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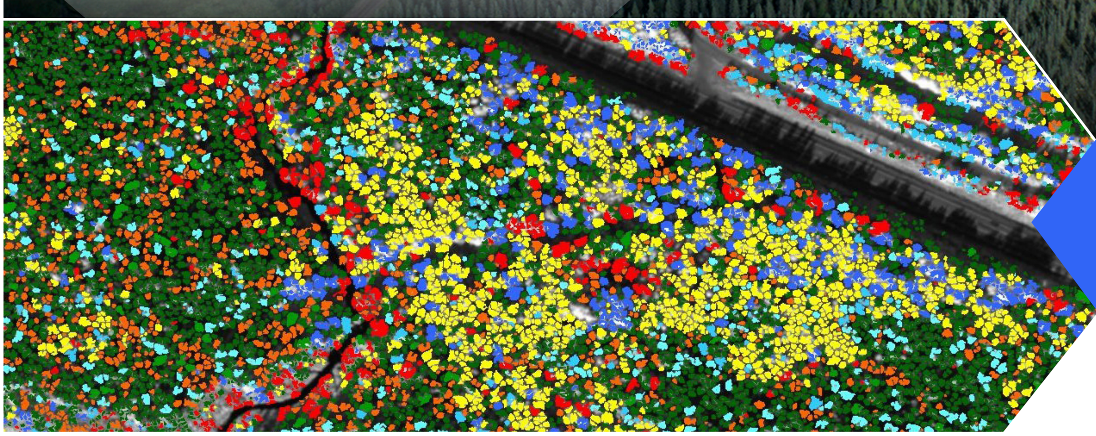

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Cover: Top, *The Forests of Canada Collection*, Natural Resources Canada (NRCan), Canadian Forest Service (CFS), 2003. Bottom, Typical individual tree crown delineations and classifications possible from high spatial resolution images (less than 1 m/pixel) obtained from satellite or airborne multispectral sensors. Courtesy of François A. Gougeon, NRCan, CFS, Pacific Forestry Centre, Victoria, BC.

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Abstract

In Quebec, as in the other provinces of Canada, the conventional method of conducting forest inventories requires considerable resources, both human and material. The availability of high spatial resolution satellite images (less than1 m/pixel) opens the door to a new approach previously used only on aerial images: semi-automatic individual tree crown (ITC) analysis.

To test the accuracy of this approach, QuickBird satellite images of two regions in the Laurentians were acquired. After pre-processing, tree crowns were delineated on the panchromatic images and classified by species using multispectral images. For each polygon of the forest inventory, new information fields were generated that describe their forest content more precisely.

Confusion matrices generated based on the test areas indicated that the classification accuracy obtained for each vegetation class ranged from 60% to 90%. Several approaches were used to verify the results based on field sampling, but none was considered very satisfactory. Finally, the results were compared with the conventional inventory. Owing to the complex species grouping process used in Quebec at the time, the comparison proved difficult to quantify precisely, but the comparison made with the main species was very encouraging.

Introduction

In Quebec, ecoforestry maps are used as a basis for many forest management decisions. Creating and updating these maps require considerable resources, both human and material, and involve the interpretation of aerial photographs (or images). During this process, the boundaries of each forest stand are drawn based on about 10 stratification criteria (density, height, age, ecological type, etc.), including one of the most important criteria, species grouping.

In the broader context of implementing the sustainable development of forest resources, forest managers must have access to increasingly precise information if they want to optimise the potential production of timber resources, while harmonising industrial practices with other uses of the forest, such as recreational/tourism activities and wildlife management.

The availability of high spatial resolution satellite images (less than 100 cm/pixel), such as those from the IKONOS, QuickBird, GeoEye or WorldView satellites, has paved the way for a new approach to producing forest inventories. This approach, developed mainly based on aerial images, involves delineating individual trees rather than stands. Although the spatial resolution of current satellite sensors is not yet sufficient to produce an inventory that is truly accurate to the individual tree level, and since it would be difficult to integrate this type of information for large areas into current geographic information systems (GIS), this approach focuses on obtaining precise information at the stand level, particularly on species composition. In addition, when we have information that is accurate almost to the individual tree level, the process of stand delineation can be more dynamic and it becomes easier to create groupings using different criteria (e.g., wildlife management).

The availability of ITC digital information paves the way for precision forestry by improving the information provided on the Quebec ecoforestry map or possibly even replacing this map in the longer term. For the first time, thanks to these techniques, forest managers can

- easily visualise the spatial distribution of species within an ecoforest polygon (including certain minority, but high-value species);
- obtain a percentage of crown cover for each tree species present in the ecoforest polygon;
- define the areas of concentration or dispersion of a given species in an ecoforest polygon (or a large area);
- optimise their survey plan based on the species present in the ecoforest polygon;
- improve the quality of the data used to calculate the allowable cut (i.e., volume);
- determine the location and size of canopy gaps, which may be useful in wildlife management; and
- identify the location of snags useful to nesting birds.

The Canadian Forest Service of Natural Resources Canada has been working on the individual tree crown (ITC) classification method over the last 25 years (Gougeon and Leckie 2003). It is currently implemented using a powerful software suite known as the ITC Suite (Gougeon 2010), which operates under the EASI interface of the Geomatica platform of PCI Geomatics (see http://www.pcigeomatics.com).

The ITC method was originally developed using data from Canadian airborne sensors (e.g., MEIS, CASI) in the 1990s (Gougeon 1995a, 1995b; Leckie et al. 2003b). The method was tested using data from the high spatial resolution satellite sensors which became available in the early 2000s (Gougeon et al. 2001; Labrecque et al. 2002; Gougeon et al. 2003; Gougeon and Leckie 2006). The current trend is a significant return to airborne sensors (e.g., ADS, Vexcel), owing to the interest in the acquisition of these images and their stereoscopic on-screen interpretation (Pitt and Pineau 2009). However, the steadily increasing availability of high spatial resolution satellite images and their systematic storage in databases make them an indispensable tool for conducting forest inventories. Some studies have compared the results of ITC analyses using these two types of images for the same forest regions and examined the advantages and disadvantages of each medium (e.g., Gougeon and Leckie 2011). From one medium to another, the ITC method remains essentially the same, except that the aerial data require more pre-processing, file handling and post-processing, in addition to increased vigilance during contractual interactions with the suppliers of these data (Gougeon 2008, 2009).

Many other research studies have been carried out on crown delineation using high spatial resolution images (e.g., Larsen and Rudemo 1998; Brandtberg and Walter1998; Culvenor 2002; Erikson 2003; Yang et al. 2017), images of “digital canopy models”, created using high-density LiDAR data (Hyyppä et al. 2008; Leckie et al. 2003a), and even point clouds from a LiDAR or stereoscopic image autocorrelation (St-Onge et al. 2015). Some articles have reviewed and even compared these techniques (Larsen et al. 2011; Ke and Quackenbush 2011; Kaartinen et al. 2012; White et al. 2016).

The ITC delineation technique is not necessarily the best in all circumstances, but is generally well suited to Canadian forests. It also has the advantage of delineating crowns more completely (i.e., by including the shaded part of the crown), which should lead to better calculations of volume, biomass and carbon sequestration. There are also several techniques that are used only for crown detection and counts, most of which are based on the detection of local maxima (Gougeon and Moore 1989; Dralle and Rudemo 1997; Wulder et al. 2000). We now use those techniques solely, specifically the adaptive version (Gougeon and Leckie 1999), to detect and classify regeneration (i.e., very small trees) as it can function even in very open plantations.

Although several crown detection and delineation techniques exist, only a few systems, such as the ITC Suite, can perform almost all aspects of digital ITC analysis. The only other systems of this type are the exclusive preserve of private companies and we have very little information about them. The ITC Suite performs image pre-processing (normalisation, detection of non-forest areas, etc.), crown delineation or detection, species classification, evaluation of accuracy at the ITC level and grouping in forest stands. In theory, the process can be almost completely automated, and only requires the intervention of an interpreter to identify the training areas necessary for the species classification process and to monitor the quality of the results using test areas, all iteratively. Several post-processing modules are also available, such as one that summarises all the ITC information for each forest stand polygon. There are also modules for visualising relative density, canopy closure, mean height and average crown diameter; modules to verify whether a prescribed planting was carried out; others to detect canopy gaps, etc. The allowable cut (i.e., the volume) is calculated after all the image analysis is done either at the stand level with average values for each species (e.g., height, crown diameter), or at the individual tree level. Biomass or carbon sequestration can be calculated in the same way.

The pilot project to which we refer in this document (CSRE-Forêt and CLC-Camint 2003) involved several additional aspects, including the study of the coniferous understory based on satellite images taken in winter, the habitats available to white-tailed deer, the ITC method that detects only the tops of trees used in regenerating areas (in Quebec, strata less than 7 m high), the calculation of allowable cut, etc. In this article, we will focus on two of the most important aspects of this project: verification of the species obtained using the semi-automatic ITC inventory technique and its comparison with the species grouping typical of the conventional inventory in Quebec during this period.

The purpose of this document is therefore to examine whether ITC analysis applied to high-resolution satellite imagery could become a new forest management tool in Quebec and in the rest of Canada.

Description of the study sectors

The forest cover of the Laurentians region has an astonishing ecological diversity, ranging from the sugar maple-hickory stands in the far south to the balsam fir-white birch stands in the north with, between the two, a gradient of forest stands rich in plant and animal species. Originally, three study sectors were delimited in this region (Figure 1). The exact delimitation of the sectors was carried out by the members of a technical committee representing the parties that took part in this project. These study sectors were chosen to represent a mosaic of the stands typical of the Laurentians, one of the most diversified regions of Quebec.

Sector A of the northern part of the territory was supposed to cover an area of 160 km^2 (10 km wide by 16 km high), and we were supposed to use QuickBird summer panchromatic and multispectral images. However, owing to the weather conditions, we were unable to obtain sufficiently cloud-free images, despite the cloud coverage tolerance of 20%.

The area studied in this project therefore consists of two different sectors of the Laurentians region. The first is located near L'Annonciation and the second near Lachute. The forests of L'Annonciation sector are located in the sugar maple-yellow birch subdomain, while those of the Lachute sector are located in the sugar maple-bitternut hickory subdomain (Saucier et al. 2001).

L'Annonciation sector (sector B)

This study sector is located approximately 20 km from the town of L'Annonciation. The area is characterised by an alluvial valley to the east, through which the Froid Stream runs, and by numerous hills interspersed with several lakes and streams. Chaud Lake, one of the largest lakes, is located in the southern part of the study sector. The altitude varies between 240 m and 630 m.

According to the ecoforestry map of the Quebec Department of Forests, Wildlife and Parks (MFFP), deciduous stands dominate 46% of the total area of the sector, mixed stands follow with 34%, while conifer-dominated stands occupy only 5% of the forest area. Maple stands, yellow birch stands and white birch stands are more common relative to the other species groups, with 46%, 18% and 12% of the area, respectively. The species (classes) chosen for the digital analysis of this sector are listed in Table 1.

With respect to the distribution of age classes in L'Annonciation sector, 34% of the stands are classified as old, uneven-aged (VIN), 0.7% are classified as multistoried, and 20% have a young, uneven-aged structure (JIN). More than 20% of the stands are between 50 and 70 years old, while 10- and 30-year-old stands occupy only 7% of the sector.

Lachute sector (sector C)

The Lachute sector is located approximately 5 km due east of the town of Lachute. The area is characterised by the alluvial plain of the Nord River to the south, and undulating relief to the north, where low hills and valleys alternate. The elevation varies between 140 m and 340 m. The largest lakes are located in the northern and central parts of the study sector.

According to the MFFP's ecoforestry map, deciduous stands and mixed stands predominate, each accounting for 39% of the total area of the sector, while coniferous stands occupy only 5% of the forest area. Spruce stands, maple stands and coniferous stands (R) are the most common relative to the other species groups, with 33%, 31% and 15% of the area, respectively. According to the MFFP's standards, the stands classified simply

Table 1. Vegetation classes identified in each sector.

L'Annonciation	Lachute
White pine (PIB)	White pine (PIB)
Spruces (EE)	Spruces (EE)
Cedar (THO)	Cedar (THO)
Firs (SAB)	Firs (SAB)
Maples (ER)	Hemlock (PRU)
Poplars (PEU)	Maples (ER)
White birch (BOP)	Intolerant hardwoods (FI)
Yellow birch (BJ)	Tolerant hardwoods (FT)

as coniferous are those that contain at least three coniferous species, none of which occupies more than 50% of the coniferous basal area. The species (classes) chosen for the digital analysis of this sector are listed in Table 1.

Satellite imagery

Satellite products from the QuickBird high-resolution satellite were chosen in this study. This satellite offers a range of digital products derived from two types of images that it captures, that is, panchromatic images (61 cm/pixel) and multispectral images (2.4 m/pixel). For the purposes of this project, this combination proved to be very practical, since the processing method is divided into two steps, namely crown isolation carried out using the panchromatic image, followed by crown classification carried out using the multispectral image. The spectral bands captured by QuickBird are very similar to the equivalent bands of the Landsat ETM 7 satellite. Two 160-km^2 images were acquired during the summer of 2002, one of L'Annonciation sector (June 24) and the other of the Lachute sector (July 20), as shown in Figure 1.

Forest data

The forest data used in this study came from various sources and were used differently in each stage of the project. The digital layer of the ecoforestry map sheets 31G09NO, 31G09NE, 31G16SO, 31G16SE (Sector B) and 31J10SO, 31J10SE, 31J07NO, 31J07NE (Sector C), as well as a series of infrared aerial photographs (1991, 1994 and 1996), were used to identify and delimit training and test areas for crown classification.

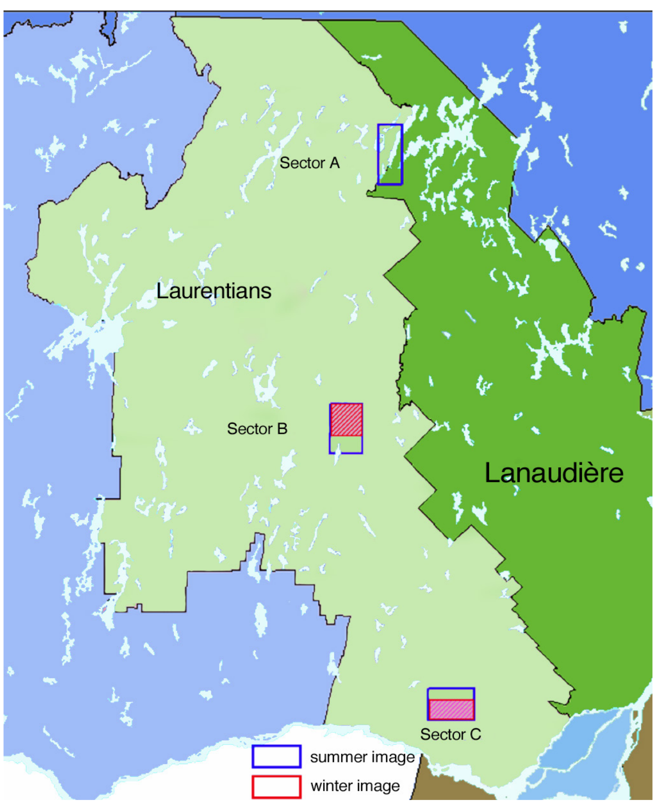


Figure 1. Location of the study sectors.

Methodology

The ITC image analysis method is divided into several separate steps, namely

1. image pre-processing and the creation of masks of the non-forest areas;
2. semi-automatic crown delineation: step that involves delineating the individual crowns (here, using the panchromatic image);
3. photo interpretation (on aerial photographs or QuickBird images or both) of training and test areas for each species of interest;
4. crown classification: step that involves creating, based on the multispectral image, ITC spectral signatures for the species of interest, which are then applied to each crown, according to a maximum likelihood method;
5. semi-automatic stand delineation: step that involves the semi-automatic creation of stand boundaries based on the analysis of crown density and canopy closure by vegetation class (and their height when a digital canopy height model is available);
6. count, by species, of crowns and their attributes (e.g., height, crown diameter) in the stands, the percentage of crown cover for each species and the creation of new fields to store the information generated for each stand; and
7. calculation of the individual tree volume with a summary by species for each stand.

The last step was not carried out during this study. However, research using aerial images is still under way in Ontario (Leckie et al. 2017) and we intend to continue until this step is completed. For this study, crown delineation was carried out using the panchromatic image (at higher spatial resolution) and the multispectral images were used without enhancement (at low resolution), to create spectral signatures. Theoretically, it is also possible to conduct an ITC image analysis based on a set of pan-sharpened multispectral images. In this case, since the panchromatic band itself is generally not available, the spatially enhanced near-infrared band would be used to delineate the crowns. It should be possible to obtain substantially the same results, if the supplier of the images has not otherwise altered them. For this study, such a set of enhanced multispectral images was nonetheless created to assist with visualisation, especially during the delineation of the training areas and test areas.

Image pre-processing

First, the images of each region must be converted from their original format (.tif) to the .pix format of the PCI standard. This format, the only one that the ITC Suite currently recognises, makes it possible to keep all the information and the intermediate processing steps performed on a given image within a single file.

The images are then orthorectified using digital elevation models. The band used to delineate the crown (the panchromatic band in this case) is smoothed using a moving average filter in a 3x3 pixel window (i.e., PCI/FAV). This eliminates background noise and smooths the slopes between the bright pixels that form the tree crowns and the surrounding shaded areas, which facilitates the crown separation process.

Finally, masks hiding the non-forest areas (roads, lakes, rivers, piers, wharfs, areas of deep shade, clouds and their shadows, etc.) are generated based on the thresholds on certain spectral bands, as well as on the base map of the region. These masks are necessary for effective crown delineation. They will also be useful during the semi-automatic creation of the forest stands and for the final mapping including the other landscape entities.

Tree crown delineation

In a forest canopy seen at high spatial resolution (less than1 m/pixel), it is generally possible to isolate the crowns of the visible trees (sometimes of groups of trees), using the valleys of shade that usually separate them. These valleys of shade may be present on the ground, in the understory or in certain parts of the crowns (Gougeon 1995b).

The isolation process (ITCVFOL) (all references like ITCxxx correspond to the ITC Suite programs [Gougeon and Leckie 2003; Gougeon 2010]) begins with thresholding of the forest areas of the image to eliminate the large shaded areas. It then identifies the local minima (i.e., the darkest pixels of the shaded areas between the crowns) and, based on these points, it systematically follows the valleys of shade between the better-lit crowns. The result is a bitmap illustrating these valleys of shade, which clearly separate certain crowns, while others are only partially separated.

Next, crown separation continues using a rule-based algorithm (ITCISOL). Starting from a minimum area (2x2 pixels), which is not part of a valley of shade (therefore potentially part of a crown), it detects the valley of shade running to its left and therefore potentially a little of the perimeter of this crown. It then follows this perimeter, keeping crown material to its right, favouring clockwise movements. If after several movements of this kind, the algorithm returns to its starting position, a crown or group of crowns was delineated. This technique is applied to all the forest parts of the image, resulting in the delineation of millions of objects. Subsequently, more complex rules are applied in an effort to separate the objects that appear to correspond to more than one crown. Finally, after several iterations, a bitmap with all the crowns of the forest portion of the image is obtained and also, at the last iteration, the tree clusters that could not be separated.

Photo interpretation of the training and test areas

By interpreting aerial photographs and QuickBird images, 20 to 25 representative polygons (i.e., including many trees of the same species) were created for each vegetation class. Of these 20 or so polygons, half were used to create the spectral signature of the vegetation class (the training areas), while the other half (the test areas) were controls and were used to determine the percentage of classification accuracy at the end of the process. High purity in representation of the vegetation class must ne ensured. In fact, impurities (i.e., the trees of another species) affect the quality of the classification by introducing a bias in the calculation of the mean spectral value of a signature, which reduces accuracy.

Tree crown classification

For each image to be classified, the spectral signatures of each vegetation class are generated based on the training areas, which originate only from the image itself (i.e., without signatures from other images). For each tree crown (or tree cluster) in these areas, the signature generation process (ITCSSG) creates first a spectral signature of the crown based on the multispectral values of the pixels within this crown. Then, the average values of each crown are combined to create the spectral signature of the vegetation class. The spectral signature of a class therefore corresponds to the mean multispectral value of all the crowns that are located within the training areas and to the covariance between these crowns, and not between their pixels.

A significant variation of this technique (and almost always used) involves considering only the well-lit pixels of each crown, rather than all the pixels of the crown. Indeed, one of the advantages of crown delineation using the valleys of shade technique is generally to obtain more complete crowns, for example, with the shaded side of each crown. This facilitates estimation of the diameter at breast height (DBH) or the volume of each tree based on the area of each crown, but the presence of the shaded (dark) pixels adversely affects the classification process. The ITCMG process is therefore used; it creates a mask so that only the well-lit side of each crown is taken into account during signature creation and the classification of each crown.

The classification process itself (ITCSC) calculates the mean multispectral value of the pixels of each entity (tree or group of trees) in the image, and compares it with the signatures of all the vegetation classes. A vegetation class is assigned to an entity by applying the maximum likelihood rule, which is circumscribed by a confidence level.

Semi-automatic stand delineation

This step involves creating polygons corresponding to the forest stands present in each image by regrouping based on the classified tree crowns (see Figure 2 in Gougeon and Leckie 2003). The method used relies on the raster image of the isolated crowns and the raster images of the classified crowns, such as those created in the preceding steps. The groupings are generally based on stand density, canopy closure and, of course, species composition. It is also possible to incorporate stand height when this information is available (i.e., the canopy height model derived from LiDAR data or from automatic stereo-correlations). Only stem density was used in this project.

The STEMDENS module creates an image of stem density by reducing each crown to its centre of gravity and by counting the number of stems in a moving window of fixed size, which expresses the density in a given neighbourhood. The information on species composition results "indirectly" from the application of this process to each bitmap of the classified crowns, each bitmap representing a single species. Combining the resulting intermediate images using an automatic classification process (PCI/FUZCLUS) results in areas that closely match the forest stands (owing to their content). The user obtains a degree of control over the precision of the content by including more or fewer classes in the classification process. Some of these classes may also be grouped if the user or interpreter so wishes.

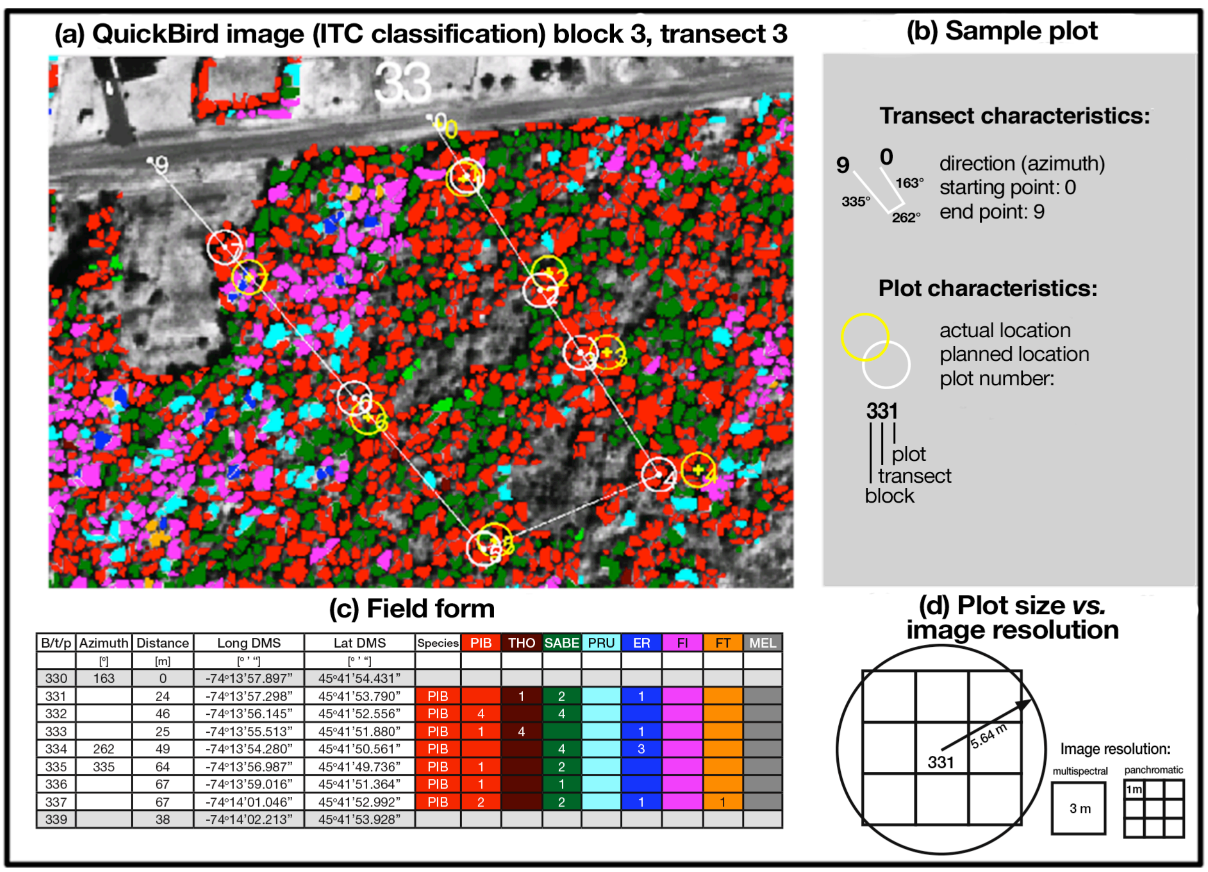
The groupings whose area is too small (less than 1 ha) are eliminated by merging them into the surrounding groupings (PCI/SIEVE), then the boundaries of the groupings are smoothed using a filter (PCI/FMO). The non-forest elements (lakes, rivers, roads, etc.) that were isolated and masked at the pre-processing step can then be reintroduced. The raster image of the groupings is then converted to polygons. Finally, this vector layer can be edited using a GIS to refine the delineation of the forest polygons.

Once these forest stand polygons are considered acceptable, fields summarising all the ITC forest information contained in each polygon (ITCPCD), such as the percentages of crown cover of each species, can be attached to them. In this study, comparing the results obtained from the ITC analysis process and the more conventional results from the interpretation of aerial photographs, the polygons of the stands of the current inventory (from the interpretation) as established by the MFFP will of course be used.

Techniques for verifying the results

a) Confusion matrices

One of the conventional techniques used in remote sensing to verify classification results is confusion matrices, which provide the count (or percentage) of trees of each species (or class) within test areas that are presumed to contain only a single species (or class). If these test areas are sufficiently representative, the percentage on the diagonal of the matrix corresponds to the probability that a crown of species A will be classified as "species A" in this image, the other percentages indicating the probability that it will be classified otherwise. These test areas were determined by photo interpretation at the same time as the training areas.



B/t/p	Azimuth	Distance	Long DMS	Lat DMS	Species	PIB	THO	SABE	PRU	ER	FI	FT	MEL
	[°]	[m]	[° ' "]	[° ' "]									
330	163	0	-74°13'57.897"	45°41'54.431"									
331		24	-74°13'57.298"	45°41'53.790"	PIB		1	2		1			
332		46	-74°13'56.145"	45°41'52.556"	PIB	4		4					
333		25	-74°13'55.513"	45°41'51.880"	PIB	1	4			1			
334	262	49	-74°13'54.280"	45°41'50.561"	PIB			4		3			
335	335	64	-74°13'56.987"	45°41'49.736"	PIB	1		2					
336		67	-74°13'59.016"	45°41'51.364"	PIB	1		1					
337		67	-74°14'01.046"	45°41'52.992"	PIB	2		2		1		1	
339		38	-74°14'02.213"	45°41'53.928"									

Figure 2. Characteristics of the DIF plot transects.

b) Verification done by the MFFP using transects of sample plots

Another technique for verifying the results of the ITC classification is to compare the species compositions generated in this manner with the stem counts of each species from transects or sample plots in the field. Such a verification was undertaken by the Direction des inventaires forestiers [Forest Inventory Branch] (DIF) of the MFFP. To increase the likelihood of targeting the right place, the DIF recommended locating these plots within the purest stands, insofar as possible. This was done for species such as spruce (EE), fir/spruce (SABE), maple (ER) and poplar (PEU), which form more homogeneous stands. For the other species, it was difficult to establish plots in pure stands.

Blocks were also selected by considering site access. Since each transect includes on average six circular plots (maximum eight) each with an area equivalent to one hundredth of a hectare (5.64-m radius), it is characterised by a starting point and an end point and by directions expressed in terms of azimuths as well as the travel distance between each plot; see Figure 2.

In L'Annonciation sector, five blocks were selected and sample plots laid out to have approximately 7 to 15 plots per stratum (Table 2). In Lachute, eight blocks were selected and then 17 transects were drawn. The distribution of the 94 plots by stratum and by block is provided in Table 3. For each plot, the coordinates of the centre were recorded and species identification and stem counts were carried out (Figure 2). In the case of mature stands, only stems more than 7 m high were taken into account.

c) Verification using blocks of sample plots

To minimise the potential effects of positioning errors, a second field verification was carried out. The degree of match was evaluated by comparing the percentage of crown cover of vegetation classes estimated with the ITC method with the percentage of crown cover obtained for temporary plots within 0.49-ha (i.e., 70-m by 70-m) blocks.

For each of the four plots with a fixed radius of 11.28 m within the 0.49-ha blocks, all the stems whose crown was "visible from a satellite" were counted and their DBH measured. This count made it possible to determine the basal area and, consequently, the percentage of this area for each vegetation class within each block.

The comparison prioritised the three most important groupings for each sector. Thus, in L'Annonciation sector, the ER, BJ and BOP groupings were visited, while in Lachute, it was the SABE, ER and R groupings. In each grouping visited, five 0.49-ha blocks (i.e., 70-m by 70-m) were delimited, within which four inventory plots were established. The ecoforestry map was used to spatialise the groupings, while the panchromatic image was used to locate the most homogeneous areas within these groupings.

d) Verification using continuous observation transects

In L'Annonciation, a third type of field verification was carried out. This test was based on the species composition from the transects producing a continuum of observations (i.e., without sample plots). This kind of transect could offer a better integration of spatial variability and make it possible to reduce positioning errors. To reduce the lack of accuracy related to positioning, the transects were established for large, homogeneous areas that exhibit distinct trends in terms of the ITC results. The length, orientation and position of the transects were determined visually, based on the ITC classification and the road network.

In the field, the starting point of each transect was determined by GPS (Global Positioning System). All the other points were determined using a compass and string box. Observation points were determined every 15 m along the transect. For each point, qualitative (visual) observations were carried out and recorded on forms prepared for this purpose. The area covered by each observation point incorporates the data between the point measured and the next point. The information collected tells us about the percentage of each species of the dominant and codominant strata, the density of each stratum and crown size.

e) Comparison with the conventional forest inventory

Another approach for verifying the results of the ITC image analysis is to compare the species compositions obtained in this manner with those of the conventional forest inventory, using the polygons of this inventory. Although this kind of comparison is often requested and may be helpful in understanding the relationship with the ITC method for forest managers who are accustomed to using the conventional inventory, this relies on the basic assumption that the conventional inventory accurately represents reality. Unfortunately, the little information that exists concerning the

Table 2. Distribution of the DIF plots in L'Annonciation sector.

Block	**Strata >7 m high**							
	PIB	**EE**	**THO**	**SABE**	**ER**	**PEU**	**BOP**	**BOJ**
1	2	3			3	12		
2	5			1	7	1		6
3		4	2	5			8	
4	3							
5			8	7			7	5
Total	**10**	**7**	**10**	**13**	**10**	**13**	**15**	**11**

Table 3. Distribution of the DIF plots in the Lachute sector.

Block	Strata >7 m high						
	PIB	THO	SABE	PRU	ER	FI	FT
1		1		2			
2	3		13	5	4	1	
3	12		1				
4			5				6
5		2	1				1
6		3	1	13	3		1
7			3		2	4	1
8	3		2				1
Total	**18**	**6**	**26**	**20**	**9**	**5**	**10**

Table 4. Confusion matrix for L'Annonciation sector.

			% of ITC classified for each class							
Class	ITC[a]	NC[b]	PIB	EE	THO	SAB	ER	PEU	BOP	BJ
PIB	393	2.8%	**60.1%**	7.9%	5.6%	14.5%	0.0%	0.8%	4.1%	4.3%
EE	633	4.3%	2.8%	**90.0%**	2.5%	0.3%	0.0%	0.0%	0.0%	0.0%
THO	573	2.4%	0.3%	18.2%	**76.3%**	2.4%	0.0%	0.0%	0.3%	0.0%
SAB	724	0.4%	6.4%	0.8%	13.4%	**76.7%**	0.0%	0.0%	2.2%	0.1%
ER	2332	1.6%	0.1%	0.0%	0.0%	0.0%	**85.2%**	1.3%	0.8%	11.0%
PEU	704	2.6%	0.0%	0.0%	0.6%	0.3%	0.4%	**82.0%**	8.2%	6.0%
BOP	503	5.2%	0.4%	0.0%	1.6%	2.4%	1.2%	10.7%	**69.6%**	8.9%
BJ	1046	2.2%	0.2%	0.0%	0.1%	0.3%	8.2%	5.4%	8.5%	**75.0%**

Note: See Table 1 for the vegetation classes.
[a]ITC: Number of ITC included in the test.
[b]NC: Percentage of ITC not classified.

accuracy of the provincial inventories is rather discouraging in this respect. In Quebec, the work carried out in connection with the Coulombe Commission Report (Bibliothèque nationale du Québec 2004, p. 106) appears to indicate a degree of match between photo interpretation and the reality in the field of about 64% (55% to 76%) for the main coniferous species, and 48% (40% to 53%) for the main deciduous species, for pure stands. The degree of match is often less than 20% for stands containing more than one species. Studies done in Ontario (Thompson et al. 2007) report incorrect species compositions (chi-square) of 64% in boreal forest stands compared with ground transects.

There are also a few problems intrinsic to this comparison. First, in an ecoforestry map, stand type is defined according to the "basal area" of the dominant species that comprise it, while with the ITC method, the dominance of a species is based on the "percentage of crown cover" of this species. The proportion of small-crowned conifers (e.g., black spruce) will therefore tend to be underestimated relative to the other species in the same stand. Second, a very small discrepancy in percentage can be sufficient to shift a stand from the EoR type (red maple/coniferous) to an REo type stand (coniferous/red maple), for example.

Results

a) Confusion matrices

Initially, we used independent training and test areas for each species, but ultimately we regrouped certain classes because it proved difficult to obtain sufficiently homogeneous spectral signatures to obtain a sufficiently accurate classification. For example, in the Lachute sector, we preferred to regroup the poplar and white birch classes under the intolerant hardwoods grouping and the beech and oak classes under the tolerant hardwoods grouping. These groupings made it possible to increase the accuracy of the new classes.

The classification results are generally very encouraging if we consider the accuracy rates obtained with the confusion matrices. Indeed, the accuracy obtained for each vegetation class ranges from 60% to 90% for L'Annonciation sector (Table 4). The same is true for the Lachute sector, where the accuracy varies between 74% and 89% (Table 5). With eight classes of mature trees, an accuracy of about 70% to 75% is considered very good and the confusion between species does not appear to indicate a major problem.

The confusion matrix is used to determine the distribution of accuracy following the classification step. Given the statistical nature of the classification process, it is normal to always obtain a certain amount of confusion between species. Hence, only the significant confusions (more than 10%) should be addressed. For example, for mature trees in L'Annonciation sector (Table 4), white pine has the lowest classification accuracy (60.1%) and appears to often be confused with spruce at the rate of 7.9% and cedar at the rate of 5.6%, but mainly with balsam fir at the rate of 14.5%. For mature trees in the Lachute sector (Table 5), white pine has a much higher classification accuracy (88.3%), the pattern of confusion with balsam fir being somewhat reversed (i.e., more firs classified as PIB and fewer PIB classified as fir), while there is less confusion with other species.

These possible confusions between species predicted by the ITC analysis process will be considered during comparison with the data collected in the field or with the conventional inventory.

b) Verification by the MFFP using transects of sample plots

The data collected in the field by MFFP personnel, using a predetermined form (Figure 2), were compiled and organised to calculate confusion matrices that translate the degree of match between the classification and the reference in the field.

For L'Annonciation sector, the classification results may be encouraging if we consider the degree of accuracy in classifying stands by species, such as spruce (EE), fir/spruce (SABE), maple (ER) and poplar (PEU), which form more homogeneous stands. In fact, the accuracy obtained for each of these vegetation classes ranges from 71.2% to 92.2% (Table 6).

The low average accuracy of 47.8% can be explained by the poor match between the classification and the reference for white pine (0%) and cedar (3.4%). When these two species are excluded from the analysis, the average accuracy of the classification increases from 47.8% to 63.1%. A very low accuracy rate is observed for white birch (17.5%), and a fairly low rate (32.8%) for yellow birch.

For the Lachute sector, apart from fir, maple and white pine, for which the accuracy rate is 69.2%, 57.5% and 52.8%, respectively, the accuracy of the other classes is quite low and ranges from 21.6% to 48.5% (Table 7). White pine (52.8%) and cedar (48.5%) are more accurately classified in this sector compared to L'Annonciation sector.

c) Verification using blocks of sample plots

Here, the degree of match was evaluated by comparing the percentage of crown cover of the vegetation classes estimated using the ITC method with the percentage of crown cover of the vegetation classes obtained from sample plots in the 70-m by 70-m (0.49-ha) blocks. In L'Annonciation sector, for example, only the groupings designated ER, BJ and BB were visited. The dominant tree species (ER, BJ and BB [white birch]) can therefore be compared with/without some associated species. Since the detailed results of this comparison take up 46 pages of the main report (CSRE-Forêt and CLCCamint 2003), we will simply review the highlights.

In L'Annonciation sector, maple is underestimated when it is the main species (54% *vs.* 76% in the field) and also when it is a secondary species (by 11% in the BJ blocks and 16% in the BB blocks). Yellow birch (BJ) is very near the mark when it is the main species (47% *vs.* 48% in the field), but overestimated when it is the secondary species (by 24% in the BB blocks and 14% in the ER blocks). White birch is underestimated in its area (16% *vs.* 28% in the field), and overestimated (by 18%) in yellow birch areas, where it is absent on the ground. This probably indicates spectral confusion between the two birch species. In both cases (ITC or field), the blocks designated "white birch" do not even appear to merit this designation (with 16% and 28% cover).

In the Lachute sector, where the SAB, ER and R groupings were visited, maple is slightly overestimated by the ITC when it is the main species (60% *vs.* 55% in the field), but underestimated in the SAB blocks (8% *vs.* 28% in the field) and R blocks (2% *vs.* 26% in the field). In the blocks designated conifer-dominated, which are composed of white pines, spruces, cedars, firs, hemlocks, maples,

Table 5. Confusion matrix for the Lachute sector.

			% of ITC classified for each class							
Class	**ITC[a]**	**NC[b]**	**PIB**	**EE**	**THO**	**SAB**	**PRU**	**ER**	**FI**	**FT**
PIB	496	4.8%	**88.3%**	0.2%	0.2%	6.5%	0.0%	0.0%	0.0%	0.0%
EE	425	4.9%	1.2%	**85.6%**	4.9%	0.7%	2.6%	0.0%	0.0%	0.0%
THO	692	2.0%	2.0%	11.4%	**74.0%**	9.1%	1.4%	0.0%	0.0%	0.0%
SAB	324	0.3%	10.8%	0.9%	3.7%	**82.4%**	1.5%	0.0%	0.3%	0.0%
PRU	399	3.3%	5.3%	1.3%	2.0%	4.5%	**77.2%**	3.3%	1.5%	1.8%
ER	815	3.7%	0.0%	0.0%	0.0%	0.0%	0.1%	**89.4%**	0.5%	6.3%
FI	308	1.0%	3.6%	0.0%	0.3%	0.6%	2.9%	3.2%	**84.7%**	3.6%
FT	1119	3.8%	0.1%	0.1%	0.1%	0.1%	1.9%	12.1%	1.5%	**80.4%**

Note: See Table 1 for the vegetation classes.
[a]ITC: Number of ITC included in the test.
[b]NC: Percentage of ITC not classified.

intolerant hardwoods and tolerant hardwoods, the ITC method yields the following percentages: 28%, 1%, 4%, 35%, 19%, 2%, 9% and 0%, respectively, while field sampling yielded 9%, 18%, 33%, 4%, 5%, 26%, 5% and 0%. The ITC method appears to overestimate pine, fir and hemlock, and underestimate spruce and cedar. The presence of maples is also significantly underestimated. For instance, in the blocks designated fir-dominant in the forest inventory, the ITC method yields the following percentages: 13%, 4%, 10%, 15%, 18%, 8%, 19% and 7%, respectively, while field sampling yielded 4%, 6%, 5%, 2%, 39%, 27%, 10% and 7%. In both cases (ITC or field), these blocks do not even appear to merit their designation as fir stands (with 15% and 2%).

d) Verification using continuous observation transects

Field verification was carried out using transects established in sectors exhibiting distinct trends in terms of the ITC results. This made it possible to verify the species composition derived from the ITC classification compared with that obtained in the field. The results were presented graphically to facilitate qualitative analysis of the differences.

Observations made at each observation point were compiled for each transect. After transposing the transects and the observation points on the image, the ITC-derived species composition around each observation point was summarised similarly (CSRE-Forêt and CLC-Camint 2003). The results were presented graphically to be interpreted for the 26 transects and only a few general considerations were highlighted.

As a rule, the density of a species appears to be more decisive than its hierarchical position in the forest cover. Indeed, the species captured using the ITC method are characterised by a high density in the field, regardless of whether they are part of the dominant or codominant stratum. Apparently, the ITC method overestimated PIB and THO to the detriment of EE, BOP to the detriment of BJ and BJ to the detriment of ER.

e) Comparison with the conventional forest inventory

Finally, to demonstrate the potential of the ITC method for the identification and mapping of forest stands, the results of the ITC classification will be compared with the MFFP's ecoforestry map, produced using the conventional photo interpretation method and the nomenclature in effect at the time (Bérard 1996). Obviously, in this comparison, the polygons of the ecoforestry map will be used and not those generated semi-automatically using the ITC method. Although the ITC classification uses abbreviations such as ER and BJ (in upper case), when this information is summarised at the stand level, we use the nomenclature of the ecoforestry map, namely Er, Bj, ErBj, etc., to compare the dominant classes of the ITC with those of the map.

Table 6. Confusion matrix for the DIF field verifications for L'Annonciation sector.

	Number	PIB	EE	THO	SABE	ER	PEU	BOP	BOJ
PIB	27	**0**	18.5	25.9	18.5	0	18.5	3.7	3.7
EE	77	0	**92.2**	0	3.9	0	0	3.9	0
THO	119	0	5	**3.4**	82.4	0	1.7	3.4	4.2
SAB	96	1	2.1	2.1	**87.5**	1	1	2.1	3.1
ER	49	0	0	0	0	**77.6**	2	4.1	10.2
PEU	156	0	0	0	2.6	15.4	**71.2**	7.1	3.2
BOP	126	0	0	0.8	50.0	5.6	12.7	**17.5**	13.5
BJ	67	0	0	0	11.9	37.3	11.9	4.5	**32.8**

Average accuracy = **47.76%**.
Overall accuracy = **49.09%**.

Table 7. Confusion matrix for the DIF field verifications for the Lachute sector.

	Number	PIB	THO	SABE	PRU	ER	FI	FT	EE
PIB	108	**52.8**	29.6	13.0	0.9	2.8	0	0.9	0
THO	66	0	**48.5**	9.1	12.1	6.1	0	12.1	12.1
SAB	250	2.4	13.6	**69.2**	2.4	8.0	2.0	1.2	0.8
PRU	172	0	22.1	8.1	**30.8**	21.5	4.7	7.0	5.8
ER	66	0	1.5	10.6	6.1	**57.5**	1.5	22.7	0
FI	35	2.9	0	22.9	2.9	25.7	**40.0**	5.7	0
FT	74	0	4.1	2.7	8.1	58.1	4.1	**21.6**	1.4

Average accuracy = **45.78%**.
Overall accuracy = **49.68%**.

To fully appreciate this comparison, it is important to consider that species composition, and therefore the type of stands in an ecoforestry map, is defined based on the “basal area” of the dominant species, while with the ITC method, the dominance of a species is based on the “percentage of crown cover”. There will therefore be differences in the estimation of the relative proportions of each species, and therefore in the potential stand designation. Indeed, for an identical DBH, the size of the crown of a coniferous tree will be smaller than that of a deciduous tree, which will affect the proportions mainly in mixed stands as the proportion of coniferous trees will typically be underestimated in such stands.

In addition, although this comparison has been made using the conventional forest inventory as a “reference”, it is very important to remember that this method also has precision and accuracy problems, as pointed out earlier.

L’Annonciation sector

In the stands designated Er in L’Annonciation sector, which correspond to areas where deciduous trees constitute more than 75% of the basal area and sugar maple more than 66% of the deciduous trees, 66% of these polygons were identified as Er with the ITC method, according to the dominant species, in this case ER (Tables 1 and 8). However, in these 98 polygons, the average crown cover of sugar maples accounted for only 57% (σ=12 [standard deviation]) of the deciduous trees.

The groupings of the first two species designated by the ITC method gave the following results: 66% ErBj, 31% BjEr and 3% BjBb. If we rely on the conventional inventory, there is possibly a certain amount of spectral confusion between maple and yellow birch, which appears to favour the dominance of yellow birch in 31% of cases. This trend, which was also observed in a previous study (Gougeon et al. 2001), could also explain why maple does not always constitute more than 66% of the deciduous trees (in this case 57%), even when it appears to be the first species according to the ITC method.

Despite this, judging solely by the dominant species obtained with the ITC method, we could consider that there is a better than 66% match between the ITC method and the ecoforestry map for the stands designated Er.

In the stands designated Bj, corresponding to areas where deciduous trees constitute more than 75% of the basal area and yellow birch more than 50% of the deciduous trees, 79% of these polygons were classified as Bj according to the dominant species using the ITC method (BJ), 12% Bb, 6% Er and 3% SaB (Table 8). For the polygons comprising mainly yellow birch, the average crown cover accounted for 51% (σ=6) of the deciduous trees.

In the stands designated ErBj, corresponding to areas where deciduous trees constitute more than 75% of the basal area, with maple representing 33% to 66% of the deciduous trees, and yellow birch 33% to 50%, the results of the ITC analysis indicate that only 32% of these polygons would be identified as ErBj. However, 47% would be BjEr, the other main group being BjBb at 19% (Table 8). The combinations of ErBj and BjEr alone represent 79% of cases. We can therefore imagine that it would not take very much spectral confusion to blur the slight distinction between ErBj and BjEr.

When ER dominates the polygons, the average ER crown cover accounts for 53% of that of the deciduous trees (σ=11). The average crown cover of deciduous trees by stand is 84% (σ=10).

In the stands designated EE, corresponding to areas where conifers constitute more than 75% of the basal area and spruce more than 75% of the conifers, the ITC method identified spruce as the first species in 88% of cases. However, the proportion of conifers assigned to spruce is on average only 53% (σ=12), while it should be more than 75%. This is likely attributable to the difference between an estimate based on the basal area and one based on crown cover, spruce (especially black spruce) being the species that generally has the smallest crown among the conifers.

In the stands designated SS, corresponding to areas where conifers constitute more than 75% of the basal area and fir more than 75% of the conifers, the ITC method identifies fir as the first species in only 50% of the polygons (Table 8), and the proportion of conifers assigned to fir is on average only 61% (σ=7). In the other 50% of cases, the first species is white pine (20%), cedar (20%) and spruce (10%). However in these cases, fir is the second species, in 80% of cases. White pine and cedar may be overestimated, since these species often have very wide spectral signatures.

In the stands designated ES, corresponding to areas where conifers constitute more than 75% of the basal area and spruce 50% to 74% of the conifers, with fir as the second species, the ITC method identifies spruce as the first species in 61% (23%+38%) of cases, with fir dominant in the other cases (15%). In the polygons where spruce is dominant, fir is the second species in only one third (23/61) of cases, the majority having white pine (62% [38/61]) and a few other polygons cedar (10%). White pine and cedar, with their very wide spectral signatures, again appear to be overrepresented. In addition, well-lit white spruce and fir are often classified as white pines (Gougeon et al. 2001).

In mixed stands of the Bj+R type, where deciduous trees must make up 50% to 74% of the basal area and yellow birch more than half of the deciduous trees and 51% to 74% of the stand, while conifers comprise 26% to 49% of the stand, the ITC method identifies BJ as the first species in 65% of cases, followed by BOP in 26% of cases. In the majority of cases, the second species is another deciduous species, which reinforces their dominance of the stand. The average crown cover of deciduous trees in each stand is 62% (σ=16). With respect to the contribution of conifers, it is necessary to consider the second, third or fourth species, depending on the situation. Accordingly, birch (BJ or BOP) is found to be associated with conifers in 83 forest polygons, that is, in 84% of cases.

I**n mixed stands of the Bj-R type,** where deciduous trees must make up 50% to 74% of the basal area and yellow birch more than half of the deciduous trees and 26% to 50% of the stand, while conifers comprise 26% to 49% of the stand, the ITC method identifies BJ as the first species in 85% of cases, followed by ER in 6% of cases. In the majority of cases, the second species is still another deciduous species. With respect to the contribution of conifers, it is necessary to consider the second, third or fourth species, depending on the situation. Accordingly, birch (BJ or BOP) is found to be associated with conifers in 28 polygons, that is, in 82% of cases.

In mixed stands of the Bb1S type, where deciduous trees must make up 50% to 74% of the basal area, white birch 51% to 75% of the deciduous trees and spruce or fir more than half of the conifers, the ITC method identifies white birch as the first species in 49% of cases. Even after grouping the two types of birch (as Bs: 79% of cases) and combining fir and spruce under the nomenclature 1S, the Bs1S combination is obtained in only 38% of cases.

Lachute sector

In the stands designated Er in the Lachute sector, corresponding to areas where deciduous trees constitute more than 75% of the basal area and maple more than 66% of the deciduous trees, 96%

Table 8. Comparison with the conventional forest inventory for L'Annonciation sector.

	Designation	No. polygons	FOREST TYPE		FOREST GROUPING		Results of ITC method[b]			
			Ecoforestry standard	ITC[a]	Ecoforestry standard	ITC[a]				
Deciduous	Er	148	Deciduous trees >75% of the stand	87% (8)	Er >66% of the deciduous trees	57% (12)	Er 66%	Bj 34%		
Deciduous	Bj	34	Deciduous trees >75% of the stand	78% (15)	Bj >50% of the deciduous trees	51% (6)	Bj 79%	Bb 12%		
Deciduous	ErBj	183	Deciduous trees >75% of the stand	84% (10)	Er 33–66% of the deciduous trees	53% (11)	ErBj 32%	BjEr 47%	BjBb 19%	
					Bj 33–50% of the deciduous trees	49% (21)				
Coniferous	EE	33	Conifers >75% of the stand	85% (9)	E >75% of the conifers	53% (12)	EE 88%			
Coniferous	SS	10	Conifers >75% of the stand	76% (10)	S >75% of the conifers	61% (7)	SaB 50%	Pb 20%	THO 20%	
Coniferous	ES	13	Conifers >75% of the stand	81% (9)	E 50–74% of the conifers	50% (8)	ESaB 23%	EPb 38%	SaBE 15%	
					S second species	16% (9)				
Mixed (F)	Bj+R	106	Deciduous trees	62% (16)	Bj >50% of the deciduous trees	49% (5)	BjSaB 8%	BJBb 37%	BbBj 15%	BjEr 13%
					Bj >51–74% of the stand	33% (6)				
					R 26–49%	27% (14)				
Mixed (F)	Bj-R	34	Deciduous trees 50%–74% of the stand	59% (19)	Bj >50% of the deciduous trees	51% (6)	BjSaB 12%	BjBb 47%	BjEr 15%	
					Bj >26–50% of the stand	33% (7)				
					R 26–49%	27% (14)				
Mixed (F)	Bb1S	32	Deciduous trees 50%–74% of the stand	49% (20)	Bb 51–75% of the deciduous trees	49% (9)	Bs1S 38%	BsEr 22%	BsPeu 19%	
					SaB+E >50 % R	52% (11)				

Good match of forest type

Good match of forest grouping

Borderline match

[a] The value in parentheses indicates the variance.

[b] Percentage of the polygons of the conventional inventory where this species is dominant in the ITC classification. Only the results greater than 10% for species other than the target species are shown. Hence, some discussions of the results occasionally refer to more specific percentages.

of these polygons were classified as Er using the ITC method (Table 9). This high percentage appears to indicate excellent discrimination of maples with the ITC method. However, the average crown cover of ER among the deciduous trees is a little low, that is, 60% (σ=11). Therefore, a little spectral confusion exists with the other deciduous trees.

In the stands designated Eo, corresponding to areas where deciduous trees constitute more than 75% of the basal area and red maple more than 50% of the deciduous trees, 86% of the polygons were identified as Er, based on the predominant species according to the ITC method (ER). The Eo grouping was compared with the Er species, since during our analysis, all maples were combined into a single class owing to the problems of spectral discrimination that they presented. This high percentage indicates excellent discrimination of maples with the ITC method, but it is difficult to differentiate red maple from sugar maple using the QuickBird data.

In the stands designated ErFt, corresponding to areas where deciduous trees constitute more than 75% of the basal area, maple 33% to 66% of the deciduous trees, and tolerant hardwoods 33% to 50% of the deciduous trees, 62% of the polygons were classified as ErFt with the ITC method. In addition, 17% of the polygons were classified as ErFi and 7% as FtEr. The average crown cover of maple where it is dominant is 57% (σ=9) of the deciduous trees, and the other tolerant hardwoods (Ft) 32% (σ=8) of the deciduous trees. Good discrimination of the ErFt grouping is therefore achieved with the ITC method.

In the stands designated EoR, corresponding to areas where deciduous trees constitute 50% to 74% of the basal area, red maple more than 50% of the deciduous trees, and conifers 26% to 49% of the stand, 67% of the polygons are dominated by maple (Table 9). For these polygons, the average crown cover of ER among the deciduous trees is 59% (σ=13) and conifers occupy 34% (σ=17) of the stand.

In the majority of cases, the second species is another deciduous species, which reinforces their dominance of the stand. With respect to the contribution of conifers, it is necessary to consider the second, third or fourth species, depending on the situation. Accordingly, maples are found to be accompanied by conifers in 85 polygons, that is, in 55% of cases.

In the stands designated REo, corresponding to areas where conifers constitute 50% to 74% of the basal area and red maple more than 50% of the deciduous trees, examining the list of the main, and even secondary, species provides little information. It is necessary to first regroup the conifers under the R heading and then consider the deciduous trees. Accordingly, 50% of the polygons would be classified as RFi, 16% as REr and 7% as RFt, which indicates spectral confusion between ER and FI. However, conifers are clearly dominant in 73% of the polygons.

The average coniferous crown cover by stand is 51% (σ= 16) which is barely higher than the average deciduous crown cover, that is, 46% (σ=16); however, one must consider the aforementioned basal area to crown cover aspect.

In the stands designated FtR, corresponding to areas where deciduous trees constitute 50% to 74% of the basal area, tolerant hardwoods constitute more than 50% of the deciduous trees, and conifers 26% to 49% of the basal area, examining the list of the main, and even secondary species, provides little information. They first must be regrouped. Since the Ft designation includes the ER species, maple was combined with tolerant hardwoods (FT) under the Ft heading, and all the conifers were regrouped under the R heading, which yields new combinations, not found in Table 9.

Nonetheless, the FtR combination appears in only 24% of cases, and it is the FtFi combination that is dominant (59% of cases). However, this combination is accompanied by conifers in 100% of cases, which indicates simply that there is considerable confusion between the classes of tolerant and intolerant hardwoods.

In the stands designated PbPb, corresponding to areas where conifers constitute more than 75% of the basal area and white pine more than 75% of these conifers, only 50% of the polygons were classified as Pb with the ITC method and, in these polygons, PIB comprises only 58% (σ=8) of the conifers. In 39% of cases, SAB dominates these polygons. However, when SAB is the first species, it is accompanied by PIB in 86% of cases. Moreover, when PIB is the first species, it is accompanied by SAB in 100% of cases. Here, the ITC analysis appears to have difficulty separating white pine from fir.

Discussion

a) Confusion matrices

The use of confusion matrices is the conventional approach for determining precision or accuracy in remote sensing. Here, we mainly use the term “precision”, reserving the term “accuracy” for comparisons in the field. This classification precision is quantified by using areas considered pure by an interpreter, that is, that essentially consist of only a single species. A classification with results of about 70% to 75% for eight classes is typically deemed very good. Our matrices therefore provide good results, and confusion between the species does not appear to be a major problem (Tables 4 and 5).

b) Verification using transects of MFFP sample plots Verification done by the MFFP using transects of sample plots

The results obtained with the transects of sample plots are more mixed. For example, in the most homogeneous stands of L’Annonciation sector, accuracy is greater than 70%, while it is much lower in the others. Certain species seen in the field, such as white pine or cedar, do not even appear to be present in the classification process (Table 6).

In the Lachute sector, the results are better distributed (Table 7), white pine and cedar having a detection rate similar to the other species, but species recognition appears to be quite low.

It is possible, and even probable, that this phenomenon is due to three overlapping factors: a) the use of plots with a radius of 5.64 m entails a substantial potential for positioning errors; b) these small plots typically contain only about 10 trees and only 4 or 5 individual crowns; and c) all the stems more than 7 m high are listed, regardless of their visibility from the air (e.g., in the satellite image).

In addition, the Coulombe Commission Report (Bibliothèque nationale du Québec 2004) points out that conventional plots are not very useful for verifying the composition of the stands in an inventory. They are useful mainly for calculating the volume by stratification.

c) Verification using blocks of sample plots

The purpose of this verification using 70-m x 70-m blocks, considering only the trees potentially visible from the air, was to avoid the shortcomings related to approach b (above). Maple appears to be underestimated in L'Annonciation sector, whether it is the main or secondary species, while in the Lachute sector, it is overestimated as the main species and underestimated as a secondary species. In l'Annonciation, yellow birch is close to the mark as the main species, but overestimated as a secondary species. These overestimations and underestimations are about 20%.

However, we also found that, on a few occasions, whether the individual crown count (ITC) or the field counts were used, certain blocks do not even appear to attain the percentage that would justify official designation of the stand in which they are located. This could indicate that even 70-m x 70-m blocks are not sufficiently representative.

d) Verification using continuous observation transects

A third type of field verification of the ITC classifications was undertaken by creating long transects where the species composition was noted at several stopping points along these transects. In this exercise, the transects were established in sectors exhibiting distinct trends in the ITC results rather than in the MFFP's inventory.

Table 9. Comparison with the conventional forest inventory for the Lachute sector.

Forest type	Designation	No. polygons	FOREST TYPE: Ecoforestry standard	FOREST TYPE: ITC[a]	FOREST GROUPING: Ecoforestry standard	FOREST GROUPING: ITC[a]	Results of ITC method[b]			
Deciduous	Er	94	Deciduous trees >75% of the stand	80% (11)	Er >66% of the deciduous trees	60% (11)	Er 96%			
Deciduous	Eo	104	Deciduous trees >75% of the stand	76% (16)	Eo >50% of the deciduous trees	58% (12)	Er 86%			
Deciduous	ErFt	116	Deciduous trees >75% of the stand	80% (11)	Er 33%–66% of the deciduous trees	57% (9)	ErFt 62%	ErFi 17%	FtEr 7%	
					Ft 33%–50% of the deciduous trees	32% (8)				
Mixed (F)	EoR	154	Deciduous trees 50%–74% of the stand	63% (17)	Eo >50% of the deciduous trees	59% (13)	ErPu 8%	ErFt 33%	ErFi 26%	FiEr 17%
					R 26%–49% of the stand	34% (17)				
Mixed (R)	REo	68	Conifers 50%–74% of the stand	51% (16)	Eo >50% of the deciduous trees	59% (15)	SaBP 13%	PbFi 10%	FiEr 10%	
Mixed (F)	FtR	34	Deciduous trees 50%–74% of the stand	62% (15)	Ft >50% of the deciduous trees	51% (16)	ErPu 21%	ErFt 21%	FiEr 18%	ErFi 12%
					R 26%–49% of the stand	35% (14)				
Coniferous	PbPb	18	Conifers >75% of the stand	79% (11)	Pb >75% of the conifers	58% (8)	Pb 50%	SaB 39%		

Good match of the forest type

Good match of the forest grouping

Borderline match

[a] The value in parentheses indicates the variance.

[b] Percentage of the polygons of the conventional inventory where this species is dominant in the ITC classification. Only the results greater than 10% for species other than the target species are shown. Hence, some discussions of the results occasionally refer to more specific percentages.

The results presented graphically (CSRE-Forêt and CLC-Camint 2003) allow the differences to be analysed only "qualitatively," with the hope that the observation points are located in approximately the same place in the field and on the image, which is probably more or less the case. For each transect, a few observations were made concerning the underestimation or overestimation of certain species, but these are only very local findings. Some more general characteristics emerge, such as the overestimation of white pine and cedar at the expense of spruce, and the overestimation of white birch at the expense of yellow birch, and of yellow birch at the expense of maple.

Although these findings may potentially help guide us when producing a new classification using the ITC method, they are not useful for quantifying the accuracy of such a classification. In another study (Leckie et al. 2003b), transects were used to quantify the accuracy of the classification by noting the species of all trees at a distance of 1 m to the right and to the left of the transect line continuously, and then comparing the species composition thus obtained with that obtained using the ITC method for the stand in which it was located. The presence of the main species in a given stand was within 10% of the field count and the secondary species representing more than 25% of the stand were within 15% of the field count. However, these were much simpler stands, originally even-aged plantations.

e) Comparison with the conventional forest inventory

If, allowing ourselves a little latitude, we summarise in the simplest way the comparison of the results of the ITC method with the conventional forest inventory for L'Annonciation sector, the degree of match for the stands designated Er, Bj, ErBj, EE, SS, ES, Bj+R, Bj-R and Bb1S is 66%, 79%, 79%, 88%, 50%, 69%, 65%, 85% and 68%, respectively, based essentially on the dominant species established in the ITC classification (Table 8).

In the Lachute sector (Table 9), this comparison yields good results in some cases and poorer results in others. Firstly, the degree of match for the stands designated Er, Eo and ErFt is 96%, 86% and 62%, respectively. Secondly, the stands designated EoR, REo and FtR present more complex situations to analyse. In the stands designated EoR, maple dominates 56% of the polygons, but conifers are associated with maple in only 55% of these cases. In the stands designated REo, conifers are clearly dominant in 73% of the polygons, but these polygons would be classified as RFi, REr and RFt in 50%, 16% and 7% of cases, respectively. In the stands designated FtR, the FtR combination itself appears in only 24% of cases. It is the FtFi combination that is dominant (59% of cases), but this combination is accompanied by conifers in 100% of cases. These last two results indicate that there is substantial confusion between the classes of tolerant hardwoods, intolerant hardwoods and maple.

Finally, in the stands designated PbPb, only 50% of the polygons would be recognised as Pb by the ITC method, followed by 39% as SaB. But when SAB constitutes the first species, it is accompanied by white pine in 86% of cases, and when PIB is the first species, it is accompanied by SAB in 100% of cases. Therefore, a significant degree of confusion exists between these two species. This confusion was observed in the confusion matrices (Tables 4 and 5), but did not appear to be as significant.

Despite the many shortcomings of this kind in the comparisons, if we re-examine all the results by allowing ±10% for interpretation errors and ±10% for classification errors with the ITC method or for the difference between the percentages of basal area compared with the percentages of crown cover, the degree of match between the conventional inventory and the ITC inventory is nonetheless fairly impressive.

After reviewing all the results obtained for each stand, the following conclusions can be drawn:

- For the 16 types of stands analysed, except for Bb1S, all the stands meet the percentage defined in the ecoforestry standard with respect to the definition of forest types.
- At the forest grouping level, the percentages obtained with the ITC method generally closely match those defined in the ecoforestry standard, although the values correspond more to the lower limits of the classes. This situation is undoubtedly due to the fact that, during crown delimitation using the ITC method, the interstices between the crowns constitute unclassified areas, which are excluded from the cover calculations. Therefore, considering these areas should increase the percentage of crown cover of each species, which would bring them closer to the central values of each class.
- At the species grouping level, the degree of match is good for the deciduous and coniferous stands composed of a single species, such as the Er, Eo, Bj and EE classes, as well as for a few stands composed of more than one species, such as ErBj and ErFt. Generally, the degree of match was found to be lower for mixed deciduous stands and mixed coniferous stands, such as the Bj+R, Bj-R, Bb1S, FtR, EoR and REo classes. As already mentioned, the lower degree of match observed in mixed coniferous stands and mixed deciduous stands is partly explained by the measurement parameter used. Indeed, when estimating the basal area of conifers, the photo interpreter applies a correction factor to estimate the coniferous basal area from the crown area, while the proportion of conifers obtained with the ITC method takes only the crown area into account.
- The analysis of the different species groupings also identified the presence of spectral confusion between certain species, particularly BOP and BJ, at least with the QuickBird images used. In addition, tests combining BOP and BJ yielded results closer to those of the ecoforestry map. Also, for conifers, it was found that PIB was generally overestimated.
- The lack of a perfect match between the ITC method and the ecoforestry map is explained partly by the spectral confusion between certain species, in certain specific cases. The ER and BJ species of the Er, Bj and ErBj stands provide a good example. For the Er stands, a certain amount of confusion is evident between the crowns classified as ER and those classified as BJ, while there is no such confusion for the Bj stands. Hence, BJ is overestimated at the expense of maple, a pattern also seen in the ErBj stands, which are more often classified as BjEr than ErBj.

- However, spectral confusion cannot be the only cause of the observed differences, and it appears that the measurement parameter used also plays a role. Indeed, on numerous occasions, in mixed coniferous stands and mixed deciduous stands, conifers are ranked third and fourth instead of first or second. However, since the rank assigned by the ITC method is based on the percentage of crown cover, and since this method, in comparison with the measurement of basal area, underestimates the proportion of conifers, this could explain the more significant difference observed between the ITC method and the ecoforestry map for mixed groupings.

Conclusion

In this document, we summarise one of the main aspects of a pilot project involving Quebec forests (CSRE-Forêt and CLC-Camint 2003): the results of the application of a semi-automatic inventory technique called the individual tree crown (ITC) method. This study, focusing mainly on species recognition, was carried out in several ways: first, by using test areas based on the images, then, by conducting several types of field verifications, but mainly, by comparing species compositions at the forest polygon level with the conventional Quebec inventory for the period.

QuickBird images were acquired for two regions in the Laurentians. After pre-processing, the tree crowns were delineated on the panchromatic images and classified by species using multispectral images. The confusion matrices indicate good species classification. In fact, the precision obtained for each vegetation class ranged from 60% to 90% in L'Annonciation sector and from 74% to 89% in the Lachute sector.

This study also demonstrated that it can be difficult to verify the accuracy of the ITC classifications by comparing them with field data. Field verification using plots, transects and even large blocks (70 m x 70 m) can easily become single tree pseudo-tests, and therefore become heavily dependent on very good geographic positioning. In addition, for a good comparison, it is necessary to consider only the trees that are visible from a satellite. There are no conclusive results concerning plots, blocks or transects in the field, other than the finding that such comparisons are extremely difficult. For research purposes, we can carry out ITC verifications with great care (Leckie et al. 2005), but this is not practical for large areas.

The trees were also regrouped according to the forest stand polygons of the existing conventional inventory to compare the species composition. In L'Annonciation sector, the stands designated Er, Bj, ErBj, EE, SS, ES, Bj+R, Bj-R and Bb1S were assigned to the same class in 66%, 79%, 79%, 88%, 50%, 69%, 65%, 85% and 68% of the cases, respectively. In the Lachute sector, the stands designated Er, Eo and ErFt were assigned to the same class in 96%, 86% and 62% of cases, respectively. Other results showed a poorer match. For example, a substantial amount of confusion exists between the PIB and SAB classes, and PIB is generally overestimated. Perhaps the introduction of parameters such as crown size or shape would allow superior discrimination.

With the ITC method, the stand level forest information is likely to be just as (if not more) representative of reality as the conventional method (Potvin et al. 1999; Pinto et al. 2007), and we would have information on the geographic dispersion of each species within each stand. Rather than interpreting entire forests, photo interpreters would only have to identify sampling areas for each species (and possibly also a few specific situations for certain species) to initiate the classification process, and identify other areas to verify the results, with a feedback process to ensure the quality of the product.

Although this is called an individual tree crown (ITC) inventory, we are still quite far from attaining this level of precision in reality. Regardless of the spatial resolution, there will always be tree clusters that are difficult to separate. In addition, this will always be only an inventory of trees visible from the air (mainly the dominant and codominant trees). Over the years, it has become clear that, although factors such as the type of sensor (aerial or satellite), spatial resolution (if fairly close to 50 cm/pixel) and the classification process (maximum likelihood *vs.* neural networks) have some importance, they have less importance than the number of species or species in specific situations (i.e., the number of classes) to recognise.

Since ITC techniques are still quite experimental (Leckie et al. 2016a–c), few large-scale studies have been done (Chubey et al. 2009). For example, our most recent studies analysed 18 species at a 228-km^2 Ontario site using multispectral aerial images of 40 cm/pixel (Leckie et al. 2017). These data will be used for other comparisons of species composition with the conventional inventory, but by 10% segments. In addition, incorporating information from LiDAR data or from automated stereo-correlations to produce canopy height models (White et al. 2013) will make it possible to estimate tree-based volume at the stand level, using average values for each species. In the near future, calculation of forest yield on an individual tree basis (volume, biomass, carbon) could provide much more precise information than all the current systems (Bernier et al. 2010). In the longer term, ITC information could perhaps allow us to completely abandon the concept of the forest stand and manage the resource at the individual tree level.

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