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Pacific Forestry Centre • Victoria, British Columbia

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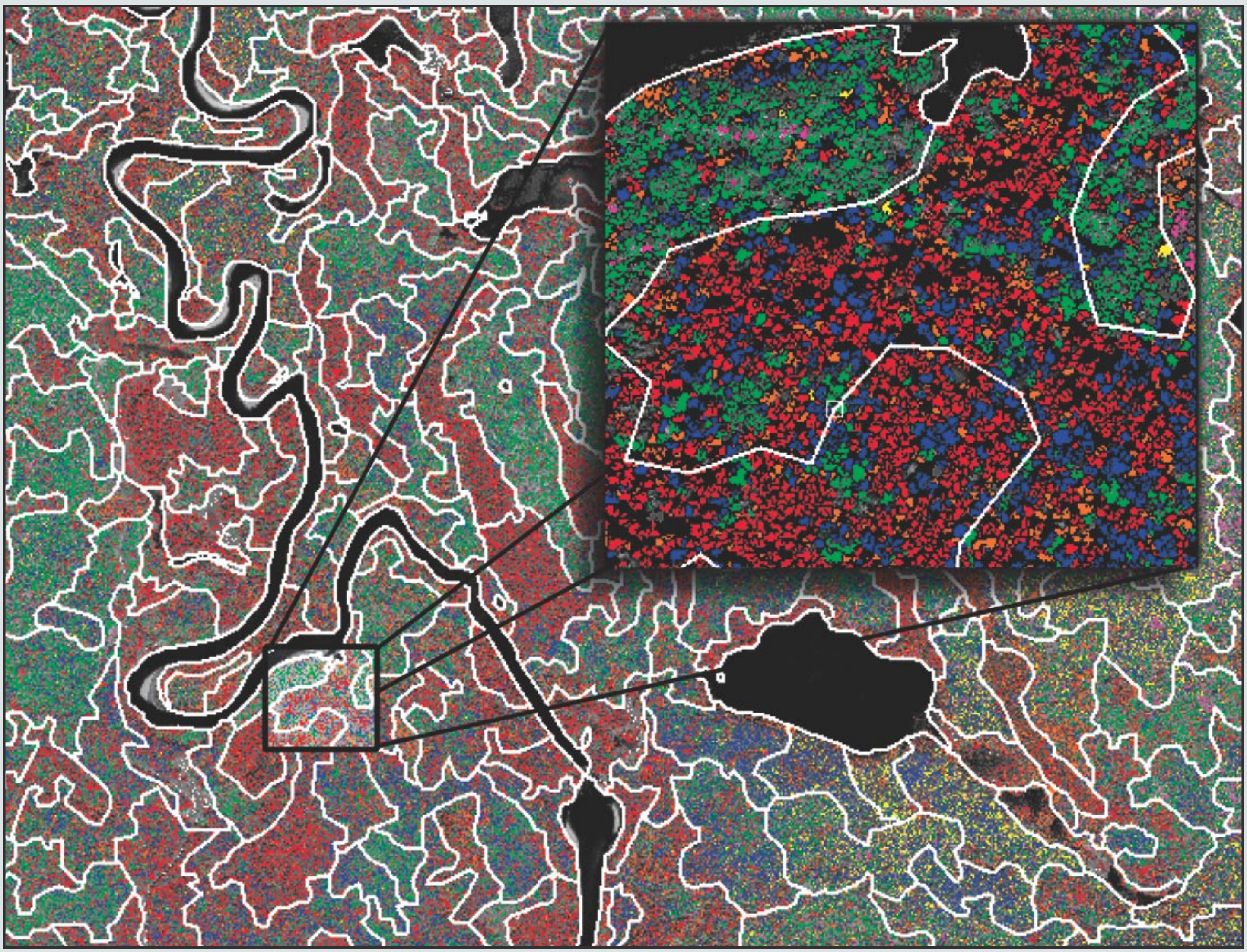

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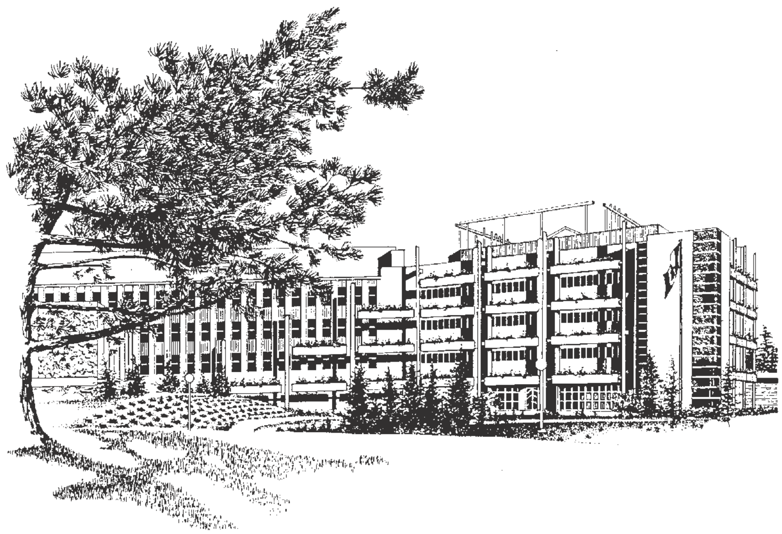

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Contents

Cover Image – Results of species classification and regrouping of individual tree crowns and tree clusters over the original panchromatic IKONOS image (1 m/pixel) for part of a 10 000 ha area (11.7 x 8.6 km^2) in the Lac à l'Ours region of Quebec that was analyzed with the individual tree crown approach. This work was done in collaboration with CLC-Camint (Gatineau) and Industries Davidson Inc. and was funded in part by the "Programme de mise en valeur des ressources du milieu forestier - Volet 1" of the Quebec Department of Natural Resources. The tree species in the forested areas are indicated by the following colours:

(red)	White pine
(dark red)	Fir-Spruce
(orange)	Cedar
(magenta)	Maple
(blue)	Poplar
(grey)	White birch
(yellow)	Yellow birch
(dark green)	Other hardwood
(green)	Regeneration
(white)	Bare area

Abstract

Most foresters would agree that there is a pressing need to improve the precision, accuracy, timeliness, completeness and cost-effectiveness of forest information. These goals may be difficult to reach without a major shift in paradigm such as the one presented in this report: the computer analysis of high spatial resolution (10-100 cm/pixel) multispectral aerial or satellite images to produce individual-tree-crown–based (ITC -based) forest inventories. This report describes some of the techniques, methods and tools for ITC-based information extraction that have been developed by the Canadian Forest Service over the last fifteen years, and it summarizes some of the results related to the production of highly detailed forest inventories. Other forestry applications of an ITC-based approach are also briefly mentioned. The recent availability of high spatial resolution (cm/pixel) satellites delivering good quality images of map sheet size should make the production of ITC-based inventories very efficient.

Résumé

La plupart des intervenants forestiers seraient d'accord pour dire qu'il y a un besoin pressant pour améliorer la précision, l'exactitude, l'opportunité, l'envergure et le coût de revient de l'information forestière. Ces buts pourraient être très difficiles à réaliser sans un changement majeur de paradigme tel que celui présenté dans ce rapport : l'analyse numérique d'images multispectrales aérospatiales à haute résolution spatiale (10-100 cm/pixel) pour produire des inventaires forestiers « à l'arbre près ». Ce rapport décrit quelques unes des techniques, des méthodes et des outils se rapportant à l'extraction d'information « à l'arbre près » développés par le Service canadien des forêts au cours des derniers quinze ans et résume certains résultats reliés à la production d'inventaires forestiers très détaillés. D'autres applications forestières de l'approche « à l'arbre près » sont aussi mentionnée brièvement. La disponibilité récente de satellites à haute résolution spatiale (cm/pixel) produisant des images de bonne qualité et d'une grandeur commensurable avec les cartes forestières devrait rendre possible une production très efficiente d'inventaire « à l'arbre près ».

Introduction

A worldwide economy, global and local environmental concerns, and the relative scarcity of old-growth forests are leading to stricter forestry legislation, certification pressures, and a general trend towards more sophisticated forestry practices (i.e., precision forestry). Whether for global, national, provincial, or regional reporting requirements, local certification or operational use, there is a need to improve the precision, accuracy, timeliness, completeness, and cost-effectiveness of forest information. Such improvements could come about gradually via incremental changes to existing methods (e.g., more detailed plots, more field visits, or different sampling schemes), but not without serious cost considerations. Budgetary constraints might force us to opt for more innovative measures and even, possibly, a major shift in paradigm: a transition from mapping relatively homogeneous forest stands and interpreting their content from medium-scale aerial photographs to the semi-automatic computer analysis of high spatial resolution (10-100 cm/pixel) multispectral aerial or satellite images on an individual tree crown (ITC) basis. The increasing availability of such remotely sensed images, or even of digitized aerial photographs in interpretive "soft copy" environments, and the ongoing development of image analysis tools based on this new model make the analysis of forested areas on an ITC basis an interesting option. Although a major paradigm shift, such a transition could be fairly gradual. Indeed, even though the analysis is done mostly by computers and on an ITC basis, it is still possible to report the information by forest stands.

Over the last fifteen years, techniques, methods and processes have been developed to separate forested from non-forested areas, delineate individual tree crowns, identify their species, and if needed, regroup them into automatically generated forest strands or environmental strata. From this detailed information, numerous parameters in addition to those found in conventional inventories can be easily extracted (e.g., snag locations, forest gaps, health status, and locations of highly valued trees). With time and improved computing power, forest managers will possibly forego static regroupings and keep all of the information about the individual trees (e.g., position, crown area, height, species, and dominance). Regrouping may be done on demand, for each specific application, if it is done at all. This may also lead to more precise volume and biomass estimates and foster the use of individual tree growth models.

This report, describes some of the techniques, methods and tools that have been developed by the Canadian Forest Service towards the realization of this new ITC-based forest inventory paradigm. Image preprocessing requirements are outlined and some application-related heuristics are given. Important parameters in the delineation of individual tree crowns from high spatial resolution images using a *valley-following* technique that capitalizes on the shaded areas between the crowns are discussed. The creation of species and situation-specific ITC-based signatures and the supervised classification process that assigns a species to each tree crown are explained. Methods to regroup tree crowns into forest stands and to assess accuracy are also discussed. The *tree-top* technique, an ITC approach more appropriate to regeneration assessments, is examined, as well as one of its variants useful in more open plantations. Finally, significant results from the use of these tools at essential steps of the semi-automatic production of detailed forest inventories are summarized. Current limitations and ongoing research directions are also outlined. Readers interested only in forestry applications results might choose to skip the "Techniques and Methods" section.

Techniques and Methods

A relatively new field of research, ITC-based approaches can be divided into three main streams based on the information obtained: tree location, tree location and crown dimension parametrization, and full crown delineation. Furthermore, the techniques themselves can be separated into two groups – those based on modeling the appearance of a tree crown in an image and those based on more conventional image processing algorithms.

Finding tree locations can be achieved by simply detecting image local maxima in dense forest areas (Gougeon and Moore 1989; Eldridge and Edwards 1993; Dralle and Rudemo 1996). Provided that the filter size and image smoothing parameters are appropriate for the tree sizes and the image resolution, this works well for coniferous stands where the local maxima often correspond closely with the tree tops. Locally adaptive processes have also been developed (Gougeon and Leckie 1999; Wulder *et al*. 2000). Such approaches lead to stem count estimations and even to relatively good species classification using conventional pixel-based maximum likelihood classifiers (Gougeon and Moore 1989).

Techniques for finding tree locations and crown dimensions are either based on finding local maxima and then finding the edge of the crown (Pinz 1991; Uuttera *et al*. 1998; Pouliot *et al*. 2002), or based on matching image features to those of two-dimensional instantiations of tree crown models (specific crown type and diameter) (Pollock 1994; Larsen and Rudemo 1998). Such approaches can lead to stem counts, species classifications and crown area estimations. If tree locations and rough sizes can be ascertained, alternate species classification techniques, such as those based on neural nets, have also been tried (Pinz *et al*. 1993).

Techniques based on full individual tree crown delineation are image processing algorithms either following valleys of shade between tree crowns in an intensity image (Gougeon 1995b; Andrew *et al*. 1999; Culvenor 2000) or, following edges created by gradient operator and analyzing their curvature (Brandtberg 1999). Such approaches can lead to tree counts, ITC-based species classifications, crown area and canopy closure estimations, gap analysis, biomass estimations (Bhogal *et al*. 2000) and possibly, volume estimations (Magnussen *et al*. 1999; St-Onge 2001). They may lead to complete and precise ITC-based forest inventories in the near future.

This report will explain several of the techniques and methods centered around one automated tree delineation method – the valley following approach (Gougeon 1995b) – and will briefly describe the tree-top technique (Gougeon and Moore 1989), one of the most popular tree localization and counting approaches. These techniques will be described in enough detail for a thorough comprehension of some of their important parameters, their weaknesses, limitations and appropriate forestry applications. This report will also address the techniques used to extract specific forest-based or stand-based parameters (e.g., species classification, ITC regrouping) and describe four possible ways to do accuracy assessments. Pre- and post-processing needs are also considered. The “ITC Suite” of programs will be constantly referred to and used to focus the reader’s attention on critical aspects of this type of image analysis. The flowcharts in Figures 1 and 2 illustrate some of the essential steps and the main ITC Suite programs used in obtaining ITC-based species composition of forested areas seen in high spatial resolution multispectral images.

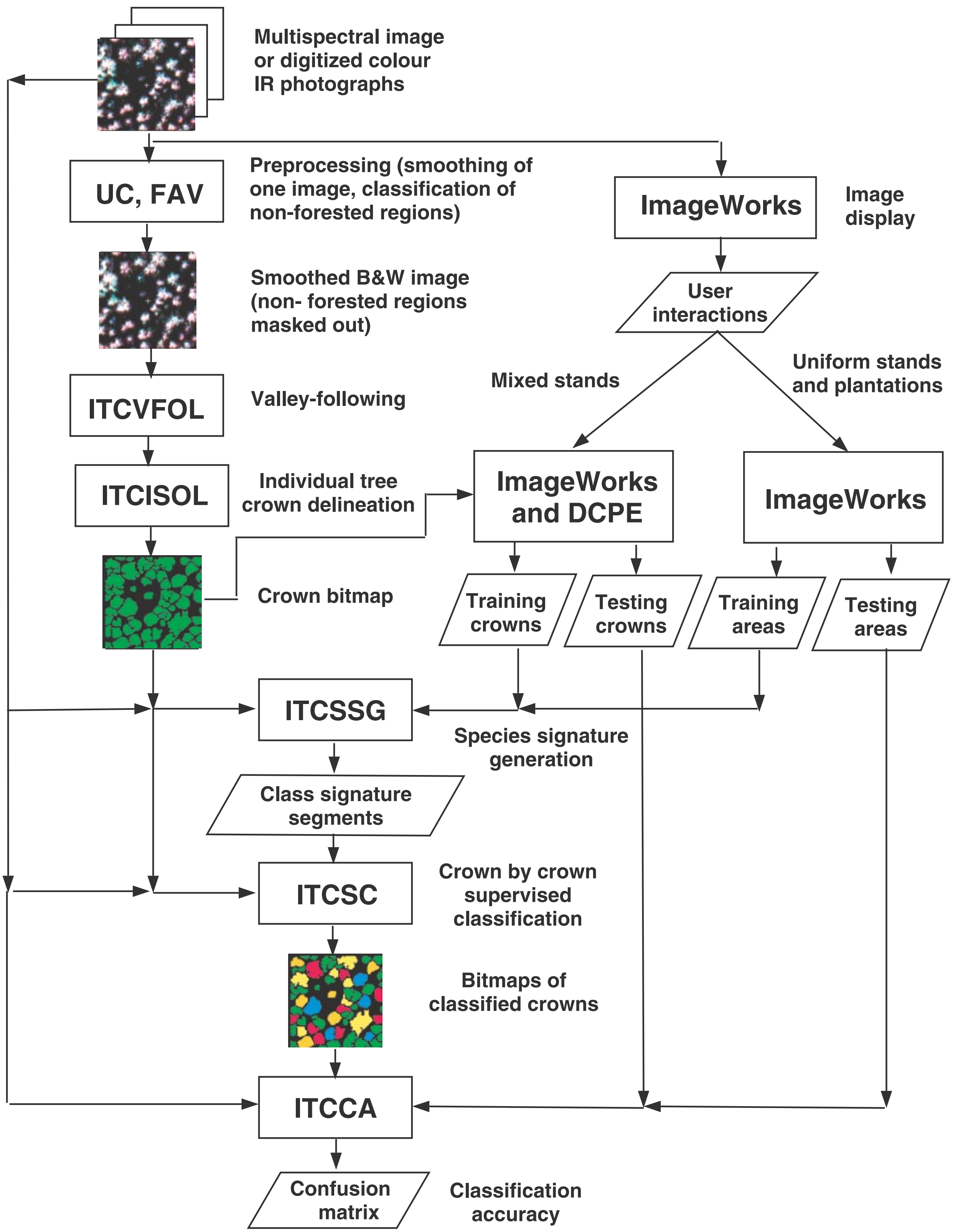

Figure 1 – *Methodology for individual tree crown delineation and supervised classification from high spatial resolution multispectral images (from Gougeon 1997).*

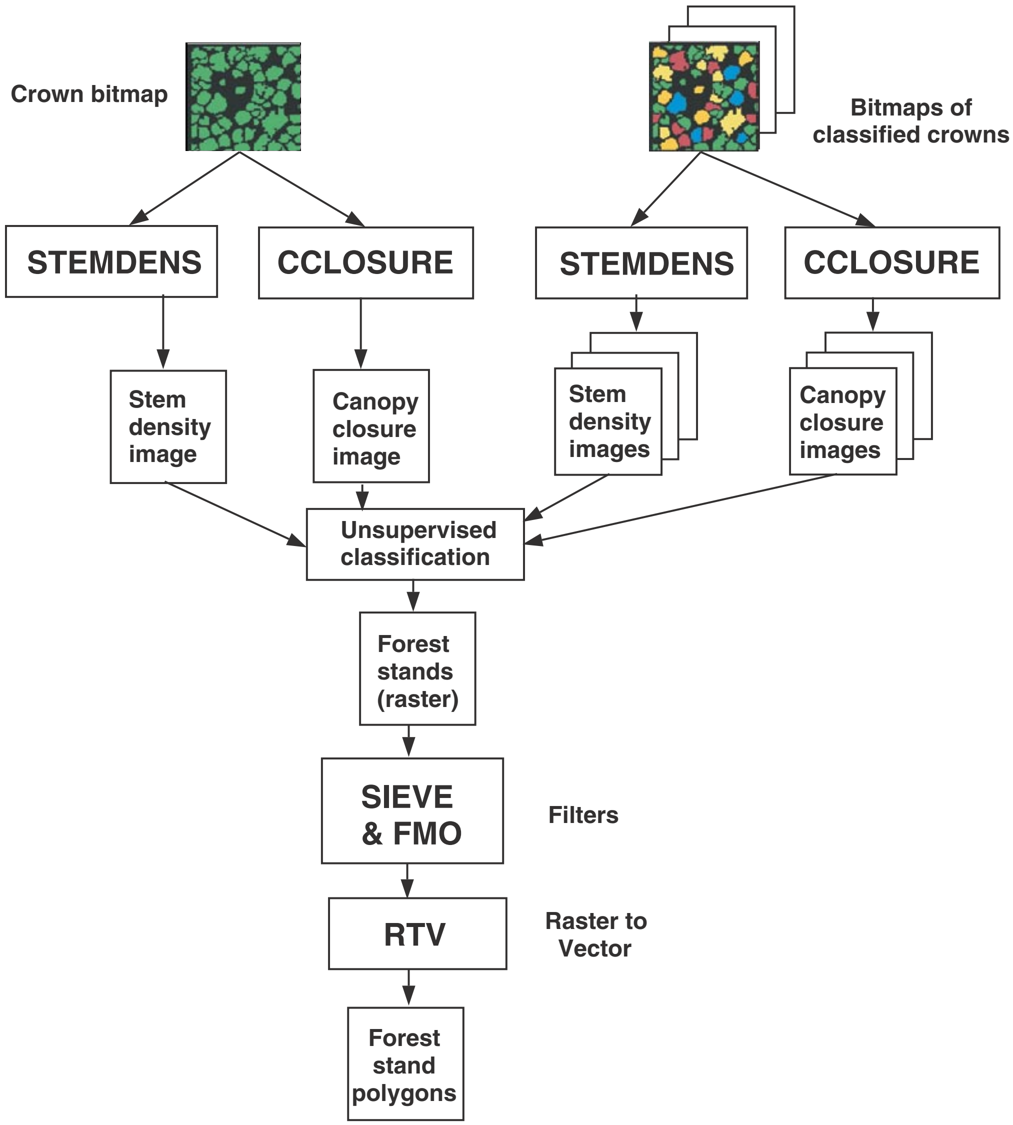

Figure 2 – *Methodology for generating forest stand polygons from individual tree crown information (from Gougeon 1997)*

Image preprocessing and mask generation

Preprocessing is necessary to select and prepare an appropriate illumination image for the crown delineation process and to create masks to ensure that the delineation process concentrates on the medium to dense forested areas for which it is most appropriate.

With a multispectral image, the selection of an appropriate band as the illumination image often depends on the intended forestry application. For a generic forest inventory, the near-infrared band is usually preferred although the green band can work effectively. For defoliation assessment, the blue band may be more appropriate. It is also possible to generate an illumination image from various band combinations or with processes such as principal component analysis or intensity-hue-saturation transformations. When a raw channel is selected, it is usually smoothed to facilitate crown delineation although this may not be necessary when the illumination image is the result of a transformation process. Also, since the delineation process presently functions best at spatial resolutions around 30-60 cm/pixel, it is appropriate to resample higher resolution images (say 10 cm/pixel images) to 50 cm/pixel. This also makes for smaller images and so less computing resources are required. When dealing with lower resolutions, for example a 1 m/pixel IKONOS image, better results are also obtained by resampling to 50 cm/pixel. Even though there is no information gained by doubling the resolution, this leads to more precise tree crown boundaries and the detection of smaller trees. Indeed, the delineation process starts detecting and delineating crowns only if they are at least 2 × 2 pixels in area.

Masks should also be created in order to eliminate some areas from further analysis. Otherwise, the tree delineation process can easily misinterpret the dashed lines on a highway as tree crowns. After all, the dashed lines conform to the main assumption of the delineation process: they are compact objects more brilliant that their surroundings (i.e., the pavement). With multispectral imagery, one can sometimes rely on the multispectral information itself to create such masks. For example, a pixel-based classification (UC in Figure 1) or a vegetation index analysis on a degraded resolution image can often be used to eliminate areas containing man-made features, lakes, and other areas that are not of interest. This approach has the added benefit of producing thematic layers that could be useful in the rendition of a final classification of a vast region or in the production of multilevel coverages when transferring the resulting information to a geographic information system. When only vegetative areas remain, one can often use texture measures to separate the forested areas from non-forested areas. With georeferenced images, data from a geographic information system can be used to generate various masks. For example, lakes, river beds and bog areas are easily extracted from an existing forest inventory or base map.

Forested yet fairly open areas present more difficulties. Again, multispectral data can often be of help. This is typically the case when the background material is made of woody debris (e.g., a partial cut), lichen, sand, rock outcrops, soil, or senescing herbaceous material (with an early spring or fall image). Here, simple multispectral rules, such as “detect pixels having near infrared radiances smaller than their mean visible band radiances” can create effective non-vegetation masks within these forested areas. Areas with mature trees that are open enough to show a vegetative understorey (hardwood, softwood or brush) are still problematic.

Texture is typically the only recourse when analyzing panchromatic imagery. Non-forested areas can usually be eliminated based on their different texture characteristics. Similarly, regenerating areas can often be separated (Figure 3). However, since texture is essentially an area-based measure, this approach works better when dealing with sizeable areas and, even then, problems are to be expected at mask boundaries. Minor inhomogeneity within a texture may also create artefacts that may or may not be easy to remedy without human intervention.

If medium (m/pixel) to high (cm/pixel) spatial resolution LiDAR height data is available, simple thresholds can be used on a canopy height model to separate ground-level vegetated areas from regenerating (or brushy) areas, and to separate both of these from forested areas. This also facilitates a separate analysis of the regenerating areas, which depending on the age of the regeneration and the spatial resolution of the imagery, can be better accomplished with the “tree-top” or “locally adaptive tree-top” approaches (see appropriate section below). With high spatial resolution LIDAR data, brush or natural regeneration can even be masked in areas of mature trees with an opened canopy. In fact, tree crown delineation can be performed directly on the canopy height model, either alone or in synergy with the delineation from an image (Gougeon *et al*. 2001b).

Finally, if all else fails, or perhaps only for the sake of expediency, regions can be quickly eliminated by manually delineating them on the screen and saving them as binary masks. If organized by categories, these masks can also be very useful in the rendition of the final products.

Figure 3 – *Example of using texture analysis to separate almost automatically forested from non-forested areas so that the individual tree crown analysis process can concentrate on only the forested areas.*

Individual tree crown delineation

When the non-forested areas have been masked out and a proper illumination image has been selected or generated, the crown delineation is performed in two main steps. First, based on the assumption that tree crowns are perceived as distinct in high resolution images because they are bright entities separated by areas of shade, a “valley following” process follows multiple paths through the trees in the same way as one would follow valleys among mountains (Figure 4). This results in a fairly good, yet often incomplete, separation of tree crowns (Figure 5a, b). Then, a rule-based process addresses potential trees individually and follows their crown boundaries favoring clock-wise moves and aiming to delineate closed shapes. Higher level rules can make decisions about using additional tools to further separate or regroup these closed shapes (Figure 5c). From then on, individual tree crowns (or tree clusters with poorer resolution images) are considered and treated as distinct objects in any further analysis. With a multispectral dataset, the crowns are fed to a species signature generation process and then to a classification process to identify their species. However, even with a panchromatic image, interesting forestry information can be extracted at this point in the analysis. For example, the resulting bitmap of ITCs can be used to analyze crown closure, stem densities, crown size and forest gaps. The valley-following algorithm and subsequent rule-based program have been described in Gougeon (1995b). Here, we will address practical considerations when using them.

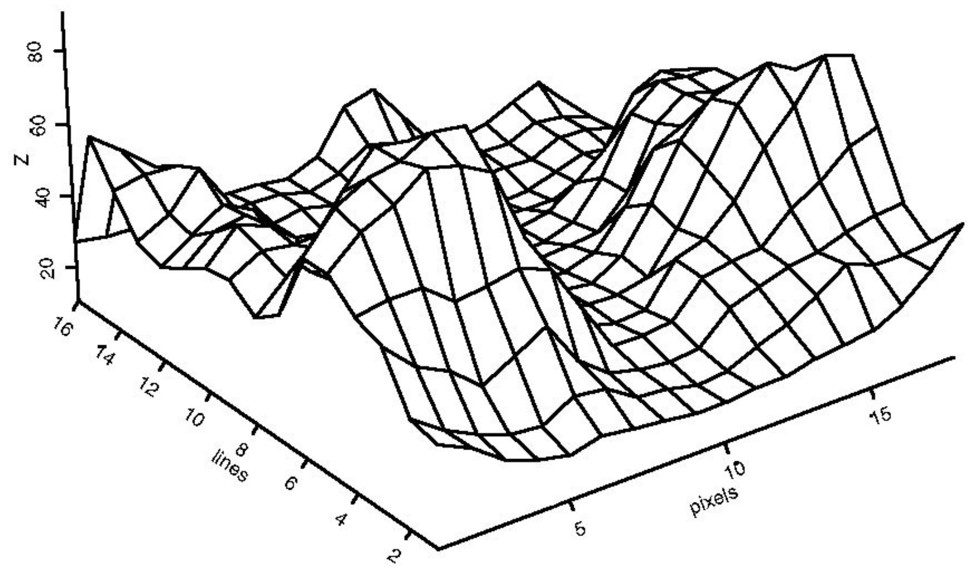

Figure 4 – *A three-dimensional view of a small section (16x20 pixels) of image showing the brighter tree crowns as mountains often separated by valleys of shade (from Gougeon 1999).*

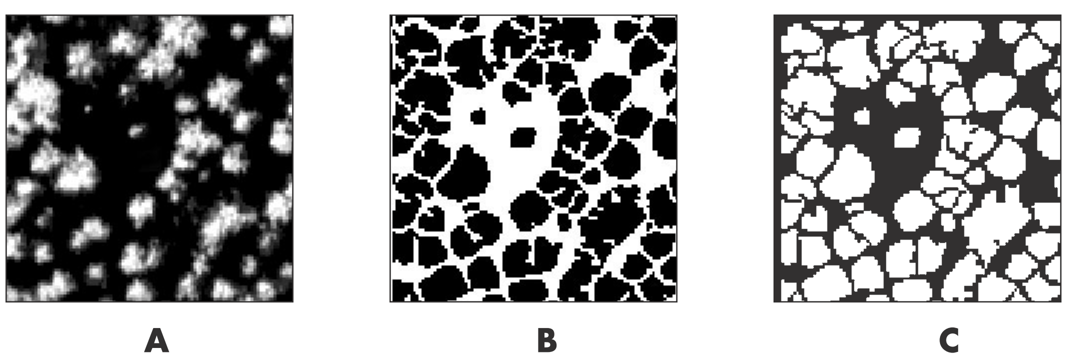

Figure 5 **(a)** – *Section (100 × 100 pixels) of a 31 cm/pixel image illustrating how distinct individual tree crowns can appear in medium-density to high-density forests where they are usually separated by shade (from Gougeon 1995b).*

*(***b***)* – *Results after the completion of the valley-following program (ITCVFOL). Large shaded areas were masked using the lower threshold and valleys of shade were followed in an attempt to separate individual tree crowns (from Gougeon 1995b).*

(c) – *Results after the completion of the rule-based crown delineation program (ITCISOL). Using the jump factor, some inlets into tree clusters have been elongated resulting in more ITCs being separated (from Gougeon 1995b).*

From the borders of the masked areas and from initial local minima in the forested areas, the valley-following process (ITCVFOL, see Figure 1) follows pixel-by-pixel multiple paths through the small corridors of shade that exist between the brighter tree crowns. The process presently relies on three thresholds. Although efforts have been made to make their selection automatic, the results are not always fully satisfactory. Facilities exist to input them manually, or even to preset them for repetitive or batch runs. Understanding the thresholds' role and their side effects is important to ensure better crown delineations.

The first threshold, generally referred to as the *lower threshold*, is meant to eliminate from processing those regions devoid of significant trees and those that are essentially in the shade (e.g. , fully shaded forest openings). It is used as a simple threshold throughout the image and will mask out any pixel with a grey level lower than itself. This speeds up the processing and prevents the valley following algorithm from creating useless and inconsequential valleys in those areas. If this threshold is set too high, the shaded parts of tree crowns may also get masked out leading to poorly formed crowns for which crown area measurements will not be appropriate. If set too low, some separation of crowns within tree clusters may be hindered (Gougeon 1999). These effects are more or less pronounced depending on the radiometric resolution of the image.

For these reasons, an appropriate way to select the *lower threshold* is to estimate, by checking various image sections, which gray level can generally distinguish between the shaded sides of tree crowns and the more deeply shaded surrounding areas. This can be a difficult process as images are rarely uniform (due to, for example, local haze, view angle differences, etc.) and forest density and species composition will also affect this value. Fortunately, in practice the selection of the lower threshold is not too critical for most applications. Its selection may gain importance when precise crown area measurement are needed to estimate volume on an individual tree basis. Then, a locally adaptive threshold algorithm will be considered.

The second threshold, generally referred to as the *upper threshold*, is meant to distinguish between valleys that are helpful in separating tree crowns from those, generally found at higher spatial resolutions (10-40 cm/pixel), that tend to separate a tree crown into several parts, especially in the star-like crowns of species such as Norway spruce (*Picea abies* [L.] Karst.). This threshold is only of concern when such situations occur. In such cases, the user can easily select an *upper threshold* by examining the various situations of this type in the image. Again, thresholds being the simplistic instrument that they are, something more adaptive would no doubt be desirable. Alternatively, the implementation of sophisticated regrouping rules in the second part of the crown delineation process, the rule-based system, could make such thresholds obsolete.

The third threshold, generally referred to as the *valley noise* threshold, is a measure of how much radiometric instability should be expected and tolerated in the valleys. The shade valley between two crowns is not usually a smooth and simple environment: sensor noise can occur in dark image areas, lower tree branches can extend to a neighboring crown, understorey material can be slightly illuminated, and other image features can complicate crown delineation. The valley following algorithm progresses from one shaded pixel to another (starting from local minima in the forested parts of the image) by looking one pixel ahead for a pixel of low value in between two pixels of higher values assumed to be parts of crowns on each side of the valley. However, valleys are not always one pixel wide; consequently, allowances are made to have valley floors that could be a few pixels wide. Such valley floor pixels may not have exactly the same gray level. The *valley noise* threshold specifies the range of gray level differences (generally 1, 2, or 3 for 8-bit images) that will be tolerated, and it generally needs to be set higher for sensors with higher radiometric resolutions. In general, since a higher threshold facilitates valley progression, higher thresholds may lead to valleys that would be absent (or interrupted) with the use of a smaller threshold, thus separating more crowns, but this will result in wider valleys that may lead to an underestimation of crown areas.

The second part in the delineation of individual tree crowns is done by a rule-based program (ITCISOL, see Figure 1) which uses the results from the valley-following algorithm. For each 2×2 pixels of tree material, it goes left to the closest boundary and attempts to follow the boundaries of the potential crown favoring clockwise turns until it gets back to its initial position (indicating closure). This works well for crowns already well separated by the valley-following process. However, because valleys are sometimes interrupted (for example by a branch sticking out of a crown into the next one), high-level rules exist to decide whether such interruptions should be bridged or not. A user-set parameter, the *jump factor*, tells the program how many pixels it is allowed to bridge. A user need only specify whether they are dealing with a mature forest or a regenerating one. In mature forests, bridges up to 1 m in length are allowed (calculated in pixels by the system) and, in regenerating forests, bridges up to 0.5 m are allowed. There is also a "prompt" mode where the user can specify the distance in pixels. In addition, higher level rules try to detect other situations where clusters of trees rather than individual trees have been delineated (tree clusters are frequent in lower-resolution images, such as those in the 80-100 cm/pixel range). Capitalizing on indentations in cluster boundaries as possible indications of where to separate them into ITCs, the program succeeds in breaking some tree clusters. Various other splitting criteria and algorithms are being tested. None is without side-effects. Higher-level rules to identify and regroup segments of crown into single crowns have not been implemented yet. These would be mostly useful with hardwood crowns in higher resolution images (i.e., 10-30 cm/pixel). When all possibilities using existing rules have been exhausted, the program iterates several times through the image, managing to delineate more ITCs with each pass, until little progress is made. Then, a bitmap of ITCs and "isols" (remaining tree clusters) is generated (Figure 6). These are treated as objects in all further analyses.

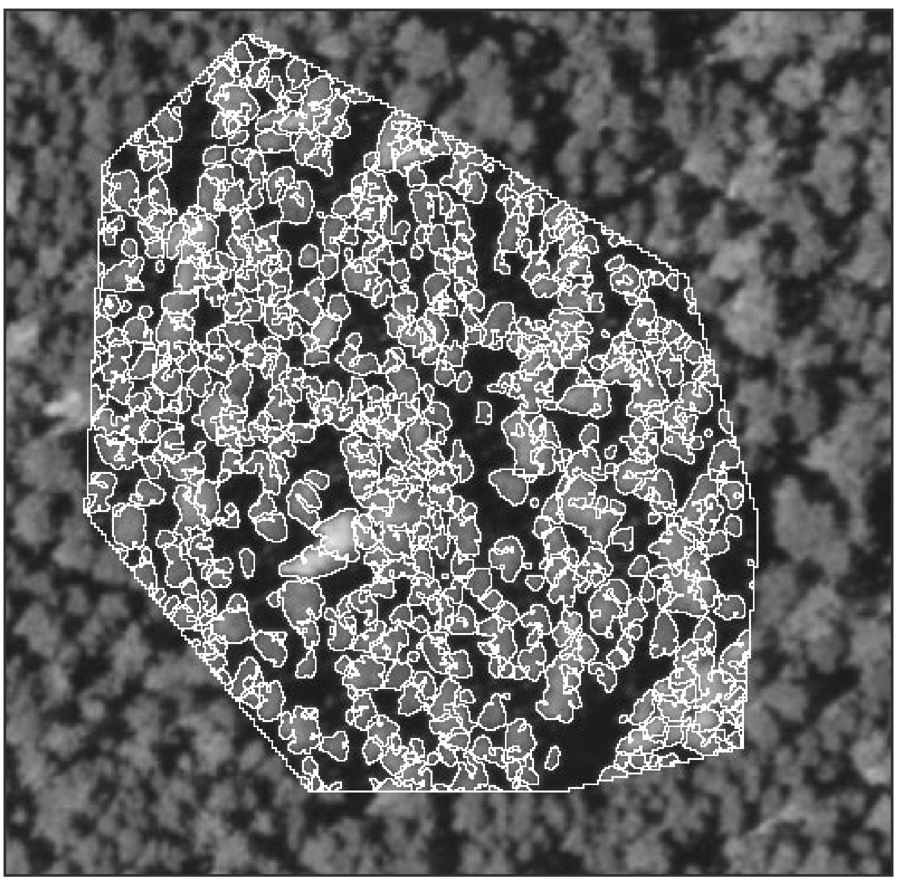

Figure 6 – *The delineated individual tree crowns (ITCs) and remaining tree clusters (isols) from a digitized (1 m/pixel) panchromatic photograph of a test area. Here, the typical bitmap produced by the sequential applications of ITCVFOL and ITCISOL is rendered in vector form to let the image show through the crowns in order to emphasize the resulting delineation details.*

Individual tree crown classification

With multispectral imagery, the delineated ITCs or isols are usually fed to a supervised classification process which attempts to identify their species. Typically, single-species, single-situation training areas are delineated on the image in order for ITC-based signatures to be generated for each class of interest. Using the ITC bitmap generated by ITCISOL, the signature generation process (ITCSSG, see Figure 1) extracts the ITCs within the training areas, generating ITC-specific signatures, and combines them into class signatures. When dealing with a very mixed forest, it is also possible to create species signatures by selecting ITCs rather than using "impure" training areas. Typically, the average ITC multispectral mean and the covariance of the ITC means are used as the multispectral signature. However, with the creation of an *a priori* mask (using the program ITCMG), it is possible to generate signatures based on only the crown pixels from the lit side of trees. This generally leads to better classifications. Using the same approach, it is possible to use only the shaded side of tree crowns or only the most brilliant pixel within a tree crown. In addition to, or instead of, these typical multispectral signatures, numerous other types of signatures can be generated which take into account texture, structure, or other image features. Context can also be considered by introducing extra feature channels such as digital elevation, or slope and aspect, or sensor look angle, etc. The creation of an ITC identification system taking all of these factors into account in an intelligent way will be the subject of future research.

The present classification process (ITCSC) uses a maximum likelihood decision rule. ITCs are taken one by one from the ITC bitmap of the full image. Their signatures are calculated using the same features and parameters as in the class signature generation process. Their likelihoods of belonging to the various classes are calculated, and a final decision is made taking a confidence interval into consideration. That is, an ITC is assigned to the class with a signature closest to its own, unless that closest signature is distant enough that we have no confidence in such assignment. In that case, the ITC is left unclassified. When all the trees have been classified, results can be displayed and evaluated. The formal evaluation methods described below (see the following section on accuracy assessments) are typically used only once a suitable classification has been achieved. Until then, more informal ways are often used to assess the classification, to decide whether it needs improvement, and to decide how to improve it. For example, aerial photos of the area or an old forest inventory map can used to assess the weaknesses of the current run. Only rarely are classifications suitable on the first attempt.

There are numerous factors that can affect the results of a classification and numerous ways to improve them. One of the most important factors is the selection of appropriate classes. For example, it may be better to regroup species that are difficult to separate (such as poplar and birch) as a single class, unless one can tolerate the remaining uncertainties. The number of species one is trying to separate relative to the spectral and radiometric resolution of the sensor is also a factor. In general, for a given sensor, the more classes one wants to separate the poorer the classification. Some of these factors can be assessed prior to the classification process using programs that evaluate signature separability (e.g., ITCSSBD - Species Signature Bhattacharyya Distances). They can pinpoint the most important channels or features for separability and indicate the degree of class separability.

A standard approach consists of refining ("purifying") the training areas or the selection of individuals in order to produce more precise, narrower signatures. This approach involves making sure that training areas do not contain trees of other species or removing individuals that are outliers. Another approach consists of considering additional information. For example, if white spruces on north facing slopes appear different than other white spruces, create two distinct classes, or add a digital terrain model to the classification, or do a separate classification for all north facing areas, or combine these approaches. Environmental factors can also create a diversity of problems. Obviously, clouds are a problem. So are cloud's shadows. Although, with some high-radiometric-resolution sensors, it may be possible to analyze the forest within shadows. This is typically done as a completely separate classification and often meets with limited success.

Atmospheric haze is an even more subtle environmental factor, one that is extremely difficult to alleviate. In addition, the image analyst is often unaware of the problematic presence of haze.

Accuracy assessments

In remote sensing, the prevalent way to evaluate classification accuracy is to delineate test areas (similar to yet independent of the training areas used to generate the class signatures) from which a confusion matrix is calculated (ITCCA, see Figure 1). One or more test areas (ideally with their content as pure as possible) are delineated for each of the classes found in the classification. Within each of these areas (representative of a given class), the resulting class composition is ascertained and reported. The classification accuracy of a given class corresponds to the proportion of ITCs within the corresponding test area that are of the correct class. The confusion matrix also contains information on errors of commission (ITCs from other classes' test areas that are assigned to that class) and errors of omission (ITCs assigned to a different class within the test area). Table 1 shows the confusion matrix for the Nahmint area classification reported in Gougeon *et al.* (1999). For that project, the selection of training and testing areas was easy since these were planted stands and thus, nominally, contained only a single species. The application of this method to a more natural forest would require interpretive skills (or additional information) to identify areas with single-species content on the image or, preferably, on aerial photographs with a more suitable scale. Variations on this method include selecting test ITCs rather than test areas, or knowingly dealing with test areas that contain more than one species as long as the species composition is known.

Other accuracy assessment procedures, procedures that may have more appeal and credibility with practicing foresters, involve comparing the ITC species composition in given stands to that reported by an existing forest inventory, or to the species compositions obtained from ground transects within the stands. Given existing stand polygons (and attributes), the program ITCPCD (ITC Polygon Content Description) can report on their ITC species composition and various other stand and ITC attributes. A comparison with the existing inventory stand attributes is then easily done. Such comparisons illustrate vividly the precision,

Table 1 – *Example of a confusion matrix from ITC species classification in the Nahmint area of British Columbia (from Gougeon* et al. *1999). Average accuracy was 59.8%.*

	Actual species					
	Douglas-fir	Grand fir	Amabilis fir	Western redcedar	Western hemlock	Hardwood
Crowns	108	100	40	102	106	72
Species detected						
Douglas-fir (*Pseudotsuga menziesii*)	**69 (63.9%)**	16 (16.0%)	3 (7.5%)	35 (34.3%)	12 (11.3%)	0 (0.0%)
Grand fir (*Abies grandis*)	10 (9.3%)	**59 (59.0%)**	10 (25.0%)	9 (8.8%)	3 (2.8%)	0 (0.0%)
Amabilis fir (*Abies amabilis*)	12 (11.1%)	21 (21.0%)	**28 (57.5%)**	27 (26.5%)	2 (1.9%)	0 (0.0%)
Western redcedar (*Thuja plicata*)	2 (1.9%)	3 (3.0%)	2 (5.0%)	**28 (27.4%)**	1 (0.8%)	13 (18.1%)
Western hemlock (*Tsuga heterophylla*)	15 (13.9%)	1 (1.0%)	2 (5.0%)	3 (2.8%)	**88 (83.0%)**	9 (12.5%)
Hardwood - mostly of alder (*Alnus rubra*)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	**49 (68.1%)**
Unclassified	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (1.4%)

accuracy and usefulness of ITC analyses from high-resolution images (as seen in the application section below) but is limited by the precision of current inventories.

A comparison (using the program ITCCAF) of ITC species composition with that of ground transects within new automatically generated stands was reported in Gougeon *et al*. (1999). This also illustrates the power of the ITC analysis as, on average, species composition is only 10% off for the main species, and 14% off for any other species that occupied more than 25% of a given stand. However, when considering such encouraging results, one should keep in mind the special nature of the experimental site: relatively uniform plantations of single species containing rather young individuals. Although younger ITCs can be harder to separate spatially because of their small sizes, they often have very good spectral separability into species. Older trees, with their less compact crowns, their possible health issues, and their inconsistent illumination due to more open crowns and diverse dominance situations, can be harder to classify.

Considering that the above comparison was done for the same ITC classification as the one involved in Table 1, this also illustrates a standard weakness of simple assessments conducted on test areas: such assessments make the assumption that the test areas are pure and not contaminated by species other than the nominal one. The poorer relative results in this case are attributed to ingrowth of other species within the supposedly pure stands.

Another accuracy assessment procedure (using the program ITCMARA), one that is more research oriented, involves comparing individual tree counts, species and locations (and even crown areas) from detailed field plots with the results from the computer analysis. This allows for a separate parametrization of delineation and classification accuracies as well as the delineation precision. However, extremely detailed field plot information is required, followed by extensive on-screen manual crown delineations. Such a complex accuracy assessment procedure is necessary to completely quantify the performance of an ITC analysis for research purposes and to evaluate the strengths and weaknesses of any improvement made to the software. It is also extremely useful to quantify the performance possible with various media and at various spatial resolutions.

Individual tree crown regrouping and stand generation

Forest stands play an essential role in forest management. Presumably, it would be very difficult to get North American foresters to change to a new paradigm based on individual trees. In any case, geographic information systems are still somewhat limited in the quantity of polygons they can reasonably handle. In addition, storing information about all of the trees for a given province would produce a database of huge proportions. Transferring such information would also be problematic.

For these reasons and others, regrouping ITC information into forest stands is still a necessity. Such regrouping can be based on:

(a) forest stands from an existing forest inventory (updated for recent changes);

(b) newly generated forest stands obtained by conventional photo interpretation methods;

(c) automatically generated stands based on ITC species composition, density, and canopy closure;

(d) automatically generated stands based on texture parameters and their classification;

(e) automatically generated stands from a spectral and textural image segmentation; or,

(f) customized regrouping for biodiversity, wildlife management, or the application at hand.

Approaches (*a*) and (*b*) fit well with the present forest inventory generation procedures of most provincial governments and forest companies. Summarizing ITC-based species composition, stem density, and canopy closure this way serves to foster confidence with the people most intimately involved with forest inventories (see the section on applications). A methodology for regrouping ITCs (*c*) has been described in Gougeon *et al*. (1999). It consists of generating crude images of crown closure and stem density for each species and feeding them to a pixel-based unsupervised classification process where classes correspond to a variety of stand types of different species compositions and densities (Figure 2). Classes are regrouped until the desired breakdown is achieved. Regions smaller than a statuary minimum are merged into dominating stands and a raster-to-vector conversion is performed. This methodology generally achieves very good stand delineation (which is discussed more fully in the applications section). One possible disadvantage is that stands may not cross wide roads. They may also be sensitive to the presence of streams. However, if desirable, regrouping of neighboring stands with similar content is easily achieved as automatic post-processing in modern geographic information systems. Another weakness stems from the main assumption behind our crown delineation technique, the presence of shade between tree crowns, which at this point in time prevents the analysis of relatively open areas. In order not to confuse the crown delineation process, these areas are masked out before the ITC analysis and are thus not available for further breakdown by the stand delineation process.

Relatively fair forest stands can also be achieved by a classification of texture features (*d*) or by using a segmentation process (*e*) which would take both spectral and textural information into account (Gougeon and Wong 1986; Definiens Inc. 2000). Segmentation processes, whether based on edge-following or region-growing, will often have a tendency to create stand boundaries that follow stream beds or geological features, although the better ones may give the user some control. They are generally designed to pick up distinct objects and have difficulties with subtle boundaries like those typically found by forestry interpreters (Leckie *et al*. 2002a). An unsupervised classification of texture parameters can often lead to better results. Because texture parameters are usually extracted from image areas, stands can often span boundaries that are small in size, like roads or streams. However, such an approach does not directly take species into consideration. Efforts to add a multispectral component to such an analysis are usually futile as it becomes a very difficult balancing act between the spectral and textural information. It usually leads to a species classification rather than stand delineation.

Novel custom regroupings (*f*) are also possible. This may become an important benefit of using an ITC approach. For example, an ITC analysis of a region can lead to very precise information on canopy gap locations and areas, and their spatial distributions. This should be of importance to wildlife management as big and small mammals have preferred patterns of canopy openings. Individual tree crown analysis may also facilitate the determination of buffer zone widths for riparian areas (Paradine *et al*. 1999). Practicing foresters can easily come up with numerous applications where decisions could be based on individual tree information, whether directly or indirectly.

The regrouping techniques of types *c*, *d*, *e*, and *f* are the subject of ongoing research. When fully developed, they will need to be evaluated formally to see if they are acceptable by state and provincial authorities and the forest companies which are increasingly responsible for forest inventories. However, if these automatic techniques do not meet all standards, they might still find an important role in computer-assisted stand delineation procedures. Whatever the regrouping technique that is used or judged adequate, an ITC-based approach permits the generation of precise species composition and numerous other interesting statistics about the stands. In time, the demands made by modern forest management and ever-increasing computing power will allow us to forgo these static regroupings in favor of keeping all of the information about the ITCs (e.g., position, crown area, height, species, and dominance). Regrouping may then be done on demand, for each specific application, if it is done at all.

The tree-top approach

An individual tree approach need not always imply full tree crown delineation, classification and regrouping. Interesting forest attributes can be extracted with simpler methods such as the ones based on the very popular local maxima or "tree-top" technique (Gougeon and Moore 1989). This technique is often used with lower-resolution images (1-2 m/pixel) to establish tree locations, counts, density and even to determine species. The technique is also used with smaller trees in high-resolution images (30 cm/pixel), for example in very young regenerating areas (Gougeon 1997). It consists of scanning an illumination image with a fixed window (e.g., 3 × 3, 5 × 5, or 7 × 7 pixels) and detecting the most brilliant pixels (or local maxima) within it and hopefully locating only one such pixel within each tree crown (see Figure 7). It generally works well for conifer crowns seen close to nadir, where such pixels are often located on the sunlit side of tree crowns near the tree top (hence the name). Most of the successful applications of this technique have been limited to tree counting under such ideal circumstances. For hardwood trees, with their more rounded structures, the relationship is not as straightforward, as multiple bright pixels can often be found within their crowns. Conifer crowns seen significantly off-nadir often present the same problem. In these cases, the relationship can be strongly dependent on the size of the viewed crowns relative to the spatial resolution of the image and the window size used by the local maxima operation. Locally adaptive methods (e.g., Wulder *et al*., 2000) can alleviate this problem to a certain extent by dynamically adjusting the window size being used. Mixed forests, with their variety of species, crown shapes and sizes, present a real challenge for such techniques. In complex situations, tree counts are typically unreliable. However, species recognition is often unaffected. Indeed, the local maxima pixels found in each tree crown are still among the purest pixels and these generally classify well.

The tree-top technique (using the program TREETOPS) has essentially the same preprocessing requirements as the valley-following crown delineation approach (see the preprocessing section). An illumination image is selected or created and then smoothed. Non-forested areas are masked out. Within the forested areas, a threshold is used to eliminate most shaded pixels. It is similar to the *lower threshold* discussed

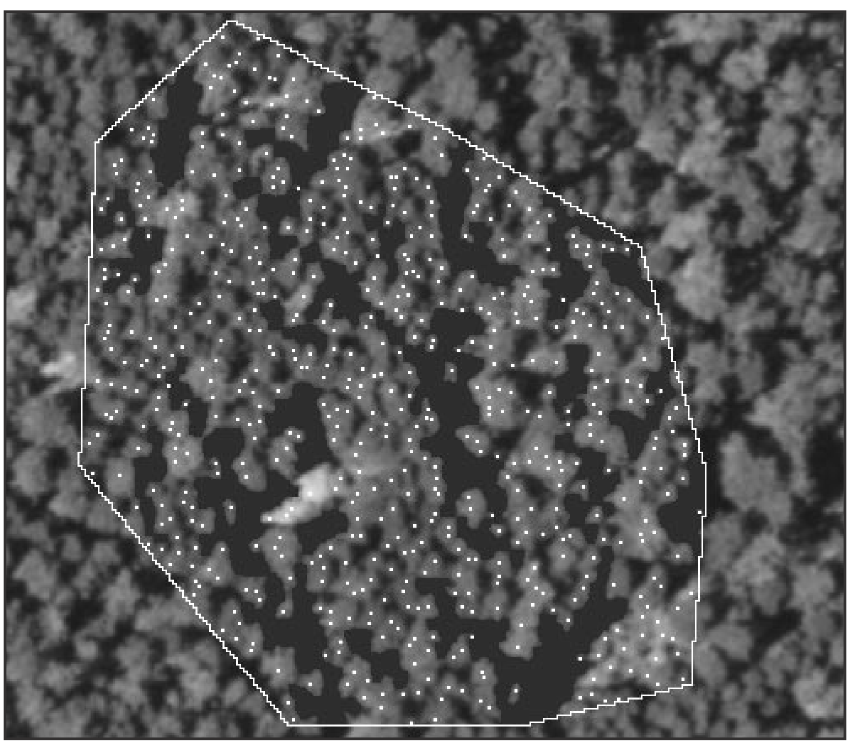

Figure 7 – *The tree-top technique applied to the same area as that in Figure 6. At such "low" spatial resolution (1 m/pixel), results from the TREETOP algorithm could be use in ITCISOL to help separate the remaining tree clusters (isols) into ITCs.*

earlier, but it can typically be set to a higher value as crown boundaries are not a concern in this case. It is also affected by various illumination modulation factors such as topography, haze, or tree spacing which will affect the darkness of the shade between trees. The technique is thus designed to be primarily useful in medium-density to high-density areas containing softwood and can easily be applied to extract tree counts, even from scanned panchromatic aerial photos (Figure 7).

In order to deal with trees in more open areas, a variation of the tree-top approach (using the program SHADOWTT) which looks for a specific shadow for every tree crown has been developed (Gougeon and Leckie 1999). With the sun's position as an input parameter, it looks in the opposite direction for a dark pixel to associate with each local maxima. This technique has been highly successful in eliminating false positive tree detections from the background material of open areas (Figure 8). To deal with both situations, a locally adaptive approach (using the program LATTOPS) capable of switching between the traditional and the shadow-specific tree-top techniques has also been developed. The switching is based on an *a priori* directionality analysis that detects areas of high directionality at an angle commensurate with the sun's illumination (i.e., the high directionality caused by the specific shadows). Although there are potential problems at the boundaries between dense and open stands, this automatic approach generally leads to more accurate tree counts overall. It may also be possible to apply such an approach to the full crown delineation paradigm, but separating the crown's well lit sides from the well lit, often vegetated background would be non-trivial. Then, the creation of another locally adaptive approach capable of switching between the tree-top and the ITC paradigms based on an *a priori* guess at crown sizes would make the analysis of large diversified regions more complete and more automatic.

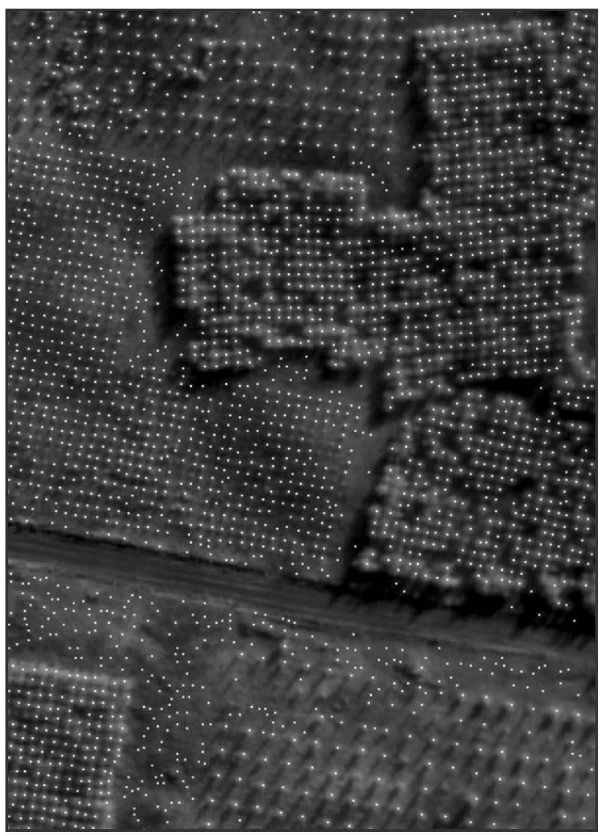

Figure 8 – *The locally adaptive tree-top technique (LATTOPS) applied to a 30 cm/pixel aerial image of young (< 10 years old) regeneration. The detection of a specific shadow for each tree made the difference in the more open regeneration areas at the bottom and at the top of the image, eliminating a lot of false tree detection from the grassy areas between the trees. The conventional tree-top (i.e., local maxima) technique is quite appropriate for the other (denser) areas (adapted from Gougeon and Leckie 1999).*

Forest inventory applications

From the above brief description of techniques to analyze high spatial resolution images for forestry purposes, it becomes obvious that numerous forest parameters of interest for management inventories or operational use can easily be extracted from such images. With only panchromatic images (or scanned black and white photos), information such as stem density, canopy closure, crown areas and stocking are at hand, while in the near future individual tree locations might be preserved. With multispectral images, precise and detailed species composition to a few percent with explicit mention of all minority species within each stand is a possibility. Regrouping to forest stands that are more refined than those currently used or keeping ITC information for direct use or to create on-demand application-oriented regroupings are also possible. Other forestry parameters that have not been available previously, such as gap locations and sizes (Figure 9), or gap distributions and connectivity, can now easily be extracted, even without species classifications. Species and gap distributions can be used to create maps of potential wildlife habitats. Immature, mature, and old-growth forests have different gap patterns. Snag detection is often possible and is of importance in assessing areas for their nesting bird potential. Individual tree assessment of defoliation or health could also be of interest, especially for very localized outbreaks such as outbreaks of root rot. An ITC classification of a panchromatic image into several classes might even be used in computer–assisted or fully automated interpretation of stand boundaries. Finally, full ITC-based analysis could lead to much needed detailed mapping of riparian areas, "just in time" helicopter logging of valuable wood, or the modeling of growth and competition on an ITC basis. Moreover, recent and upcoming high spatial resolution satellites (such as IKONOS and QuickBird) will make the whole analysis process easier (i.e., no need for photo mosaics and narrower field of view) and will speed up considerably the forest information extraction process.

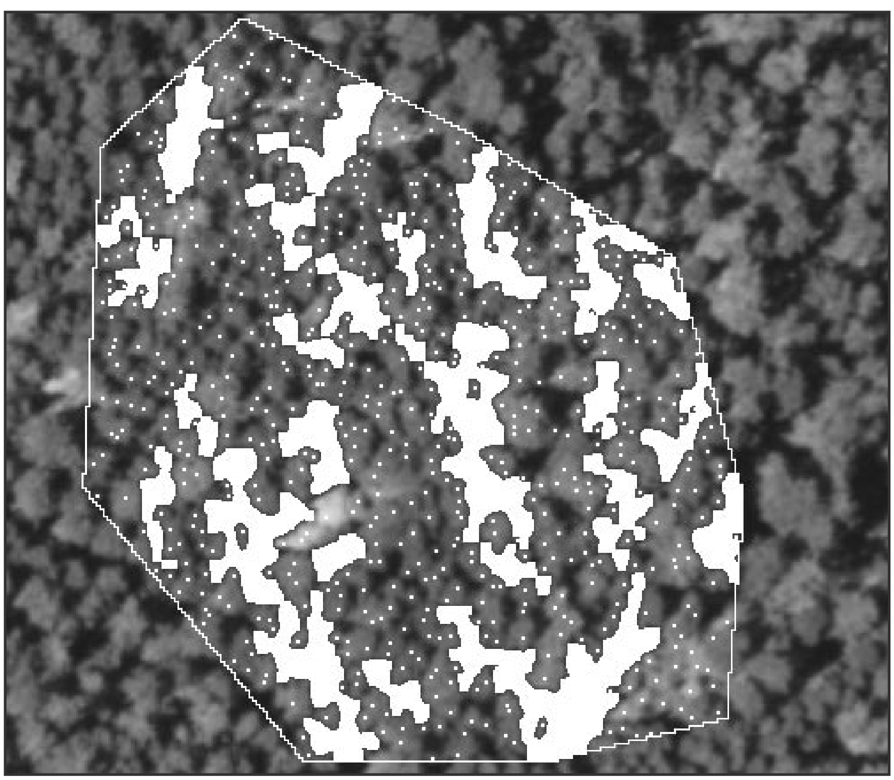

Figure 9 – *Even panchromatic images can deliver some of the modern forest parameters automatically such as locations and sizes of significant gaps. Currently, such information is not readily available.*

The ultimate goal behind the development of these ITC image analysis techniques is the production of detailed, precise, accurate and timely forest inventories. ITC-based information is so detailed that it can be regrouped using different abstraction levels depending on specific management or operational needs. Our hope is that ITC-based approaches will gradually replace the photo interpretation processes currently used throughout Canada. In the long run, the availability of information at the ITC level could alter the basis on which forests are managed, from a largely stand-based premise to a tree-based one. So, how close are we to ITC-based forest and vegetation inventories?

Work with multispectral aerial images at a resolution of 31 cm/pixel has demonstrated that, under ideal circumstances (medium-density softwood plantations, and at this high spatial resolution), 81% of the crowns delineated by the valley-following approach were the same (1:1) as those counted by photo interpreters using the same imagery (Gougeon 1995b). Figure 10 illustrates the capabilities of the delineation process at such high spatial resolution. Of course if lower resolution images are used or if the situation is more complicated (open areas or hardwood trees for example), this level of performance is not usually achievable. For example, an ITC analysis of a 1 m/pixel IKONOS image is not likely to produce viable tree counts (Figure 6). On the other hand, the presence of tree clusters instead of actual ITCs may not interfere significantly with an analysis of species composition or the production of good stand boundaries. It may not even interfere with good assessments of densities, as they could be adjusted to compensate for a given spatial resolution. Such image analyses, ITC-based in "spirit" only in that they are often based more on tree clusters than individual trees, may still lead to the production of forest inventories that are significantly better than those achieved by photo interpretation.

Individual tree crown species recognition has also been successful (Figure 11). In our pioneering work in Eastern Canada using multispectral aerial images at 36 cm/pixel (Gougeon 1995a), classification accuracy for manually delineated tree crowns of five coniferous species was of the order of 73% when judged

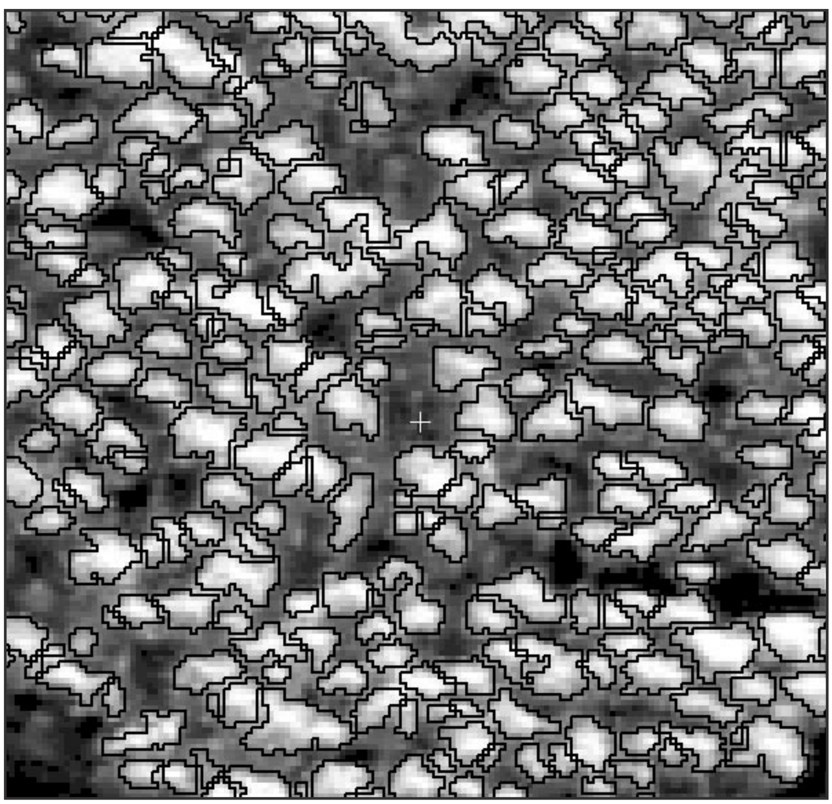

Figure 10 – *The type of ITC delineation achievable with a 36 cm/pixel airborne sensor image. There are still some tree clusters (isols) left, but very few (adapted from Gougeon and Leckie 2001).*

using independent test trees. More recently, an area in British Columbia populated by five coastal coniferous species was analyzed using 60 cm/pixel multispectral aerial data (Gougeon *et al*. 1999). The supervised classifications of automatically delineated tree crowns were compared with field transects through sixteen stands. On average, the species compositions from the analysis were found to be 12% different from those obtained using the transects. The dominant species proportion was only 10% off and any species covering more than 25% of the stand was 14% off. However, one should keep in mind that such successes were achieved with relatively young coniferous trees in plantations and there were only five species to differentiate. Even-aged young trees are typically easier to differentiate among themselves than mature trees where health and varying canopy openness often interferes with species recognition (Leckie *et al*. 1999c). In other work in which more species were considered, including hardwood trees, average classification accuracies of 56% for eight coniferous species and 65% for three hardwood species were achieved (Leckie and Gougeon 1999). Results were within 15% of those of photo interpreters using the same images. Even lower spatial resolution sensors like IKONOS, with its 1 m/pixel panchromatic band and 4 m/pixel multispectral images, can produce very encouraging species recognition results. In western Quebec, two areas spanning over 10,000 ha each were analyzed using an ITC approach. With relatively pure training and testing areas delineated on the imagery and ascertained from aerial photos, classification accuracies of the order of 75% (56-91%) were achieved for nine classes (CLC-Camint 2002).

Automatically regrouping ITCs into credible forest stands and generating stand attributes such as species composition, crown closure, and stem density for these stands (or for conventional stands) are two subjects of major interest. Of course, summarizing ITC-based information for each existing stand polygon and storing it as polygon attributes is a straightforward process. In a recent ITC analysis of an IKONOS image, the ITC species compositions extracted for each polygon of the existing provincial forest inventory were found to correspond very well with the compositions in the inventory, and precision was increased

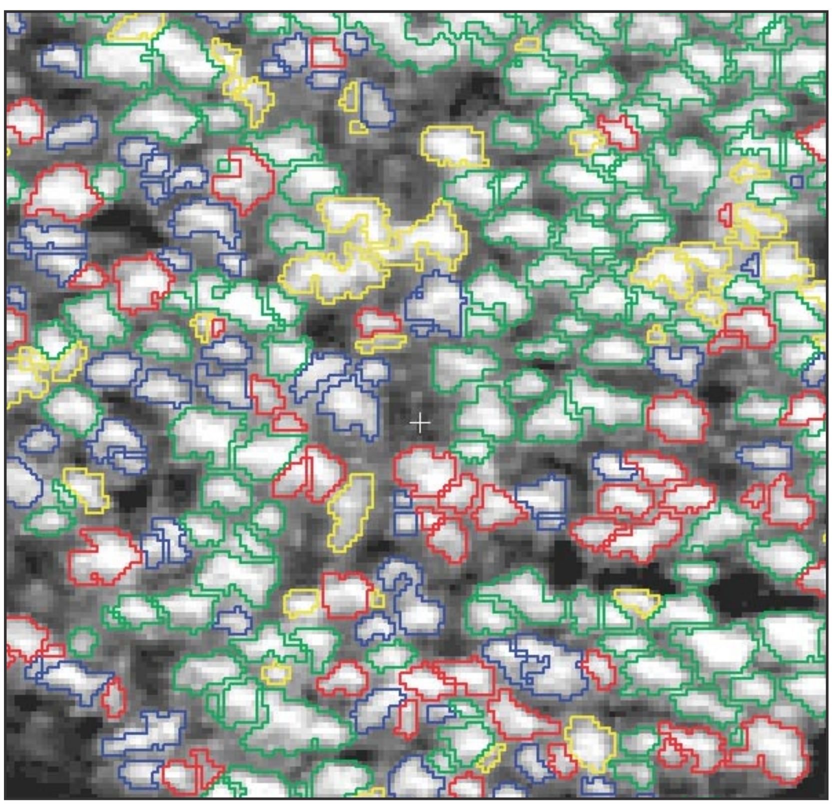

Figure 11 – *The ITCs from Figure 10 classified into species: white spruce (red), red pine (green), red spruce (blue), and white pine (yellow) (from Gougeon and Leckie 2001).*

(CLC-Camint 2002). This could mark the end of species composition in increments of 10% (sometimes 25%), with only two or three main species reported, which is standard practice in most Canadian provincial inventories (Leckie and Gillis 1995). In the same study, automatic stands were also generated using the methodology described in Gougeon *et al*. (1999). Figure 12 shows a near-infrared rendition of part of that IKONOS image with the provincially sanctioned stand boundaries, while Figure 13 shows the ITC analysis with the ITC-based stands. The stands are remarkably similar in shape, and the latter provides additional subtleties.

Semi-automatic forest inventories will only be fully acceptable with a proper tree or stand volume assessment scheme. Of course, the present system of regional stratification and volume assessment from stratum-representative plots could be used without any change. The better species compositions available from ITC analysis should already lead to better volume assessments. In addition, with airborne LiDAR (Light Detection and Ranging) systems slowly gaining acceptance within the forestry community, tree heights might be acquired remotely and new methods could be developed. Within the forest inventory context, LiDAR can be useful on three levels: *a*) to produce a detailed Digital Terrain Model (DTM), mostly useful for forest engineering applications but also necessary for the following two applications; *b*) to sample stands and get estimates of dominant tree heights; and *c*) in high spatial resolution mode, to get heights of individual trees, help in their delineation, and even delineate their crowns. For the moment, application (*a*) is the most documented. Application (*b*) has also been well researched, for example (Magnussen *et al*. 1999). We will briefly address application (*c*).

An interesting synergy can be achieved between high spatial resolution multispectral data and LiDAR data with resolution of the same order when georeferenced to one another. As mentioned in the preprocessing section, LiDAR data can be useful to separate mature forest from regenerating areas, for which different image analysis techniques are often required, or to help with the analysis of mature yet more open stands where illuminated understorey or forest floor material is visible. LiDAR data can also be used in a synergistic way to improve tree crown delineation (Gougeon *et al*. 2001b). Indeed, delineation with visible light can be hampered by the lack of shade between trees when rows of trees are at 90^o to the sun's illumination. A LiDAR-generated canopy height model, being unaffected by this phenomenon, can provide proper crown delineation and prevent the formation of numerous tree clusters. Given a well delineated tree crown, a local maxima operator should provide the biggest height within it. However, because there is no guarantee of hitting tree tops, the actual tree height may have to be inferred. Equations relating heights, crown areas, species and densities may be used to infer volume on an individual tree basis (Larocque and Marshall 1994). Growth models and volume projections through time could also be done on an ITC basis.

Even though the ITC-based approach to forest inventories can often lead to improved species composition and thus, most likely, to better volume and allowable cut assessments, and even though this can be accomplished in a very efficient and economical manner, ITC-based inventory will undoubtedly be accepted only very gradually. In addition, there are still several issues that need to be researched further. For the moment, the ITC approach will probably gain more acceptance when used to fill novel or relatively unexplored niches, especially if its use solves problems that current inventories don't handle well, for example:

- specialized inventories targeting only the spatial distribution of a few highly valued species,
- inventories of forest gaps and snags for wildlife management,
- detailed mapping of riparian areas, or
- inventories or assessments of partial or selective cuts.

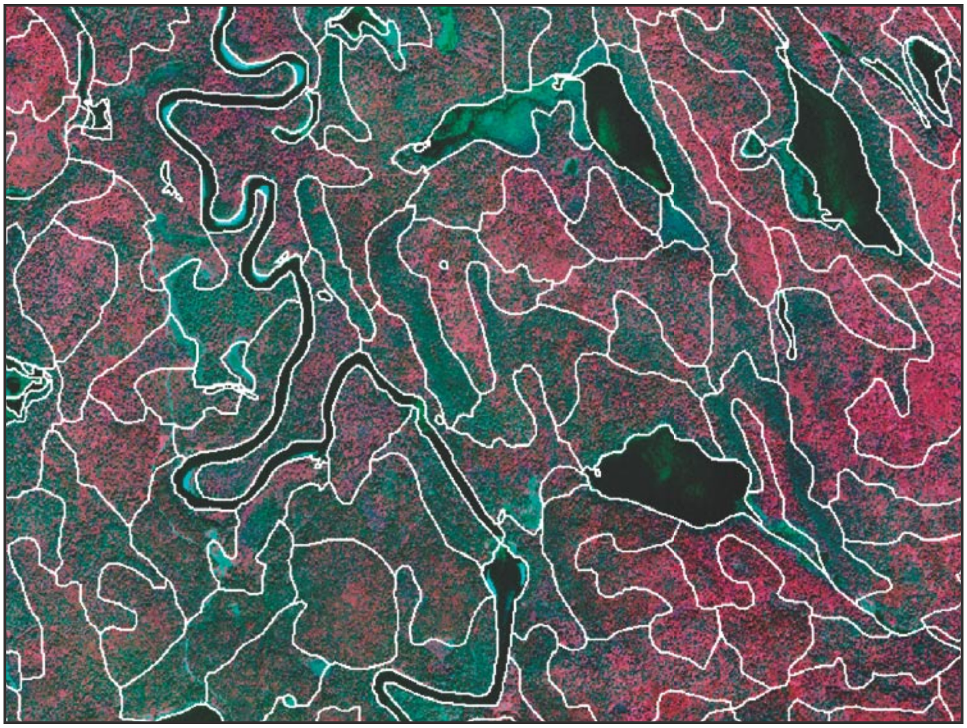

Figure 12 – *Provincial forest inventory stand polygons over a near-infrared rendition of part of an IKONOS image (4 m/pixel) from the Lac à l'ours area of Québec (Note: IKONOS panchromatic and pan-sharpened multispectral images are at 1 m/pixel, making an ITC analysis possible).*

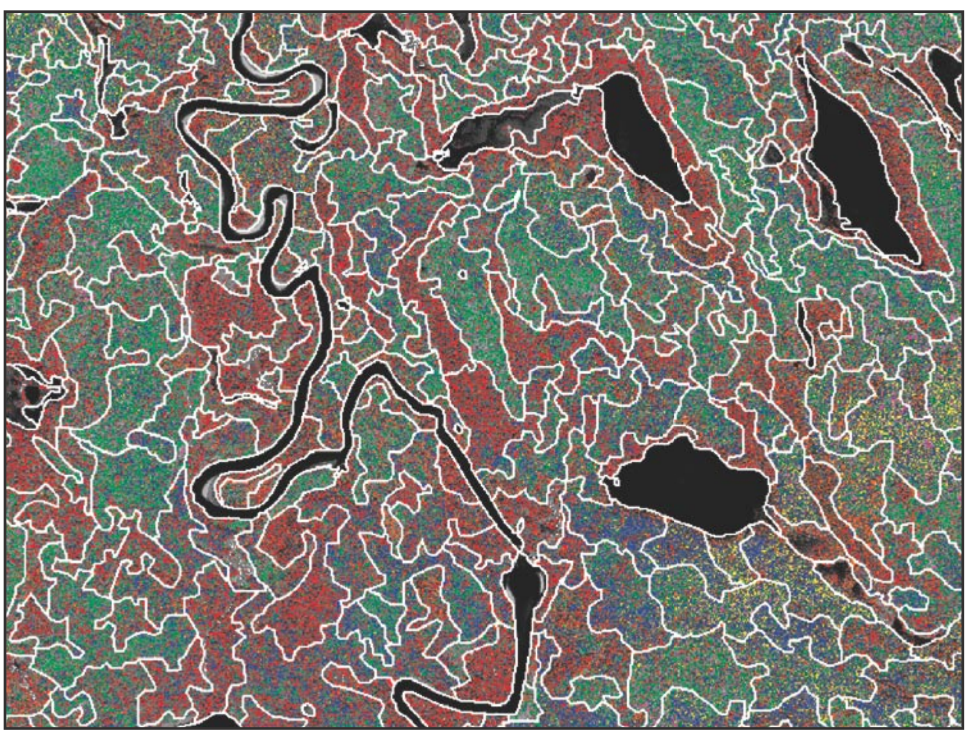

Figure 13 – *ITC analysis of the region in Figure 12, this time with computer-generated forest stands based on ITC species composition, density and closure. The classes are: white pine (in red), spruce-fir (brown), cedar (orange), maple (magenta), poplar (blue), white birch (gray), yellow birch (yellow), tolerant hardwood (dark green), regeneration (lite green), and non-vegetated (white).*

As mentioned before, several of these specialized inventories need not be truly ITC-based, but can work well although they are ITC-based in spirit only, in that they use tree clusters rather than ITCs. This means that the ITC approach can be used successfully with cruder high spatial resolution data (such as 1 m/pixel), implying lower data acquisition costs and less demanding computer processing constraints. Some ITC analysis may even be carried out using scanned panchromatic aerial photographs.

For example, a pilot project targeting white pine and yellow birch in the Outaouais section of the province of Quebec, Canada, and carried out using an IKONOS image (Gougeon *et al*. 2001a; CLC-Camint 2001) was highly successful. A major objective was the detection of the mere presence of these two species in areas where the conventional forest inventory did not even mention them. (In most conventional forest inventories, species that are a minority species within a stand, say less than 10% of canopy closure, are typically ignored. These minority species could nevertheless be highly valued, or valued by a specific forest company that made that species their specialty.

There are numerous other forestry applications that might benefit from an ITC approach. Table 2 outlines several applications that have been investigated and gives references to relevant scientific literature. Although some of the results are extremely promising, keep in mind that this is a new and emerging field and even though a lot of technology and techniques are presently available, there are still research issues and practical problems to resolve. Numerous factors have not yet been taken into consideration: topography, seasonal variations, atmospheric conditions, etc. The techniques need to be refined and proven under these various conditions. More importantly, results need to be assessed for precision and accuracy depending on which types of images are used (digitized black and white or color aerial photos, or aerial or satellite images from various sensors) and on their spatial, spectral, and radiometric resolutions. Simple quantitative data such as density, canopy closure and crown diameters still need to be validated, especially relative to the various spatial resolutions (10-100 cm/pixel) and image types.

Table 2 – *Other forestry applications investigated with ITC image analysis and corresponding references*

Forestry application	Reference
Automatic crown recognition vs with visual recognition	Leckie and Gougeon 1999
Individual tree crown species signature and classification	Gougeon 1995a
Individual tree crown regrouping	Gougeon *et al*. 1999
Damage assessments	Leckie *et al*. 1999a, 2001
Synergy with high resolution LIDAR data	Gougeon *et al*. 2001b
Synergy with low resolution LIDAR data	Magnussen *et al*. 1999
Specialized inventories for minority species	Gougeon *et al*. 2001a
Regeneration assessments	Gougeon and Leckie 1999
Interpretation assistance	Leckie *et al*. 1999b
Old growth forest assessment	Leckie *et al*. 2002b
Effects of spatial resolution	Leckie and Gougeon 1999
Forest gap analysis	Leckie *et al*. 1999c
Riparian area assessment	Paradine *et al*. 1999

Conclusion

This report presented some of the available image analysis techniques, methods and tools to extract ITC-based information from high spatial resolution images and introduced the reader to the potential of an ITC-based approach for forest inventory. We believe that ITC-based forest inventories would be more precise, accurate and timely than conventional inventories. In addition, the unprecedented level of detail would allow the extraction of a variety of additional multiresource management information, such as snag locations, forest gap sizes and distribution, highly valued tree locations, or riparian zone mapping.

Until very recently, such ITC analysis was only possible with images from airborne sensors. Their unstable platforms, narrow swaths and wide fields of view necessitated substantial preprocessing efforts to compensate for airplane instabilities, to normalize images, and to create mosaics in order to cover significant areas. The present availability of high spatial resolution satellites (and forthcoming improved satellites) with their stable platforms, narrow fields of view, and world-wide coverage can produce very good quality images of map sheet size, and could make ITC-based inventories very efficient.

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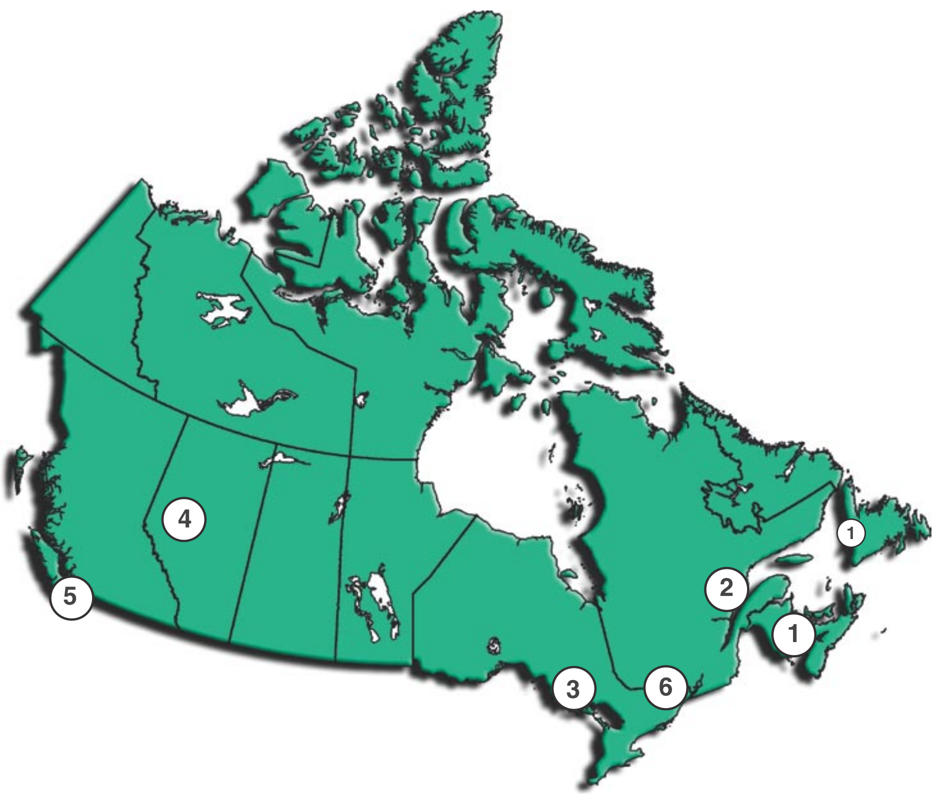

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