologies to assess mapping accuracy takes advantage of a widely available tool for effectively assessing map accuracy. In summary, the method proposed provides the means for mapping very large areas of forested ecosystems at regular intervals with accuracies comparable to current inventory requirements. This cost-effective and innovative method proposes new ways to map boreal ecosystems.

Some improvements can be brought to the proposed methods. For instance, predictable improvements in the quality, availability, and cost of satellite images are likely to facilitate the application of our method. Similarly, the availability of airborne LiDAR data has proven to be an effective tool in

providing precise digital elevation models and assessing a wide array of forest attributes. Accessibility to large computing capabilities is also an important asset when dealing with wide-area mapping. Requirements for reporting relatively good precision level for huge area mapping, to the point of being compatible with official forest inventories of southern areas, provide a supplemental argument in favor of the method proposed, as it would provide a strong base from which useful map products could be made available.

ACKNOWLEDGMENT

The authors would like to thank the Ministère des Forêts, de la Faune et des Parcs, Quebec, QC, Canada, for the development, the funding, the dataset and support for the project. They would also like thank all the team for their contribution in the project: I. Baril, L. Bourque, É. Dufour, P. Grondin, C. Morneau, A. Robitaille, M.P. Samson, and É. Vaillancourt; W. F. J. Parsons for his help on the English review of the paper; and comments made by the anonymous reviewers that resulted in significant improvements to the paper.

REFERENCES

- [1] FAO, "Global forest resources assessment 2001," U.N. Food Agric. Org., Rome, Italy, Tech. Rep. 140, 2002.
- [2] C. Alix, "Exploitation du bois par les populations néo-eskimo entre le nord de l'Alaska et le Haut-Arctique canadien," Ph.D. dissertation, Université de Paris I-Panthéon Sorbonne, Paris, France, 2001.
- [3] J. Pojar, "Environment and biogeography of the western boreal forest," *For. Chron.*, vol. 72, pp. 51–58, 1996.
- [4] H. E. Wright Jr., "Introduction," in *Late-Quaternary Environments of the United States*, H. E. Wright Jr., Ed. Minneapolis, MN, USA: Holocene/Univ. Minnesota Press, 1983, vol. 2, pp. 11–16.
- [5] E. A. Johnson, *Fire and Vegetation Dynamics: Studies From the North American Boreal Forest*. Cambridge, U.K.: Cambridge Univ. Press, 1992.
- [6] C. Li, "Fire regimes and their simulation with reference to Ontario," in *Ecology of a Managed Terrestrial Landscape: Patterns and Processes of Forest Landscapes in Ontario*, A. Perera, D. Euler, and I. Thompson, Eds. Vancouver, BC, Canada: UBC Press, 2000, pp. 115–140.
- [7] C. R. Drever, G. Peterson, C. Messier, Y. Bergeron, and M. D. Flannigan, "Can forest management based on natural disturbances maintain ecological resilience?," *Can. J. For. Res.*, vol. 36, pp. 2285–2299, 2006.
- [8] A. J. Soja *et al.*, "Climate-induced boreal forest change: Predictions vs. current observations," *Global Planet. Change*, vol. 56, pp. 274–296, 2007.
- [9] L. H. Gunderson, "Ecological resilience—In theory and application," *Annu. Rev. Ecol. Syst.*, vol. 31, pp. 425–439, 2000.
- [10] British Columbia Ministry of Forests (Forest Analysis, and Inventory Branch, Victoria, Canada), "Photo Interpretation Procedure," 2011, 109 p.
- [11] Ontario Ministry of Natural Resources, and Forestry (Ontario Forest Resources Inventory, Sault Ste. Marie, Ontario, Canada), "Photo Interpretation Specifications," 2011, 92 p.
- [12] Ministère des Ressources naturelles (Direction des Inventaires Forestiers, Québec, Québec, Canada), "Norme de stratification écoforestière. Quatrième inventaire écoforestier du Québec méridional," 2013, 111 p.
- [13] L. A. Viereck, C. T. Dymess, A. R. Batten, and K. J. Wenzlick, "The Alaska vegetation classification," Dept. Agriculture, Forest Service, Portland, OR, USA, Gen. Tech. Rep. PNW-GTR-286, 1992, 278 p.
- [14] M. A. Wulder *et al.*, "Operational mapping of the land cover of the forested area of Canada with Landsat data: EOSD land cover program," *For. Chron.*, vol. 79, pp. 1075–1083, 2003.
- [15] A. Beaudoin *et al.*, "Mapping attributes of Canada's forests at moderate resolution through kNN imputation and MODIS imagery," *Can. J. For. Res.*, vol. 44, pp. 521–532, 2014.
- [16] L. T. Berner, P. S. A. Beck, M. M. Loranty, H. D. Alexander, M. C. Mack, and S. J. Goetz, "Cajander larch (*Larix cajanderi*) biomass distribution, fire regime and post-fire recovery in northeastern Siberia," *Biogeosciences*, vol. 9, pp. 3943–3959, 2012.

- [17] T. E. Avery and H. E. Burkhart, *Forest Measurements*, 5th ed. New York, NY, USA: McGraw-Hill, 2001.
- [18] M. Maltamo, K. Erikäinen, J. Pitkänen, J. Hyypä, and M. Vehmas, "Estimation of timber volume and stem density based on scanning laser altimetry and expected tree size distribution functions," *Remote Sens. Environ.*, vol. 90, pp. 319–330, 2004.
- [19] M. Despons and S. Payette, "Recent dynamics of jack pine and its northern distribution limit in northern Quebec," *Can. J. Bot.*, vol. 70, pp. 1157–1167, 1992.
- [20] D. Arseneault, N. Villeneuve, C. Boismenu, Y. Leblanc, and J. Deshayé, "Estimating lichen biomass and caribou grazing on the wintering grounds of the northern Quebec: An application of fire history and Landsat data," *J. Appl. Ecol.*, vol. 34, pp. 65–78, 1997.
- [21] European Commission, "CORINE land cover update," Eur. Environ. Agency, Copenhagen, Denmark, Tech. Rep. 89, 2002, 56 p.
- [22] P. Y. Bernier *et al.*, "From plots to landscape: A k-NN-based method for estimating stand-level merchantable volume in the Province of Québec, Canada," *For. Chron.*, vol. 86, pp. 461–468, 2010.
- [23] B. T. Wilson, A. J. Lister, and R. I. Riemann, "A nearest-neighbor imputation approach to mapping tree species over large areas using forest inventory plots and moderate resolution raster data," *For. Ecol. Manage.*, vol. 271, pp. 182–198, 2012.
- [24] P. T. Wolter, E. A. Berkley, S. D. Peckham, A. Singh, and P. A. Townsend, "Exploiting tree shadows on snow for estimating forest basal area using Landsat data," *For. Ecol. Manage.*, vol. 121, pp. 69–79, 2012.
- [25] S. Mei, M. M. Fenton, and R. Paulen, "Integration of remote sensing and geological data as aids to mapping surficial sediments in northwestern Alberta," Alberta Energy and Utilities Board, EUB/AGS Earth Sci. Edmonton, AB, Canada, Tech. Rep. 2005-03., 2005, 55 p.
- [26] A. LaRocque, B. Leblon, J. Harris, C. Jefferson, V. Tschirhart, and Y. Shelat, "Surficial materials mapping in Nunavut, Canada with multi-beam RADARSAT-2 dual-polarization C-HH and C-HV, LANDSAT-7 ETM+, and DEM data," *Can. J. Remote Sens.*, vol. 38, pp. 281–305, 2012.
- [27] R. A. Daigneault, "Géologie des formations en surface, région du Cap de Nouvelle-France, du Cratère du Nouveau-Québec et de Kangisujuaq," CGC, carte 1863A, 1: 250 000, 1996.
- [28] R. G. Skinner and J. S. Vincent, "Carte des dépôts de surface d'une région sise à l'est de Baie-James," CGC, Open file 178, 1: 50 000, Geological Survey of Canada, 1974.
- [29] R. Fleming, J. N. Candau, and R. McAlpine, "Landscape-scale analysis of interactions between insect defoliation and forest fire in central Canada," *Clim. Change*, vol. 55, pp. 251–272, 2002.
- [30] S. Payette, C. Morneau, L. Sirois, and M. Despons, "Recent fire history of the northern Québec biomes," *Ecology*, vol. 10, pp. 656–673, 1989.
- [31] N. Mansuy, S. Gauthier, A. Robitaille, and Y. Bergeron, "Regional patterns of postfire canopy recovery in the northern boreal forest of Quebec: Interaction between surficial deposit, climate and fire cycle," *Can. J. For. Res.*, vol. 42, pp. 1328–1343, 2012.
- [32] B. J. Stocks *et al.*, "Large forest fires in Canada, 1959–1997," *J. Geophys. Res.*, vol. 107, 2002, doi: 10.1029/2001JD000484.
- [33] A. I. Sukhinin *et al.*, "AVHRR-based mapping of fires in Russia: New products for fire management and carbon cycle studies," *Remote Sens. Environ.*, vol. 93, pp. 546–564, 2004.
- [34] E. S. Kasischke *et al.*, "Quantifying burned area from fires in North American forests: Implications for direct reduction of carbon stocks," *J. Geophys. Res.*, vol. 116, 2011, p. G04003, doi: 10.1029/2011JG001707.
- [35] D. L. Olson, J. B. Cronan, D. McKenzie, J. L. Barnes, and A. E. Camp, "Compiling, synthesizing and analyzing existing boreal forest fire history data in Alaska," Pacific Northwest Res. Station, USDA Forest Service, Seattle, WA, USA, Final Report to the Joint Fire Science Program, JFSP Project No. 06-3-1-26, 2011, 27 p.
- [36] F. Pinto, *A Method to Validate Stand Attributes in a Forest Resource Inventory: Case Study in Nipissing Forest, Ontario*. Sault Ste. Marie, ON, Canada: Ontario Forest Research Inst., 2007.
- [37] I. D. Thompson, S. C. Maher, D. P. Rouillard, J. M. Fryxell, and J. A. Baker, "Accuracy of forest inventory mapping: Some implications for boreal forest management," *For. Ecol. Manage.*, vol. 252, pp. 208–221, 2007.
- [38] J. Cihlar, "Land cover mapping of large areas from satellites: Status and research priorities," *Int. J. Remote Sens.*, vol. 21, pp. 1093–1114, 2000.
- [39] C. G. Homer, R. D. Ramsey, T. C. Edwards, and A. Falconer, "Landscape cover type modeling using a multi-scene thematic mapper mosaic," *Photogramm. Eng. Remote Sens.*, vol. 63, pp. 59–67, 1997.
- [40] PCI Geomatics Inc. "Geomatica Focus, version 9.1," 2003.
- [41] Q. Meng, C. Cieszewski, and M. Madden, "Large area forest inventory using Landsat ETM+: A geostatistical approach," *ISPRS J. Photogramm. Remote Sens.*, vol. 64, pp. 27–36, 2009.
- [42] R. M. Batson, K. Edwards, and F. M. Eliason, "Synthetic stereo and Landsat pictures," *Photogramm. Eng. Remote Sens.*, vol. 42, pp. 1279–1284, 1976.
- [43] Natural Resources Canada, "CanVec digital topographical dataset," Earth Sciences Sector; Canada Centre for Mapping and Earth Observation, Government of Canada, Ottawa, ON, Canada, 2014.
- [44] A. Leboeuf, A. Robitaille, E. Dufour, P. Grondin, and C. Morneau, "Norme de cartographie écologique de la végétation du Nord québécois. Projet du Plan Nord," Ministère des Ressources naturelles et de la Faune, Direction des inventaires forestiers, Québec, QC, Canada, 2012.
- [45] A. Elumtsoh and R. P. Shrestha, "Application of DEM data to Landsat image classification: Evaluation in a tropical wet-dry landscape of Thailand," *Photogramm. Eng. Remote Sens.*, vol. 66, pp. 297–304, 2000.
- [46] P. A. Burrough, J. P. Wilson, P. van Gaans, and A. J. Hansen, "Fuzzy k-means classification of topo-climatic data as an aid to forest mapping in the Greater Yellowstone Area, USA," *Landscape Ecol.*, vol. 16, pp. 523–546, 2001.
- [47] J. T. Tou and R. C. Gonzalez, *Pattern Recognition Principles*. Reading, MA, USA: Addison-Wesley, 1974.
- [48] R. E. McRoberts, E. O. Tomppo, A. O. Finley, and J. Heikkinen, "Estimating areal means and variances of forest attributes using the k-nearest neighbors technique and satellite imagery," *Remote Sens. Environ.*, vol. 111, p. 466–480, 2007.
- [49] E. Tomppo, H. Olsson, G. Ståhl, M. Nilsson, O. Hagner, and M. Katila, "Combining national forest inventory field plots and remote sensing data for forest databases," *Remote Sens. Environ.*, vol. 112, pp. 1982–1999, 2008.
- [50] A. Leboeuf, R. A. Fournier, J. E. Luther, A. Beaudoin, and L. Guindon, "Forest attribute estimation of northern Canadian forests using QuickBird imagery and a shadow fraction method," *For. Ecol. Manage.*, vol. 266, pp. 66–74, 2012.
- [51] R. Picard and D. Cook, "Cross-validation of regression models," *J. Amer. Stat. Assoc.*, vol. 79, pp. 575–583, 1984.
- [52] Definiens Inc., *eCognition, version 3.1*. Boulder, CO, USA: Definiens Inc., 2010.
- [53] L. Dorren, B. Maier, and A. C. Seijmonsbergen, "Improved Landsat-based forest mapping in steep mountainous terrain using object-based classification," *For. Ecol. Manage.*, vol. 183, pp. 31–46, 2003.
- [54] U. Benz, P. Hofmann, G. Willhauck, I. Lingenfelder, and M. Heynen, "Multi-resolution, object-oriented fuzzy analysis of remote sensing data for GIS-ready information," *ISPRS J. Photogramm. Remote Sens.*, vol. 58, pp. 239–258, 2004.
- [55] A. Leboeuf, E. Dufour, and P. Grondin, "Guide d'identification des milieux humides du Nord du Québec par images satellites," Ministère des Ressources naturelles et de la Faune, Direction des inventaires forestiers et Direction de la recherche forestière, Québec, QC, Canada, 2012.
- [56] A. Robitaille and M. Allard, "Guide pratique d'identification des dépôts de surface au Québec. Les publications du Québec," Québec, QC, Canada, 2007.
- [57] C. Morneau and S. Payette, "Postfire lichen-spruce woodland recovery at the limit of the boreal forest in northern Quebec," *Can. J. Bot.*, vol. 67, pp. 2770–2782, 1989.
- [58] ESRI Inc, *ArcGIS, version 10.1*. Redlands, CA, USA, 2012.
- [59] Red Hen Systems, *Geovideo for ArcGIS*. Fort Collins, CO, USA: Red Hen Systems Inc., 2004.
- [60] J. R. Landis and G. G. Koch, "The measurement of observer agreement for categorical data," *Biometrics*, vol. 33, pp. 159–174, 1977.
- [61] J. Beaubien, J. Cihlar, G. Simard, and R. Latifovic, "Land cover from multiple Thematic Mapper scenes using a new enhancement—Classification methodology," *J. Geophys. Res.*, vol. 104, pp. 27 909–27 920, 1999.
- [62] L. Dorren, B. Maier, and A. C. Seijmonsbergen, "Improved Landsat-based forest mapping in steep mountainous terrain using object-based classification," *For. Ecol. Manage.*, vol. 183, pp. 31–46, 2003.
- [63] G. J. Hay, G. Castilla, M. A. Wulder, and J. R. Ruiz, "An automated object-based approach for the multiscale image segmentation of forest scenes," *Int. J. Appl. Earth Observ. Geoinf.*, vol. 7, pp. 339–359, 2005.
- [64] M. Kim, M. Madden, and T. A. Warner, "Forest type Mapping using object-specific texture measures from multispectral Ikonos imagery: Segmentation quality and image classification issues," *Photogramm. Eng. Rem. Sens.*, vol. 75, pp. 819–829, 2009.

- [65] H. Buddenbaum, M. Schlerf, and J. Hill, "Classification of coniferous tree species and age classes using hyperspectral data and geostatistical methods," *Int. J. Remote Sens.*, vol. 26, pp. 5453–5456, 2005.
- [66] M. Immitzer, C. Atzberger, and T. Koukal, "Tree species classification with random forest using very high spatial resolution 8-band WorldView-2 satellite data," *Remote Sens.*, vol. 4, pp. 2661–2693, 2012.
- [67] S. Labrecque, R. A. Fournier, J. E. Luther, and D. E. Piercey, "A comparison of four methods to map forest biomass from Landsat-TM and inventory data in western Newfoundland," *For. Ecol. Manage.*, vol. 226, pp. 129–144, 2006.
- [68] J. E. Luther, R. A. Fournier, D. E. Piercey, L. Guindon, and R. J. Hall, "Biomass mapping using forest type and structure derived from Landsat TM imagery," *Int. J. Appl. Earth Observ. Geoinf.*, vol. 8, pp. 173–187, 2006.
- [69] G. Frazer, S. Magnussen, M. Wulder, and K. Niemann, "Simulated impact of sample plot size and co-registration error on the accuracy and uncertainty of LiDAR-derived estimates of forest stand biomass," *Remote Sens. Environ.*, vol. 115, pp. 636–649, 2011.
- [70] O. Brown, J. R. Harris, D. Utting, and E. C. Little, "Remote predictive mapping of surficial materials on northern Baffin Island: developing and testing techniques using Landsat TM and digital elevation data," Geological Survey of Canada, Current research, 2007, 12 p.
- [71] M. A. Wulder *et al.*, "Monitoring Canada's forest. Part 1: Completion of the EOSD land cover project," *Can. J. Remote Sens.*, vol. 34, pp. 549–562, 2008.



Antoine Leboeuf received the B.Sc. degree in forest management from the Université Laval, Québec, QC, Canada, and the M.Sc. and Ph.D. degrees in remote sensing applied to northern boreal regions from the Université de Sherbrooke, Québec, QC, Canada, in 2005 and 2013, respectively.

Currently, he is working as Coordinator with the Department of Mapping, Ministère des Forêts, de la Faune et des Parcs du Québec, Québec, Canada.



Richard A. Fournier received the B.Sc. degree in physics from the Université du Québec à Montréal, Québec, QC, Canada, in 1986, the M.Sc. degree in space sciences from York University, Toronto, ON, Canada, in 1989, and the Ph.D. degree in geomatics from the Université Laval, Québec City, QC, Canada, in 1997.

From 1996 to 2001, he worked as a Research Scientist with Canadian Forest Service, Victoria, BC, Canada. He has been working as a Professor with the Department of Applied Geomatics, Université de

Sherbrooke, Québec, QC, Canada, since 2001. His research interests include remote sensing applied to natural ecosystems like forest and wetlands.