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The Individual Tree Crown Approach Applied to IKONOS Images of a Coniferous Plantation Area

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Abstract

In forestry, the availability of high spatial resolution (<1 m/pixel) imagery from new earth observation satellites like IKONOS favours a shift in the image analysis paradigm from a pixel-based approach towards one dealing directly with the essential structuring element of such images: the individual tree crown (ITC). This paper gives an initial assessment of the effects of 1 and 4 m/pixel spatial resolutions (panchromatic and multispectral bands, respectively) on the detection, delineation, and classification of the individual tree crowns seen in IKONOS images. Winter and summer IKONOS images of the Hudson plantation of the Petawawa Research Forest, Ontario, Canada were analyzed. The panchromatic images were resampled to 0.5 m/pixel and then smoothed using a 3x3 kernel mean filter. A valley following algorithm and rule-based isolation module were applied to delineate the individual tree crowns. Local maxima within a moving 3x3 window (i.e., Tree Tops) were also extracted from the smoothed images for comparison. Crown delineation and detection results were summarised and compared with field tree counts. Overall, the ITC delineation and the local maxima approaches led to tree counts that were on average 15% off for both seasons. Visual inspection reveals delineation of clusters of two or three crowns as a common source of error. Crown-based species spectral signatures were generated for six classes representing conifer species, plus a hardwood class and a shrub class. After the ITC-based classification, classification accuracy was ascertained using separate test areas of known species. The overall accuracy was 59%. Important confusion exists between red and white spruces, and mature *versus* immature white pines, but post-classification regroupings into single spruce and white pine classes led to an overall accuracy of 67%.

Introduction

Today's forest management inventories are still obtained by mapping forest stands and their content via the interpretation of medium scale aerial photographs, backed by field assessments and plot measurements (Leckie and Gillis, 1995). These are both expensive and time-consuming endeavours, and the resulting stand level inventory is not always very accurate (e.g., Quebec Government, 2004). Although designed and used for long term planning and, with stratification, used in calculating wood volume and estimating allowable cut, these inventories are rarely sufficient for operational (i.e., short-term) planning. An individual tree inventory would be extremely useful in that regard. However, this may not be completely realistic yet. Our current and more modest objectives are to examine if an individual tree based approach can be used to gather detailed information at the stand level, replacing the photo-interpretation phase in the production of forest management inventories. In this paper, we take a first step in examining the appropriateness of IKONOS images for that purpose.

In forestry computer image analysis, the high spatial resolution images (10-100 cm/pixel) available from airborne multispectral sensors, digital cameras, digitized aerial photographs and the newest earth observation satellites (e.g., IKONOS, QuickBird, OrbView-3) imply a shift in paradigm from the traditional pixel-based approaches to address more directly the key structural element of such images: the individual tree crown (ITC). Information gathered at this level could become an important way to meet the detailed information requirements of modern forest inventories and the need to manage the resource in accordance with stricter rules where biodiversity, wildlife, environmental and recreational concerns are increasingly taken into account. As forest industries move towards more selective cuts, precision forestry and "just in time" logging, such ITC-based approaches may progress from being an intermediate step that permits computers to provide sufficiently precise stand-level species compositions, to a state where full blown ITC inventories are the desired products.

ITC-based approaches can be summarily divided into three main streams based on the primary type of information obtained: tree location, tree location and crown dimensions, or full crown delineation. Techniques for finding tree locations are mostly based on detecting local maxima within the forested areas of a smoothed image (Gougeon and Moore, 1989; Eldridge and Edwards, 1993; Dralle and Rudemo, 1996, 97). Provided that the detection filter kernel size is appropriate for the tree sizes and the image resolution, this technique usually produces good results in medium to dense (i.e., devoid of sunlit openings) coniferous stands. In such situations, the local maxima often correspond very closely with the tree tops of conically shaped trees. To dynamically adjust to tree sizes or to detect trees in more open areas, locally adaptive variations of the process have also been developed (Gougeon and Leckie, 1999; Niemann *et al*., 1999; Wulder et al., 2000). Such techniques lead naturally to stem counts and thus, relatively good estimates of stand densities. With multispectral images, they can even lead to stand composition information via a species classification of tree tops using a conventional pixel by pixel classifier (Gougeon and Moore, 1989; Leckie et al., 1992). The detection and count of deciduous trees is generally not as successful as they may have more than a single point of high brightness.

Techniques for finding tree locations and crown dimensions (i.e., crown diameter) are often based on first finding local maxima and then, finding some edges of the crown (Pinz, 1991; Uuttera et al., 1998; Pouliot et al., 2002). Crown edges are typically found by following transects from the local maxima in various cardinal directions until an abrupt change (i.e., high gradient) is detected. Typically, only the crown edges found on the sunny sides of the crowns are reliable. The lengths of the reliable transects are then considered representative of the radius of the crown. Another more computer intensive approach to finding tree locations and crown dimensions is based on matching image features to two-dimensional projections of tree crown models (Pollock, 1994; Larsen and Rudemo, 1998). Such process must analyse the image multiple times, once for each specific crown type and diameter, and need a sophisticated decision system to resolve conflicting evidences. Such approaches may be advantageous with trees seen at large off-nadir view angles or, as a post-processing step in refining the analysis of other, less computer intensive, techniques.

Techniques aiming at full crown delineation are either based on following valleys of shade between tree crowns (Gougeon, 1995b; Andrew et al., 1999; Culvenor, 2002); following crown edges as detected by a gradient operator while analysing their curvature (Brandtberg and Walter, 1999); or starting a region-growing segmentation from a seed point within a crown (Uuttera *et al*., 1998; Erikson, 2003; Lamar *et al*., 2005). Because of their delineation of full crowns, such approaches can better lead to ITC-based species classifications, tree-based crown area assessments, stand canopy closure estimations, canopy gap detection and distributions, and possibly, biomass or volume estimations, in addition to tree detection and counting. All of the aforementioned techniques were developed and assessed using images from airborne sensors or cameras. In the near future, given sensors of an appropriate spatial resolution, full crown delineation techniques may lead to complete and precise individual tree inventories from satellite images.

Even though the limited spatial resolution of present spaceborne sensors, especially the multispectral bands (*i.e.*, IKONOS at 4 m/pixel), may not permit the generation of "true" individual tree inventories, applying an ITC-based approach to such images has already been shown to provide information that is often superior to that of conventional forest stand species composition assessments (Gougeon *et al*., 2001; CLC-Camint, 2001, 2002). It is thus important to evaluate the effectiveness of the "low" spatial resolution IKONOS images on the detection, delineation and species classification of individual tree crowns and remaining tree clusters. In order to do such an assessment, this paper first describes an ITC-based approach (Gougeon and Leckie, 2003) where crowns in medium to high density forested areas are delineated by initially following the valleys of shade that typically lie between them (Gougeon, 1995b) and then, applies the approach to two IKONOS images (winter and summer) of mostly coniferous plantation areas. The tree counts resulting from the crown delineation are compared with field counts. Counts resulting from the applications of the tree tops (or local maxima) approach, an approach mostly used for detecting and counting trees, are also presented. These tree count results are discussed, as well as, the results of classifying the ITCs from the summer image into seven species-related classes. The paper also includes an additional section where some important considerations for the ITC-based analysis of IKONOS images are outlined.

Imagery, Study Site and Field Data

A panchromatic IKONOS image of the Petawawa Research Forest (46.0° latitude, 77.4° longitude), in north-eastern Ontario, 200 km north-west of Ottawa, was acquired on March 24, 2000, at 15:58 hr EST. It was an off-nadir acquisition (74.3° elevation, 302.7° azimuth) with a cross scan spatial resolution of 0.87 m/pixel and an along scan resolution of 0.86 m/pixel, geometrically corrected to UTM coordinates and resampled by cubic convolution to the nominal spatial resolution of 1 m/pixel by the supplier, Space Imaging. Although, not an ideal time of the year to acquire forest imagery, because of low sun elevation (42.8°) and the presence of snow patches on the ground, it nevertheless permits an assessment of IKONOS' panchromatic image quality and of its potential for automated tree detection and crown delineation. A 300x300 m sub-image of a coniferous test area, the Hudson plantation, was extracted from the full image.

An11x13 km IKONOS image of the Petawawa Research Forest was also acquired on July 6, 2000 at 15:52 hr EST. Both panchromatic and multispectral data were ordered. The acquisition was also slightly off-nadir (82.6° elevation, 50.9° azimuth), leading to pixels with a cross scan spatial resolution of 0.83 m/pixel and an along scan resolution of 0.83 m/pixel, and supplied at the nominal 1 m/pixel and 4 m/pixel for the panchromatic and multispectral bands respectively. The spectral range of each IKONOS band is shown in Table 1. To allow for the analysis of species classification capability, a slightly wider area (720x560 m) around the Hudson plantation was extracted from the original image. In addition to their relatively low spatial resolution (4 m/pixel), the IKONOS multispectral bands acquired with the summer image appear to suffer from poor radiometric resolution. The panchromatic and near-infrared bands have dynamic ranges bordering on 10 and 9 bits of radiometric resolution, respectively. The visual bands are more in the range of 5-7 bits of radiometric resolution. This may affect their species discrimination capabilities.

The Hudson test site (Figure 1) is a mature plantation setting (65-80 years old) with tree heights of 20-23 m, crown diameters of approximately 1.7 to 4.5 m, with most being in the 2.5 to 4.0 m range, and stocking of 580-1000 stems/ha. There were plantations of pure red pine (*Pinus resinosa* Ait.), Scots pine (*Pinus sylvestris* L.), white spruce (*Picea glauca* (Moench) Voss) and red spruce (*Picea rubens* Sarg.), as well as mixed red pine and white spruce. There is one open low density plantation of Norway spruce (*Picea abies* (L.) Karst.) with crown diameters of 6 to 12 m and stocking of only 93 stems/ha. White pine (*Pinus strobus*) occurred as moderate to dense stands of trees 100-120 years old with minor red pine (<7%) associated with it. As well there were several stands of dense approximately 50 year old white pine with branchy crown form. These two types of white pine were treated as separate classes within the classification (mature white pine and immature white pine). Hardwoods occurred in both mature and young stands of poplar (*Populus* spp.), white birch (*Betula papyrifera* Marsh.) and maples (*Acer* spp.). Suppressed hardwoods also occurred in open patches within some less dense stands of red and white pine. Open areas along the shore of the Chalk River (northeast corner of the subarea) consisted of low shrubs in a wetland environment. This formed the basis of the shrub class used in the study.

Within the red pine, red spruce and Scots pine plantations there was very little ground vegetation, the ground cover being mostly needle litter. The white spruce stand was more open and its ground vegetation consists of herb, low shrub, grass and moss, with litter in the dense areas. The white spruce stand suffered from patches of root disease (*Armillaria* spp. and *Inontosus tomentosus*) and had some gaps due to mortality. These gaps showed dense ground vegetation and some hardwood regeneration. The training and test trees used in this study were from the dense mostly unaffected areas of the stand.

Species composition of stands was known from plantation records and forest inventory and confirmed in the field. Tree counts were conducted within red pine, red spruce, white spruce, mixed red pine-white spruce and Norway spruce plantations. All trees within the red spruce and Norway spruce plantations were counted and rectangular or parallelogram plots aligned along plantation row directions were enumerated for the red pine, white spruce and mixed red pine-white spruce plantations (Figure 2). Plots were accurately geolocated on the imagery using identifiable reference points on the imagey and known distances and directions from these points. Plot sizes ranged from 0.21 to 0.33 ha. Dominance of each tree was recorded (dominant, co-dominant, intermediate or suppressed). Trees in the plantations were almost exclusively dominant or co-dominant with very few intermediate and some suppressed. The suppressed trees were not incorporated in the tally used for comparison with the automated tree counts. Also noted were: tree species, split crowned stems, mortality and trees leaning into other crowns or into crown locations outside the plot. Split crowns, leaning trees and mortality of dominant and co-dominant trees were minor.

Techniques and Methods

The automatic delineation of tree crowns by the valley following technique (Gougeon, 1995b) relies on the presence of shaded material between those crowns. It generally leads to good crown delineation in high to medium density coniferous forests at spatial resolutions of 30-60 cm/pixel. It is also capable of separating deciduous tree crowns but, with a lower success rate, as their rounder shapes make the presence of significant shade between them less common. Several steps are necessary in the delineation and classification of individual trees. These include: preprocessing which is typically needed to eliminate large non-forested areas and, if possible, non-treed surfaces within forested areas; selection or creation of an illumination image for tree delineation or detection; smoothing and possibly resampling the illumination image, and selecting tree isolation algorithm settings. It is anticipated that modifications to preprocessing procedures and algorithm settings will be needed due to the specific nature of IKONOS imagery (e.g., 1 m resolution of the panchromatic imagery and lack of multispectral data with corresponding resolution). Various preprocessing procedures and algorithm settings were explored. This section outlines the general procedures found appropriate with other high resolution imagery for our individual tree crown delineation and classification processes and for the local maxima tree detection technique, and discusses modifications found necessary for the IKONOS imagery.

Pre-processing

The valley following technique relies on some pre-processing to eliminate (mask-out) non-forested areas from contention. Simple thresholds or multispectral rules such as “detect pixels having a near-infrared radiance smaller than its mean visible band radiance”, can sometimes be used to create effective non-vegetation masks. Here, only the road and the snow, in the summer and winter images respectively, were eliminated this way. With the winter panchromatic image, a grey level threshold of 550 succeeded in removing most of the snow-covered areas from further analysis, including most of the snow-covered road (as seen in Figure 3). With the summer image, the road and its shoulders were masked by manually delineating them on the image.

Also, because of its basic premise (i.e., shade between trees), some pre-processing is usually desirable in the more open, lower density forested areas, where non-shaded background material is often visible between tree crowns. A pixel-based classification or a texture analysis is occasionally helpful. However, this can have important side-effects. For example in this study, the very open stand of large Norway spruce trees could not be adequately analysed on the summer imagery because crown-like reflectance from grassy areas between the trees could not be reliably removed.

As part of preprocessing, the input illumination image (here, the panchromatic band) is usually smoothed using a 3x3 mean filtering kernel, as the valley following process is facilitated by smooth spectral topography. The rule-based isolation process, which is run after the valley following process, finishes the delineation of crowns on an object-by-object basis. Various combinations of filtering and spatial resampling were tested regarding both ITC crown delineation and the Tree Tops crown detection. It was found that a doubling of the spatial resolution (to 0.5 m/pixel) by cubic convolution followed by a 3x3 mean filtering was most effective. The algorithms function better when there are not too few pixels per crown. This resampling appears to preserve or even enhance the image intensity topography that characterizes the shadow (valleys) between trees and peaks of the trees, and provides a reasonable number of pixels per crown.

Individual Tree Crown Delineation

When the illumination image has been prepared (selected or created, possibly resampled, and filtered) and the non-forested areas masked out, the delineation of individual tree crowns is performed in two main steps: the valley following and the rule-based crown delineation processes (Gougeon, 1995b; Gougeon and Leckie, 2003). In the valley following process, a threshold (the *lower threshold*) is first used to eliminate small areas of shade, areas typically devoid of significant trees in which following valleys of deeper shade would make little sense. Then, local minima are found in what are essentially the “pure” forested areas of the smoothed illumination image. They correspond to points of deepest shade, typically between four tree crowns. From these initial local minima, all possible valleys of shade in the image are followed pixel by pixel, resulting in a fairly good, yet often incomplete, separation of tree crowns. A valley pixel is defined as a pixel continuing the valley (8-connected) that has a radiance value lower than the pixels on its right and on its left, when going in the valley direction. Allowances are made for the possibility of valleys that are 2-3 pixels wide. An *upper threshold* can be used to limit valley progression into high radiance values, somewhat preventing crowns from being over-broken, especially at higher resolution. A *valley noise* threshold also exists to compensate for radiometric noise or the presence of an object in the path of a valley, such as a low completely shaded branch sticking out of one crown or a small fully shaded understorey tree.

The valley following process is succeeded by a rule-based crown delineation process that attempts to finish the separation of tree crowns and produces tree crown outlines. It results in objects that are referred to as isols (isolations) and typically represent individual tree crowns or, under certain circumstances and/or poorer spatial resolution, can be tree clusters. For each 2x2 pixel block of tree material in the bitmap resulting from the valley following, the rule-based process tries to follow the suspected crown boundaries, favouring clockwise motions and aiming for closure. High-level rules try to detect situations where clusters of trees have been delineated. They use small indentations in the cluster boundary and inlets into the clusters as potential indicators of where to separate the cluster into individual tree crowns. A user-specified *jump factor* controls the length of bridging that is allowed in this process. When additional applications of the rules lead to little progress throughout the image, a bitmap of individual tree crowns and remaining tree clusters is generated. From then on, these isols are treated as the objects of all further analysis. In one study at 31 cm/pixel over the same site (Gougeon, 1995b), 81% of the objects delineated corresponded one to one (1:1) with coniferous tree crowns delineated by interpreters. However, crown separation success is expected to decrease significantly with lower spatial resolutions. Separation is also harder for the less conical deciduous trees, as their rounder shapes make the presence of shade between them less likely and less significant.

With the smoothed winter panchromatic image, the valley following algorithm was used with the following grey level thresholds: 100, 550, 2, as lower, upper and noise thresholds, respectively. An image examination revealed that 100 was essentially the upper limit of the grey level range of fully shaded open areas. Setting the upper threshold at 550 meant that the full range of grey levels expected from treed areas would be considered, since anything above that was already determined to represent mostly snow. The valley noise threshold was set to 2 based on past experience with a radiometric resolution of about 9 bits. The “mature” tree jump factor option was used with the rule-based delineation system. With an illumination image resolution of 50 cm/pixel, this implies potential bridging of valley gaps of up to one metre, or 2 pixels.

With the smoothed summer panchromatic image, the valley following algorithm was used with the following grey level thresholds: 500, 1500, 5, as lower, upper and noise thresholds, respectively. Again, an image examination revealed that 500 was essentially the upper limit of grey levels of the fully shaded open areas and that 1500 corresponded to the upper limit of grey levels of treed material. The valley noise threshold was set to 5 similar to that used on other types of imagery with radiometric resolutions of about 10-11 bits. The “mature” tree jump factor was also used with the rule-based delineation system.

Individual Tree Crown Classification

Using a multispectral dataset, an ITC-based supervised classification typically proceeds as follows:

a) representative samples of crowns, picked individually or within training areas, are used to generate signatures for every class,
b) a maximum-likelihood classification process is run to identify the species of every tree (or isol) in the image, and,
c) the ITC classification is evaluated with single species test areas (or individually identified test trees) from which a confusion matrix is generated; alternately, the classification can be tested on a stand-composition-basis via field samples (e.g., plots, transects).

Typically, the supervised species signature generation process involves delineating on the image training areas encompassing crowns (or isols) of a single species in a single situation in order to generate that class’ signature. These areas are usually identified from a combination of auxiliary information such as aerial photographs, old forest inventories, or a pre-analysis of the image to find uniform areas, followed by field assessment of their content. Here, the well-documented uniform plantation situation makes delineating training areas simple.

Using the bitmap generated by the crown delineation processes, the signature generation program takes care of extracting the crowns (isols) within the training areas, generating crown-based signatures, and combining them into class signatures (typically, the average of the crown multispectral means and the covariance of those crown means is used). Often, as in the case here, the crown multispectral mean is generated using a subset of pixels from the crown rather than the full crown. Indeed, the valley-following-based delineation process was designed with the intent of getting the fullest crown possible (i.e., not just the bright parts of the crown as in other methods). This means that it theoretically captures the shaded side, as well as, the lit side of a crown. On the other hand, introducing pixels from the shaded sides of crowns is detrimental to the classification process as crown means become more affected by the proportion of lit to shaded pixels than by the intrinsic multispectral reflectance of a species. Thus, before the signature generation and classification processes, a mask termed the "lit-side mask" is generated from the crown (isol) bitmap and subsequently used by the two processes (Gougeon, 1995a). Presently, the lit-side is simply defined as all pixels within the crown with grey-level values higher than the mean of the full crown (in the illumination image). These pixels generally correspond well to the lit-side of crowns, with the occasional addition of an odd "brighter than normal" pixel on the shaded side. This approach generates more precise multispectral signatures known as "mean-lit" signatures and overall, better classifications.

For the crown-based classification, the crowns (isols) are taken one-by-one from the bitmap, a crown signature is generated using the same features and parameters as in the class signature generation process, its likelihood of belonging to each classes is calculated, and a final decision is made based on a maximum likelihood decision rule, taking a confidence interval into consideration. When all of the isols have been assessed, classification results can be displayed and evaluated. Here, only the summer IKONOS image, for which we have multispectral channels, was analysed.

For this study, ITC-based signatures were generated for seven classes: red pine, red spruce, white spruce, Scots pine, mature white pine, immature white pine and hardwoods. An additional class, shrubs, was introduced for completeness and to balance the classification process, even though its isols are known not to be trees, nor tree clusters. That class is not considered henceforth. The white pines were separated into two classes because their different ages and crown forms produced significantly different signatures.

The IKONOS imagery presents some new issues related to how to conduct individual tree crown classifications. As mentioned, tree crown outlines are more efficiently obtained using panchromatic data resampled to 50 cm/pixel. The increased spatial resolution facilitates crown separation. Similarly, if the multispectral data at 4 m/pixel was used directly most crowns would have very few pixels associated with them, especially if the mean-lit signatures are used. The 4 m resolution multispectral data was therefore also resampled to 50 cm by cubic convolution and used for signature generation and ITC classification. The panchromatic band, despite having little spectral information, contains greater spatial detail and is less likely to be contaminated by reflectance from outside the tree crown. An analysis of spectral distances (Jeffries-Matusita) between species classes revealed that the panchromatic band was useful to increase class separation and is thus included in the process.

In a supervised classification approach, the prevalent way to evaluate classification accuracy is to establish several representative areas to be used as test areas from which a confusion matrix is calculated. For a "real" ITC analysis, the automatically delineated crowns should be compared "tree for tree" with manually delineated crown such that delineation and classification accuracies can both taken into account to calculate an ITC recognition accuracy (Leckie *et al.*, 2004). Alternative approaches can involve comparing the species composition obtained within given stands with that reported by an existing forest inventory or with species compositions obtained from ground transects or field plots within the stands (Gougeon and Leckie, 2003). Here, with such pure plantation stands, the conventional remote sensing approach is quite appropriate and test areas were delineated for the seven classes mentioned above. Each class has 3 to 6 test areas of approximately equal size derived from 2 to 3 separate stands. Exceptions were the red spruce and Scots pine classes for which there is only one stand in the study site. Training areas used for generating the maximum likelihood classification signatures were not included in any part of the test areas. Across all test areas, the total number of isols used for each species class ranged from 68 to 364.

The Tree Top Approach

Another way to establish tree locations, estimate tree counts, make density assessments and even conduct species classification is the "Tree Top" or local maxima technique (Gougeon and Moore, 1989; Elridge and Edwards, 1993; Dralle and Rudemo, 1996, 1997). The technique is often used with mature trees in lower resolution (1-2 m/pixel) images (Gougeon and Leckie, 2003) or with smaller trees in high resolution (10-100 cm/pixel) images, such as in very young (<10 years old) regenerating areas (Gougeon, 1997a) where proper spacing and stocking need to be assessed. It consists of detecting the most brilliant pixels (or local maxima) within a moving window scanning the forest areas of an illumination image. Hopefully, only one such pixel is found within each tree crown. For coniferous tree crowns seen close to nadir, such pixels are often located on the sunlit side of the tree near the tree top, hence the name. For deciduous trees, the relationship is not as straightforward. They have more chances of yielding multiple local maxima within their crowns. The relationship is more dependent on the size of the crowns relative to the spatial resolution of the image and the window size used by the local maxima operation. This also applies to less conical coniferous tree crowns like, large eastern white pines and, applies generally, but to a lesser extent, to any coniferous tree crown. Unless some kind of locally adaptive method (Gougeon, 1997a; Gougeon and Leckie, 1999; Wulder et al., 2000) is used, tree counts can be unreliable. Multi-level canopy or random openness of the canopy can create additional uncertainties. The "standard" tree top technique is thus primarily efficient in medium to high density conically-shaped softwood-populated forest stands, as is mostly the case here.

Since local maxima techniques are prevalent in the forestry remote sensing community, the Tree Tops method is used as an additional point of comparison while evaluating the accuracy and repeatability (i.e., winter and summer) of the ITC delineation counts. The tree top technique has more or less the same preprocessing requirements as the ITC delineation approach: removal of non-forested areas and smoothing of the illumination image. It also benefits from the presence of shade between tree crowns. The use of a minimum threshold eliminates a majority of shaded pixels and limits false positives from the understorey or low branches. Here, minimum thresholds of 150 and 600 were used for the winter and summer illumination images, respectively. It however is interesting to note that the "low resolution" of the panchromatic imagery may not be as large a problem with the tree top technique as it can be with tree delineation approaches where spatial details are needed to outline crowns. Indeed, it has been observed that, if the resolution is too high, false detections related to structures within individual tree crowns can occur. Here, the same processed imagery used for the ITC crown delineation was used for the Tree Tops crown detection (i.e., the panchromatic band resampled to 50 cm and mean filtered with a 3x3 window).

Results and Discussion

Individual Tree Crown Delineation

This study assesses tree counts (TTs and ITCs) and ITC species classification accuracies. Delineation accuracy *per se* was not examined because given the spatial resolution of the imagery and the high density of trees it was not possible to match trees on the ground to trees in the imagery and thus, to compare crown size and borders. Other ongoing research studies assess delineation accuracy by comparing the automatically delineated tree crowns with those delineated based a combination of ground observation and interpretation of the imagery for a limited number of plots for which detailed field information is acquired (e.g., Leckie et al., 1999; 2004). Here, we will only comment on some of the difficulties in getting what appears to be good crown delineation in the summer and winter images.

With the smoothed winter panchromatic image (Figure 3), the individual tree crown delineation process led to relatively well delineated tree crowns, especially in the denser treed areas that are considered ideal situations for this approach (Figure 4). Tree clusters occur where separation based on shade was not possible. Odd looking crown delineations are visible, especially at stand boundaries or in the more open areas where understorey trees and shrubs are being picked-up and merged with bigger tree crowns. The simple threshold used to remove most of the snow-covered areas from further processing (i.e., by creating a mask) also created artefacts. Typically, for any given snow patch, a surrounding border of mixels (i.e., mixed pixels) makes its way through the tree delineation system and generates odd looking objects, considered trees, around that patch. Fortunately, most of our test areas are not substantially affected.

With the smoothed summer panchromatic image (Figure 5a), the settings of the individual tree crown delineation process (i.e., thresholds and parameters) also led to relatively well delineated tree crowns, although generally smaller than their winter counterparts. This is a normal side effect of using a higher valley noise threshold. Although needed to facilitate the continuation of shade valleys and thus, separate more tree crowns, a higher threshold tends to create wider valleys and thus crowns with smaller areas. There are tree clusters where separation based on shade was not possible, but the higher radiometric resolution of this summer image appears to help in the more difficult areas. For example, at the border between the red pine and red spruce plantations, there is a row of well-lit red pines (due to their superior height versus the red spruce), which is typically very hard to separate into single crowns (Gougeon, 1995b). Nevertheless, this analysis did remarkably well (Figure 5c).

Tree Detection and Counts

Tree counts or stem density is an important descriptive parameter of forest stands. The “tree top” and the “individual tree crown” approaches can both lead to specific locations for each crown, and thus, to tree counts. With the ITC approach, the crowns' centres of gravity are typically used for that purpose. In this study, we did not attempt a one-for-one comparison between the locations resulting from the two methods. Correspondence of crown delineations (ITCs) and tree tops (TTs) to actual trees were assessed qualitatively relative to the image information. Counts were used as an index of success of the algorithms. Unfortunately, such simple counts do not take into consideration errors of commission and omission. To a certain extent, these errors could balance each other and give performance results that are more optimistic. For example, work with a 31 cm/pixel aerial image of the same area reports a 7.7% error in counts, but only 81% (19% error) of the delineated tree crowns were a “one-for-one” match relative to interpreters' assessments (Gougeon, 1995b). However, visual observations of tree correspondence on the imagery for this study reveal that offsetting omissions and commissions does not appear to be a sizeable problem. A study with 36 cm multispectral image analyzed the capability for visual tree detection and counts in natural stands (Leckie and Gougeon, 1999): one-for-one correspondence accuracy was approximately 75%, with optimum detection of softwood trees occurring at resolutions providing 25-45 pixels per tree.

The counts resulting from the two methods for both the winter and summer resampled panchromatic images are shown relative to the field counts in Table 2. Correspondence of counts is reasonable. An exception is the Norway spruce stand, which has very large crowned open grown trees in a grassy field. The detection of grass patches combined with the over-splitting of the large tree crowns into several objects produced a large overcount. In many cases, large branches or groups of branches of the Norway spruces were identified as potential trees. Not taking the Norway spruce stand (stand 5) into account, Table 2 can be summarised as follows. For the summer imagery, the counts from the tree top approach (TTs) are on average 10% off from the ground counts (average of the absolute value of the difference between the automated and ground counts). Count errors ranged from +1.5 to -22.3. Counts were 17% off for the winter image, ranging from 9% to 25%. All were underestimates.

The counts for the crown delineation approach (isols) are on average 17% off, ranging from 8% to 24% for the summer imagery, and 12% off, with a range of 2% to 27% for the winter image. There was both underestimation and overestimation on the summer imagery, but error was mainly due to underestimation for the winter imagery. On average combining all of the counts of the winter and summer images, results were 15% off relative to the ground counts for both the Tree Top and the ITC approaches. The best counts were only 1% off while the worst was -27%. This is a far better result than expected from 1m/pixel imagery. In this closed-canopy conifer plantation situation, both the Tree Top and the ITC approaches seem appropriate for counting trees and are mostly independent of the season. Of course, this should be viewed only as a comparison benchmark. Such successful counts are unlikely in mixed species uneven aged stands. The technique of doubling the spatial resolution to 0.5 m/pixel was certainly an asset and should be considered for all IKONOS image analysis with the ITC approach.

This study was designed to examine the capability of automated analysis in dense conifer stands, nevertheless it is interesting to examine other types of stands. Outside of the test areas, isolation and detection results are more complex, especially as several stands are fairly open. In the summer image (Figure 5a), the Tree Top approach generates numerous false positives from understorey material in the open parts of the white spruce stand (top-center) and in the white pine stand (bottom-left). Due to the lower sun elevation and greater view angle, the situation is not as bad on the winter image (Figure 3). For the same two areas, the ITC approach applied to the winter data tended to delineate bigger objects that are often a mixture of tree crown and understorey materials. The summer image appears less prone to this phenomenon, delineating smaller objects, some for the crowns and some for understorey material. This better separation, which is more obvious in the classified image (see Figures 5d), is attributed to the better radiometric resolution of the summer panchromatic image and the more aggressive valley following, a consequence of the higher valley noise tolerance threshold.

Individual Tree Crown Classification

The best classification results were obtained with signatures based on the spectral means of the “lit-side” of the crowns (Figure 5d). However, it should be noted that the use of the mean-lit signature only brought slight improvements over the full crown based signatures and classification. The resulting confusion matrix for the seven species-related classes is shown in Table 3**.** As expected, hardwood trees are well classified (81%), as they have a broad, yet very distinct signature from the softwood classes. Within the coniferous classes, red pine fairs relatively well at 65%, with a moderate and relatively balanced amount of confusion with the other classes, Scots pine being the highest with 10% of the red pine in the test area being classed as Scots pine. Although the red spruce class also fairs relatively well on its own (63%), it has slightly more confusion with Scots pine (12%) and a noticeable number of unclassified individuals (12%). The white spruce test areas indicated that important confusion existed with red spruces (25%) and with Scots Pine (20%). The white spruces appear to have difficulty being classified, with only 37% of the isols within the test areas being recognized as such. For the Scots pines (62% correct) in the test area, important confusion with white spruce (19%) and to a lesser degree with red spruce (10%) occurred, and Scots pine generally appears to be the class creating the most confusion for other classes. Finally, the classification accuracies for the two white pine classes (50% and 53%) appear low, but some of the confusion is among each other. Mature white pine also gets confused for Scot pine (15%) or white spruce (14%), while immature white pine has more confusion with hardwood (11%). This resulted in an overall classification accuracy of 59%. A post-classification merging of the two white pine classes (accuracy of 60%) and of the white and red spruce classes (accuracy of 64%) resulted in an overall classification accuracy of 66.5%, 62.5% if only the conifers are considered. This leads to a balanced picture, with all of the coniferous class accuracies between 60% and 65%.

Such classification accuracies appear quite reasonable, especially when compared with a previous study using similar signature types and methodology (Gougeon 1995a), but with 36 cm/pixel multispectral airborne data. Results for that study indicated an overall accuracy of 74% for five coniferous species. With similar imagery (Leckie and Gougeon, 1999), visual interpretation of softwood species in natural stands was in the order of 70 to 90% accurate, with automated classification of manual delineations of the same trees generally being 15% less accurate. Because their spectral signatures are so close to each other, usually within a standard deviation, it is typically very hard to reliably separate five coniferous species. Here, one of the additional confounding factors is most likely the poor spatial resolution of the multispectral channels (Figure 5b). Indeed, because the multispectral data was resampled to 0.5 m/pixel each tree crown (or isolation) signature appears to be based on statistics from 20 to 60 pixels, but in reality these may have been derived from only a few original four metre pixels. In addition, even though the methodology implies removing valleys of shade between tree crowns and not using the shaded parts of those tree crowns (i.e., lit-side mask), the vast majority of these 4 m pixels will have been influenced by shade. This explains why using the lit mask led to only minute improvements in classification accuracy over the signature derived from the full crown. If not considered, this situation also has the potential to make species classification of IKONOS isolations fairly unstable. That is, crown signatures may become more influenced by their shade content than by species reflectance *per se*. A possible remedy may be to take stand densities as well as species into consideration when creating classes.

IKONOS Image Analysis Considerations

It is important to point out that the classification of species within this study probably benefited tremendously from the use of single species, even aged, evenly spaced plantation stands. First, this meant that all training and test areas were devoid of trees from other species, a convenience rarely available. Importantly, every 4 m pixel spanning more than one tree was not corrupted by reflectance from another species. Only the proportion of shaded material within some of the pixels contributing to a crown signature had a corrupting influence. A mixed forest would not convey the same benefits and presumably not do as well. Dealing with mature trees was also a benefit. Their bigger crowns make them easier to delineate at 50 cm/pixel and they classify better because the chance of shaded material influencing their crown signature, via the 4 m/pixel multispectral data, is proportionally less than with smaller crowned trees. A mixture of big and small trees, even though of the same species, would also likely have complicated the analysis. A classification of spruce budworm defoliation levels on an individual crown basis with IKONOS imagery (Leckie et al., 2003a) showed that this pixel contamination was important when crowns were small and composition mixed. This phenomenon is well illustrated by the differences between the shadows projected upon the road in Figures 5a and 5b.

Although the “low resolution” of the IKONOS imagery makes it incapable of generating “true” individual tree forest inventories, it is possible that the application of an ITC-based approach could nevertheless lead to extremely valuable information at the stand level. In addition, the availability of information such as tree density, canopy closure, and the spatial distribution of species over a large area (e.g., 11x11 km images) makes possible a semi-automatic delineation of forest stands (Gougeon, 1997b; CLC-Camint, 2002; Leckie *et al*., 2003b). Highly specialized inventories are also possible. For example, a recent pilot project with IKONOS imagery tackled only the distribution of white pine and yellow birch within a given management area (CLC-Camint, 2001). This type of information can be crucial for forest companies that are making a single species a specialty, especially because many inventories do not mention minority species (<10% or <25%) within stands. In addition, ITC-based forest analyses could lead to information heretofore unavailable such as: small forest gaps and their distribution for wildlife management, or snag locations for nesting bird habitat assessments.

One of the main advantages of using satellite images to produce forest management information is without any doubt its wide area coverage relative to individual aerial images or even, airborne sensor strips. In the case of IKONOS, a single image is 11km by 11km. For QuickBird, a single image can be 16.5x16.5 km, which is the approximate size of common forestry maps (Leckie and Gillis, 1995). In both cases, long continuous strips of imagery along the satellite tracks are also available. As ITC-based species classifications rely primarily on spectral signatures and spectral signatures are essentially unique to the image in which they were generated, having a single image that covers a large area is highly convenient. In addition, satellite images have a narrow field of view and can usually be acquired close to, or at nadir, minimizing view angle related problems common to aerial acquisitions. Although, computer analyses of such images can lead to rather sizeable datasets (0.5 - 10 GB) even by today's standard, their processing does not present any major problem. Of course, getting a good image acquisition (i.e., little cloud or haze and near nadir) within a limited window of opportunity (e.g., June through August) can still be a problem.

Summary and Conclusion

For forestry applications, the high spatial resolution (< 1 m/pixel) of the newest satellite images allows us to perceive individual trees whereas with previous lower resolution satellite imagery there was only forest. This commands a more object-oriented image analysis paradigm, one that drives us away from pixel-based techniques and towards the delineation and classification of individual tree crowns. Fortunately, such techniques have been developed to analyse even higher resolution images (30-60 cm/pixel) from airborne sensors. This paper analysed their application to IKONOS images of a coniferous plantation and reports on their suitability and performance.

The crown detection and classification results at spatial resolutions of 1 and 4 m/pixel are very encouraging. For both winter and summer IKONOS images, tree counts with the well known local maxima (or Tree Top) approach were approximately 15% off. Counts with the ITC approach were also only 15% off relative to a ground survey. This compares well with counts that were 8% off using 31 cm/pixel aerial data (Gougeon 1995b). However, there can be an unknown cancelling effect of omission and commission errors. Quantification of tree-for-tree correspondence of automated isolations was not possible in this study, but visual inspection indicated that clusters of two or three trees occurred. Clusters were more prevalent in the white pine and hardwood areas. Single species, even age stands of essentially conical shaped trees facilitated the delineation process. Less accurate delineation and count results are to be expected with more diverse natural forest stands. An overall ITC species classification accuracy of 66.5% was achieved, but only after separating and recombining certain hard to separate but related classes (white and red spruces; mature and immature white pines). Again, the single species, even age, plantation nature of the stands in this study probably had mitigating effects against the poorer spatial resolution (4 m/pixel) of the multispectral data.

From the above analysis, it becomes clear that IKONOS images may not be suitable to produce "real" individual tree inventories. However, it is speculated (and on-going studies seem to confirm) that using an ITC-based approach can lead to valuable results at the forest stand level, especially relative to stand species composition (CLC-Camint, 2002; 2003; Leckie et al., 2003b). It is also known that some of the information provided by such ITC-based analyses (i.e., composition, density, canopy closure) can be used to generate, almost automatically, forest stand boundaries (Gougeon, 1997b; Gougeon and Leckie, 2003), a very important step in the production of traditional forest management inventories. In addition, because species comprising less than 10% of a stand's composition (25% in some cases) are generally not mapped in typical forest management inventories, ITC-based analyses of IKONOS imagery can be used to produce highly specialized inventories, such as those based on the detection and localization of minority, yet commercially important species (Gougeon et al., 2001; CLC-Camint, 2001). The potential also exists to produce novel information for wildlife, health and biodiversity assessments (CLC-Camint, 2003; Leckie et al., 2003a). Thus, as long as "real" individual tree inventories are not expected, IKONOS image analyses with ITC-based tools can lead to very valuable, sometimes heretofore unavailable, forestry information.

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Table 1 - IKONOS spectral band characteristics				
Band	**Lower 50% (nm)**	**Upper 50% (nm)**	**Bandwidth (nm)**	**Center (nm)**
Pan	525.8	928.5	403	727.1
MS-1 (Blue)	444.7	516.0	71.3	480.3
MS-2 (Green)	506.4	595.0	88.6	550.7
MS-3 (Red)	631.9	697.7	65.8	664.8
MS-4 (VNIR)	757.3	852.7	95.4	805.0

Table 2 –Tree Tops (TTs) counts and ITC-Suite isolated objects (Isols) counts from the summer and winter IKONOS sub-images. Also given are the field counts and the percentage of difference (% diff.) from the field counts (see Figure 2 for the location of test areas 1 to 5).

Forest Stands	**Field Counts**	**Summer TTs Counts**		**Winter TTs Counts**		**Summer Isols Counts**		**Winter Isols Counts**	
	Counts	**Counts**	**% diff.**	**Counts**	**% diff.**	**Counts**	**% diff.**	**Counts**	**% diff.**
1) Red Pine & White Spruce	133	135	+1.5	121	-9.0	158	+18.8	135	+1.5
2) Red Pine	272	231	-15.1	205	-24.6	223	-18.0	199	-26.8
3) Red Spruce	215	167	-22.3	164	-23.7	197	-8.4	194	-9.8
4) White Spruce	114	113	-0.9	100	-12.3	141	+23.7	105	-7.9
5) Norway Spruce	31	111	+358.1	123	+396.8	110	+354.8	128	+412.9

Table 3 - ITC species classification confusion matrix resulting from classification test areas for white spruce (Sw), red spruce (Sr), red pine (Pr), Scots pine (Ps), mature white pine (Pwm), immature white pine (Pwi) and hardwood (H). The number of Isols assigned to each class within the test areas, plus their percentage of the total number of isols within the test areas. **Un** = unclassified; **# Isols** = Number of delineations within the test areas

Classes	Sw	Sr	Pr	H	Ps	Pwm	Pwi
Sw	**78 (36.6%)**	4 (5.5%)	19 (6.9%)	3 (1.0%)	13 (19.1%)	49 (13.5%)	2 (2.2%)
Sr	54 (25.4%)	**46 (63.0%)**	19 (6.9%)	1 (0.3 %)	7 (10.3%)	7 (1.9%)	0 (0.0%)
Pr	9 (4.2%)	1 (1.4%)	**179 (65.3%)**	0 (0.0%)	3 (4.4%)	4 (1.1%)	4 (4.4%)
H	1 (0.5%)	0 (0.0%)	1 (0.4%)	**243 (80.7%)**	0 (0.0%)	7 (1.9%)	10 (11.0%)
Ps	43 (20.2%)	9 (12.3%)	26 (9.5%)	0 (0.0%)	**42 (61.8%)**	55 (15.1%)	6 (6.6%)
Pwm	14 (6.6%)	4 (5.5%)	10 (3.6%)	4 (1.3%)	2 (2.9%)	**181 (49.7%)**	10 (11.0%)
Pwi	2 (0.9%)	0 (0.0%)	11 (4.0%)	5 (1.7%)	1 (1.5%)	35 (9.6%)	**48 (52.7%)**
Un	12 (5.6%)	9 (12.3%)	9 (3.3%)	45 (15.0%)	0 (0.0%)	26 (7.1%)	11 (12.1%)
# Isols	213	73	274	301	68	364	91
Average class accuracy: 58.6% Overall accuracy of all isols: 59.0%							

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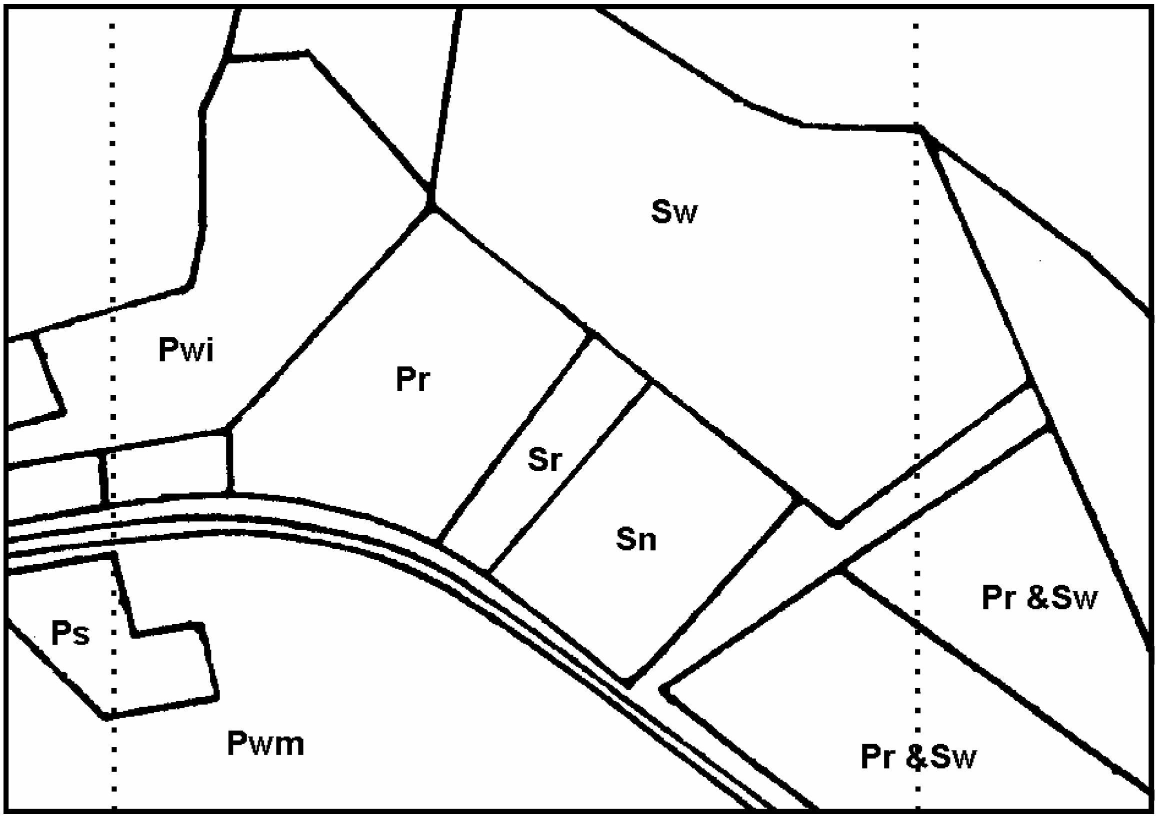


Figure 1 –The Hudson site consisting of mature plantations of white spruce (Sw), red pine (Pr), red spruce (Sr), Norway spruce (Sn), Scots pine (Ps), mature (Pwm) and immature (Pwi) white pine and mixed sites containing red pine and white spruce (Pr & Sw). The dotted lines correspond to the area extracted from the winter IKONOS panchromatic image (300 x 300m^2), as seen in Figures 3 and 4. The area extracted from the summer IKONOS images is slightly bigger (720 x 560m^2) than illustrated here, but Figures 2 and 5 have been cropped to correspond the outside boundaries of this figure, concentrating on the plantations of interest.

Figure 2 – Part of the IKONOS panchromatic sub-image showing the Hudson site on July 6, 2000 and the five tree-counting test areas used for the results reported in Table 2

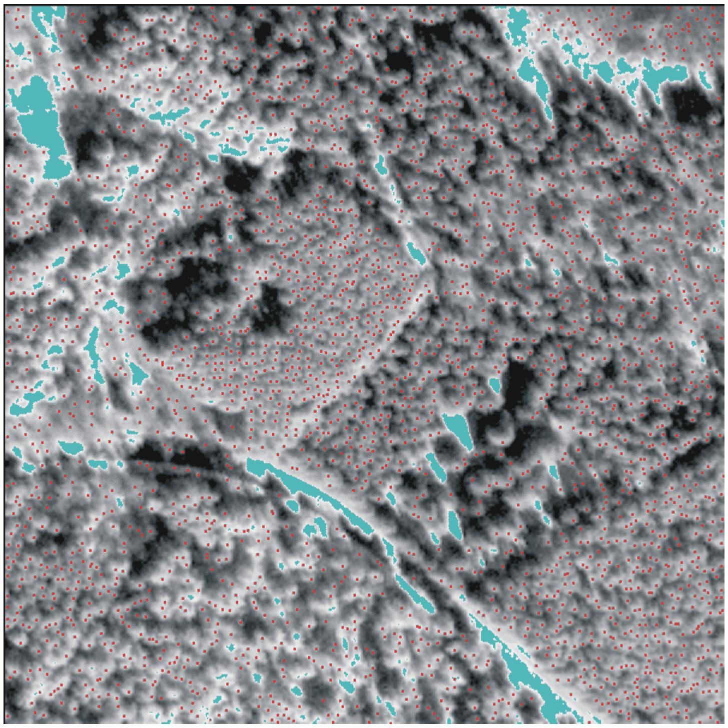


Figure 3 – Winter IKONOS sub-image of the Hudson plantation (resampled to 50 cm/pixel) with snow partially masked out (in blue) and the detected local maxima (Tree Tops) in red.

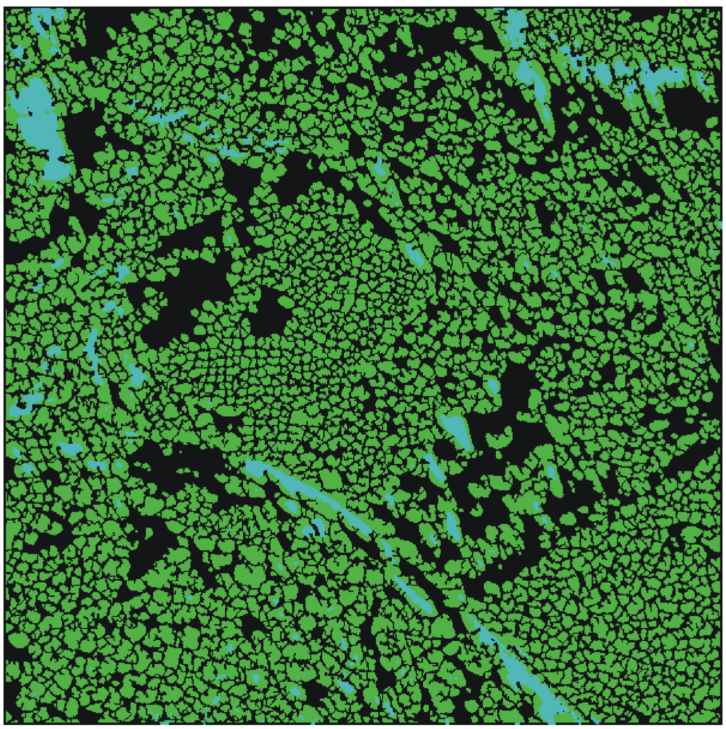


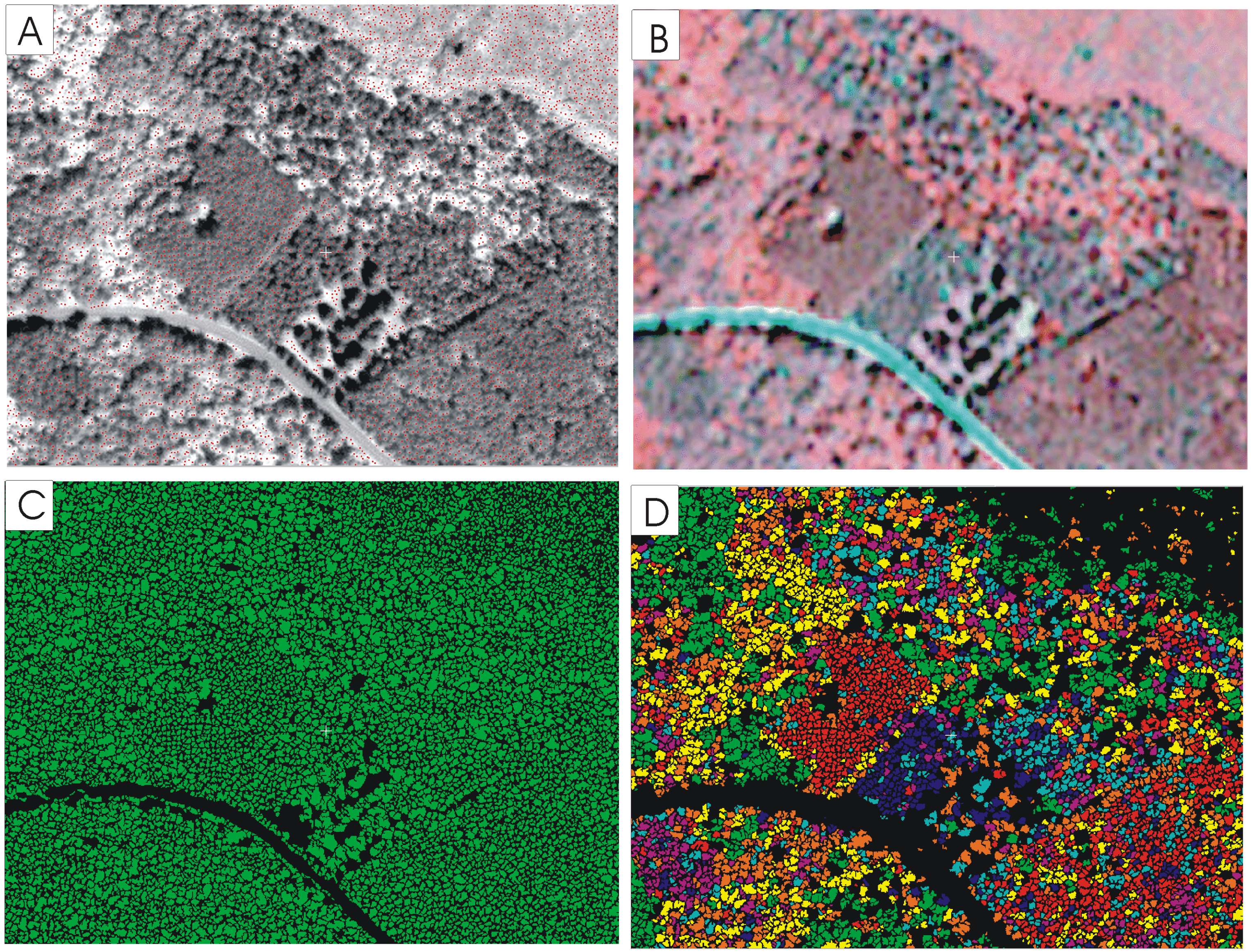
Figure 4 – Individual Tree Crowns (ITCs) and/or Isolated objects (Isols) delineated on the winter IKONOS sub-image (300 x 300m^2) of the Hudson plantation site with snow partially masked out (in blue).

Figure 5a – Summer IKONOS panchromatic sub-image of the Hudson plantation site with detected local maxima (TreeTops) shown in red.

Figure 5b – Near-infrared rendition of the summer IKONOS multispectral sub-image of the Hudson plantation site illustrating the effects of a 4 m/pixel spatial resolution (i.e., individual tree crowns (ITCs) can not be seen, nor extracted). This lower spatial resolution also has effects on the ITC species recognition capabilities of IKONOS.

Figure 5c – Individual Tree Crowns (ITCs) and/or Isolated objects (Isols) delineated on the summer IKONOS sub-image of the Hudson plantation site.

Figure 5d – ITC classification of the summer IKONOS sub-image with seven classes: red pine (red), red spruce (blue), white spruce (cyan), Scots pine (pink), immature white pine (yellow), mature white pine (orange) and hardwood (green).


A
B
C
D