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Automated tree recognition in old growth conifer stands with high resolution digital imagery

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Abstract

Automated individual tree isolation and species determination with high resolution multispectral imagery is becoming a viable forest survey tool. Application to old growth conifer forests offer unique technical issues including high variability in tree size and dominance, strong tree shading and obscuration, and varying ages and states of health. The capabilities of individual tree analysis are examined with two acquisitions of 70-cm resolution CASI imagery over a hemlock, amabilis fir, and cedar dominated old growth site on the west coast of Canada. Trees were delineated using the valley following approach of the Individual Tree Crown (ITC) software suite, classified according to species (hemlock, amabilis fir, and cedar) using object-based spectral classification and tested on a tree-for-tree basis against data derived from ground plots.

Tree-for-tree isolation and species classification accuracy assessment, although often sobering, is important for portraying the overall effectiveness of species composition mapping using single tree approaches. This accuracy considers not only how well each tree is classified, but how well each automated isolation represents a true tree and its species. Omissions and commissions need to be included in overall species accuracy assessment. A structure of rules for defining isolation accuracy is developed and used. An example is given of a new approach to accuracy analysis incorporating both isolation and classification results (automated tree recognition) and the issues this presents.

The automated tree isolation performed well on those trees that could be visually identified on the imagery using ground measured stem maps (approximately 50–60% of trees had a good match between manual and automated delineations). There were few omissions. Commission errors, i.e., automated isolations not associated with a delineated ground reference tree, were a problem (25%) usually associated with spurious higher intensity areas within shaded regions, which get confused in the process of trying to isolate shaded trees. Difficulty in classifying species was caused by: variability of the spectral signatures of the old growth trees within the same species, tree health, and trees partly or fully shaded by other trees. To accommodate this variability, several signatures were used to represent each species including shaded trees. Species could not be determined for the shaded cases or for the unhealthy trees and therefore two combined classes, a shaded class and unhealthy class with all species included, were used for further analysis. Species classification accuracy of the trees for which there was a good automated isolation match was 72%, 60%, and 40% for the non-shaded healthy hemlock, balsam, and cedar trees for the 1996 data. Equivalent accuracy for the 1998 imagery was 59% for hemlock, 80% for balsam, with only a few cedar trees being well isolated. If all other matches were considered an error in classification, species classification was poor (approximately 45% for balsam and hemlock, 25% for cedar). However, species classification accuracies incorporating the good isolation matches and trees for which there was a match of an isolations and reference tree but the match was not considered good were moderate (60%, 57%, and 38% for hemlock, balsam, and cedar from the 1996 data; 62%, 61%, and 89%, respectively, for the 1998 imagery).

Automated tree isolation and species classification of old growth forests is difficult, but nevertheless in this example useful results were obtained.

Keywords: Forest inventory; Species classification; Individual tree crown; Tree isolation; Accuracy assessment

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1. Introduction

The information needs for understanding the forest environment and managing it properly are ever increasing. This is particularly true for old growth forests. They are important in terms of biodiversity, carbon storage, wildlife habitat, and hydrological cycling, and they hold valuable timber resources and emotional attachment. Detailed inventory data is needed to document and best plan the future of such forests. Acquiring data on the distribution and species of individual tree crowns, crown sizes, crown closure, and canopy gaps would be a valuable contribution.

High resolution remote sensing imagery (<1 m resolution) from airborne sensors and new high resolution satellite systems provide a viable source of data for sample plot, site specific, and even regional mapping. Automated analyses of such imagery offer a new and potentially effective method for providing necessary forest information by extracting single tree information. This requires identification of individual trees and subsequent analysis of tree parameters such as species. There are a variety of approaches to automatically locating or outlining individual tree crowns. Most utilize the common phenomenon that, on high resolution imagery, trees generally appear as bright objects surrounded by darker shaded areas. In a valley following approach (Gougeon, 1995a; Gougeon & Leckie, 2003), this image structure is considered analogous to image intensity topography. Valleys of shade or lower intensity areas between tree crowns are identified and remaining tree material is outlined into crown-like shapes by a rule-based system. Local-maxima approaches identify the peaks in image intensity representing the location of a tree crown but not its outline (e.g., Dralle & Rudemo, 1997; Gougeon & Moore, 1989; Wulder, Niemann & Goodenough, 2000). Several methods use local maxima as a starting point and try to find the crown boundary by the intensity structure in the image (e.g., Culvenor, 2002; Pinz, 1991; Pouliot, King, Bell & Pitt, 2002). Template matching creates a model of what trees should look like under different illumination and viewing conditions and matches these to features on the imagery (e.g., Larsen, 1997; Pollock, 1996; Quackenbush, Hopkins & Kinn, 2000). This provides a tree location, estimation of crown size, and a model output shape that best fits the real crown. Other methods based on grouping textures (Warner, Lee & McGraw, 1999), morphological operators (Barbezat & Jacot, 1999), and joining convex-shaped edges (Brandtberg & Walter, 1998) have also been explored.

Once tree crowns have been delineated or pixels within a crown identified, species and sometimes damage can be classified. There has been some work in terms of automated classification of individual trees with multispectral high resolution imagery (e.g., Gerylo, Hall, Franklin, Roberts & Milton, 1998; Gougeon, 1995b; Key, Warner, McGraw & Fajvan, 2001; Leckie & Gougeon, 1999). Most of these studies use simple multispectral classification methods. Rarely is the combined effect of isolation and classification assessed. A compilation of articles on the procedures, issues, and applications of automated interpretation of high resolution digital for forestry was published in Hill and Leckie (1999).

Old growth stands offer unique opportunities and challenges to automated tree analysis. Trees are large making them easier to detect, but there can be a large variability in tree size and dominance or vertical position in the canopy. The varied vertical structure of old growth causes different illumination conditions on trees as well as shadowing and obscuration of less dominant trees by adjacent trees. Also, trees can suffer from various stresses not common in younger stands.

This study presents the use of an automated tree delineation technique to outline possible tree crowns in an old growth conifer forest followed by a spectral classification of the species of each potential crown. A valley following approach was chosen to delineate individual tree crowns. It is appropriate for this forest type and application as, by its nature, it works well in conifer stands with abundant shade between trees and it provides a crown outline that can be used to subsequently generate multispectral signatures for species classification. Building on known individual tree classification issues and spectral characteristics of species in old growth stands (Leckie et al., 2003a), the capabilities for species classification of an object-based maximum likelihood classification approach applied to the automated isolations are assessed. The following key questions are addressed.

- How effective is automated crown isolation, in particular the valley following approach? This is examined in terms of: (a) how well each actual tree within field plots was delineated by the automated technique and (b) overall correspondence of all automated tree isolations with actual trees. Types of error in tree isolation are analyzed (e.g., omissions (trees missed), commissions (isolations not associated with true trees), partial matches, splitting trees into several automated isolations, and isolations that are too large and incorporate several trees). The causes of errors are also examined in terms of the effect of crown dominance and size, species, health, and shade conditions.
- How well does the combined process of isolation and classification (i.e. tree recognition) work? For example, what is the accuracy of the tree species information provided considering that there will be isolation errors such as omission, commission, partial matches, and trees split into several isolations. In addition there is not always complete one-for-one correspondence between automated isolations and real crowns; therefore, classification accuracy assessment itself is complicated. The species classification of automated isolations is assessed in several ways: (a) the accuracy of well delineated trees, (b) for all isolations associated with actual trees accuracy is assessed against the species of the actual tree

with which the isolation is most associated, and (c) overall accuracy considering all isolations including commissions and omissions.

Two images of the same sites taken 2 years apart are used to test the robustness of the methods, and to examine the effects and contrast results of different imaging conditions such as sun and view angle (e.g., different tree shading and illumination, and exposure of different tree profiles and obscuration of trees due to different view angles).

In addition, a set of rules for describing and analyzing isolation errors are presented and a method for analyzing tree recognition (combined isolation and classification accuracy) is introduced and tested and ways of describing the error are demonstrated.

2. Site description

The study area is located on the west coast of Canada and is the site of an interdisciplinary study (MASS; Montane Alternative Silvicuture Systems) (Arnott & Beese, 1997) regarding silvicultural practices in old growth forests. It is located in central Vancouver Island, British Columbia, Canada (125°27′01″ W, 40°50′50″ N) southwest of the town of Campbell River. The area over which imagery was acquired was approximately 6.0 by 1.4 km. Although the site was in a montane moderate elevation situation (790 m above sea level), relief was low and gently rolling.

The study sites were natural old growth stands of predominantly western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), amabilis fir (*Abies amabilis* Dougl. Ex. Loud), and western redcedar (*Thuja plicata* Donn ex D. Don). There was also minor amounts of mountain hemlock (*Tsuga mertensiana* (Bong.) Carrière) and yellow cedar (*Chamaecyparis nootkatensis* (D. Don) Spach). Most old growth trees were 26–45 m in height and diameters at breast height ranged from 18 to 190 cm, most between 20 and 70 cm. Crown diameters for the codominant and dominant trees were in the order of 6–10 m. The stands contained a mixture of ages, with most overstory trees ranging from 200 up to 800 years. Stand density was 340–380 stems/ha (including suppressed trees), approximately half this for dominant, codominant, and intermediate trees. Crown closures as measured at grid points within ground plots were 65–80%. As is characteristic of old growth stands, closure and stem distribution was variable, with gaps in the canopy and some crowding of tree crowns.

3. Image data and preprocessing

High spatial resolution multispectral imagery was obtained over the site on two occasions, one in 1996 and the second in 1998. Data were acquired with the CASI imaging spectrometer. It can record imagery in up to 288 spectral bands, but for this study it was operated in spatial mode to acquire 8 bands in 1996 and 10 in 1998 (Table 1). Bandwidths were 25 nm for the 1996 data and 14 nm for the 1998 data except for the 484-nm band, which was 42 nm, and the 550-nm band with a 25-nm bandwidth. In 1996 a standard CASI sensor was used (Anger, Mah & Babey, 1994), whereas an upgraded design, CASI 2 (Babey et al., 1999), was used for the 1998 acquisition. CASI 2 has a faster integration time, which permits more spectral bands to be acquired at high spatial resolution. Nominal acquisition resolution was 70 cm for the 1996 mission and 60 cm for 1998. The 1998 data suffered from a slight defocusing caused by a temporary sensor lens problem. This made the effective resolution lower so that it probably was nearly equivalent to that of the 1996 data. With a field of view of approximately ±18° and a CCD array 512 elements wide, swath width was 360 and 310 m for the 1996 and 1998 data, respectively. The site was flown in seven adjacent and sidelapping flight lines oriented east–west. The 1996 data was acquired between 1520 and 1550 PDT, September 27. This gave a sun elevation of 36° and azimuth of 226°. The 1998 data was acquired between 1045 and 1129 PDT on September 24. Sun elevation and azimuth were 41° and 139°, respectively. Ground vegetation, shrubs and any hardwood trees were green or only slightly senesced. Conditions were cloud free over the sites. Itres Research acquired, processed and geometrically corrected the imagery.

Imagery was geometrically corrected and georeferenced. The 1998 mission was flown using a three-dimensional motion detection system (Applanix POS system) with differential GPS. The imagery was then orthorectified using a DEM from British Columbia's digital topographic mapping 1:20,000 map series (TRIM). For the 1996 mission, a two-dimensional gyro was used to provide information for correction of aircraft motion and georeferencing was less accurate. A nearest neighbour resampling was applied. Output resolution for both dates was 70 cm. The data were mosaicked, but for this study the data from the individual flight lines were used.

The data were radiometrically processed and calibrated to account for sensor and detector factors. No atmospheric correction was conducted. A correction was applied for the

Table 1
Spectral band sets used for the two CASI image acquisitions

1996 acquisition		1998 acquisition	
Band number	Centre wavelength (nm)	Band number	Centre wavelength (nm)
1	438	1	484
2	489	2	550
3	550	3	588
4	601	4	613
5	656	5	643
6	715	6	668
7	795	7	701
8	861	8	742
		9	782
		10	862

effects of bidirectional reflectance. With flight line orientation east–west and sun azimuths of 139° and 226°, the effect of viewing the sunlit side of trees on one side of the imagery and shaded on the other was quite strong. An object-oriented empirical view angle correction was applied. First an automated tree isolation procedure was applied. A preliminary classification of these tree isolations into conifers through a simple maximum likelihood classification was then conducted. Different conifer species can have different bidirectional reflectance effects and a slight bias in the correction can occur if there is an unbalanced species distribution across the image of the trees used to develop the correction curves. In this study, the distribution of species was similar throughout the study area and no such effect is expected to influence the final species classification results. The mean value in each band for the pixels in each conifer isolation was then plotted against the position of that isolation across the imagery. This was fit with either a quadratic or third-order polynomial, depending on spectral band, to give a best fit curve value for each position across the image. For each position across the image, an additive correction factor was determined as the difference between the value for the curve at that position and the curve value at nadir. A corrected value (Pc_{ij}) for every pixel in the image was then calculated for each band by adding the correction factor to each pixel based on its position across the image:

$$\mathrm{Pc}_{ij} = \mathrm{Pu}_{ij} + C_{ij} \tag{1}$$

where i is position across the image (pixels from nadir), j is the spectral band, Pu is the original uncorrected pixel value, and C_{ij} the correction factor is given by:

$$C_{ij} = X_{ij} - X_{0j} \tag{2}$$

where X_{ij} is the best fit curve value for band j at position i from nadir and X_{0j} the curve value at nadir. The view angle correction system is designed to be able to work on data after geometric correction by temporarily readjusting view angle to an approximation of that of the original data for radiometric correction and then returning it to the geometrically correct position (Leckie et al., 1999a).

There can also be differences in the overall image intensity due to changing sun elevation, atmospheric conditions, and other factors over the time period of the image acquisitions. The data from each fight line were normalized by making the mean value at nadir, to which data is corrected, the same for each flight line. In this study, data from three flight lines were used for 1996 and four lines for 1998. Imagery from most lines did not need such an adjustment.

4. Reference data

A reference data set of trees was created for signature training, and for testing classification accuracy, isolation fidelity, and their combined affect. First, trees were mapped and characterized in the field within square plots. These were carefully related to trees as observed on the imagery and the tree crowns manually delineated on the images. A set of trees outside the plots was also documented in the field, outlined on the imagery, and used as an independent training set for the automated classification. The spectral characteristics of each tree was examined and categorized for both years of imagery. Exploratory classifications using the manually delineated trees were conducted (Leckie et al., 2003a) to determine an appropriate set of spectral signatures and classes for extracting species composition at the tree level. The individual tree field data, spectral categorization, and species class were linked in a reference database for analysis of isolation and classification capability.

4.1. Field data collection

A network of five 40×40-m field plots was established in stands across the study area. Field work was done October 1996. Examinations in 1999 after the 1998 data acquisition were conducted to note any changes in the trees of the plots (e.g., blowdown). Within each plot the coordinate of every stem was mapped. For each tree, species, dominance, and diameter at breast height (dbh) were recorded. Health problems or unusual features were also noted. Dominance was assessed in four classes: dominant, codominant, intermediate, and suppressed. Height, crown diameter, and age as determined from increment cores were measured for a sample of trees. Notes on the nature of the understory and ground vegetation were made. Individual understory trees and shrubs were not routinely recorded, but zones of differing ground vegetation and understory were mapped if appropriate. A buffer of trees outside the plot, plus some selected trees were also noted and their stems were mapped in relation to the plot.

Plots were located relative to the imagery by taking a hard copy of the image in the field and marking on the imagery the location of some plot corners, selected trees within the plot, or particularly distinct trees outside the plot along with their relationship to the plot corners.

4.2. Tree crown polygon and attribute database

For both the 1996 and 1998 data, the stem maps were used to relate trees visible on the imagery to the trees identified on the ground. The outline of the tree crown was then manually delineated on the imagery as a series of vectors forming a polygon. These are termed ground reference delineations or trees (greds). Identification of some trees and determining the boundary between trees can be difficult, because of shading, obscuration of shorter trees by nearby large trees, and merging of close crowns. The whole process of tree crown delineation and reference to trees on the ground was done carefully and used independent mappings of multiple interpreters and rigorous checking. Regardless, there is potential for error and any questionable tree identification was recorded.

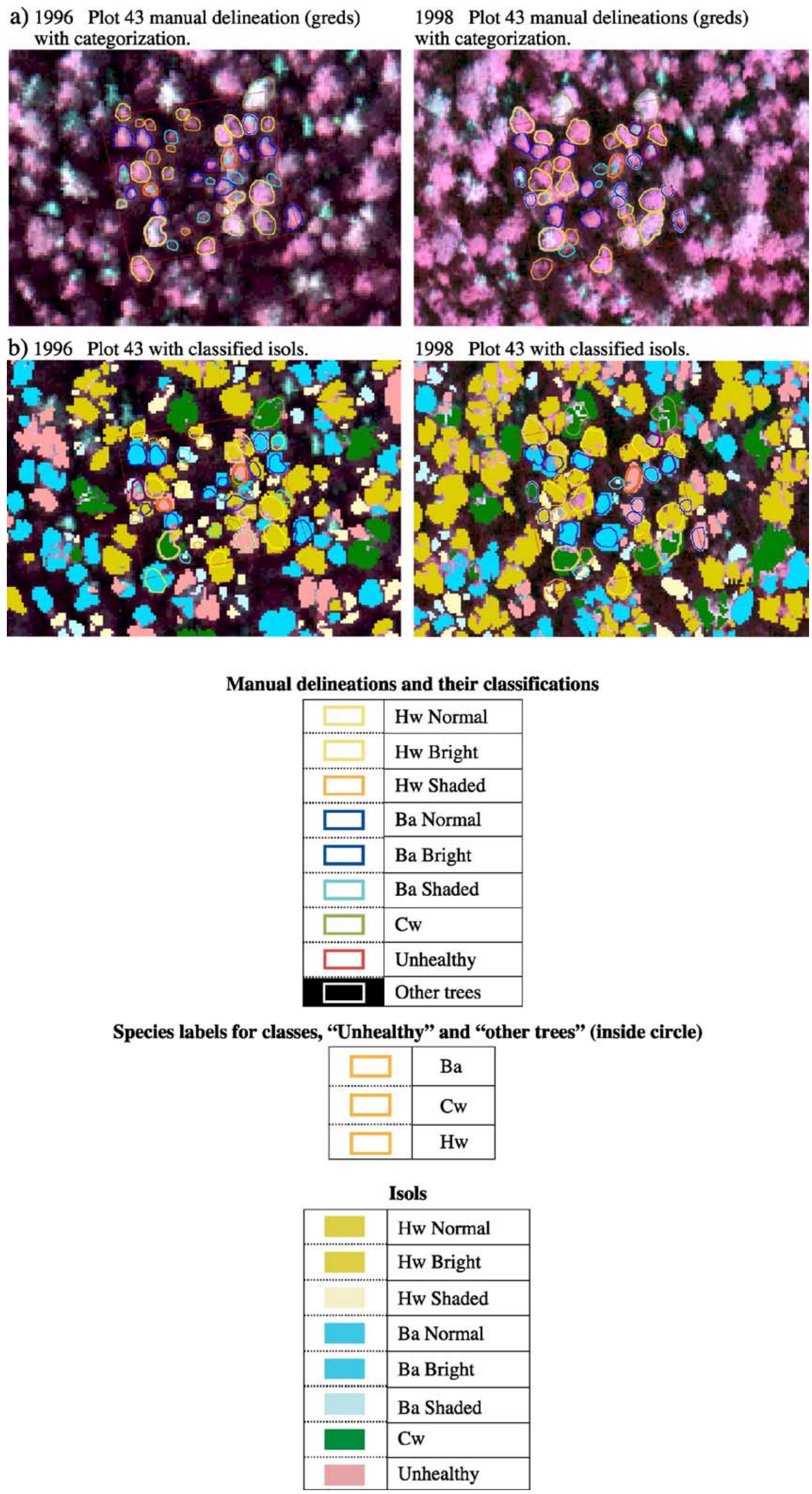

Fig. 1. Imagery, ground reference delineations with class designation, and automated isolations and classifications for plot 43 (1996 and 1998). The plot boundaries are drawn to indicate which tree crowns are in or out of the plots and are not the boundaries as laid out on the ground. Imagery is a colour infrared band combination. Image segments are 70 by 100 m. (a) Ground reference delineations within plot (i.e. test trees). For trees of the nominal classes, their class is indicated by the colour coding of the single or outer boundary of the tree delineation. For trees in the unhealthy class, the inner boundary gives their species. Other trees (not in the nominal classes) are indicated by a white outer boundary with their species indicated by the colour of the inner boundary. (b) Isols and classification of the isols. The isols are colour coded as to the nominal class to which they were assigned by the classification. Also given are the colour coded ground reference delineations.

It should also be noted that not all trees in the plot were visible on the imagery. In addition, because of differences in sun illumination and position of the plots in terms of sensor viewing angles between the 1996 and 1998 imagery, the trees identified and used in the analyses were somewhat different (e.g., Figs. 1 and 2). The 1996 imagery was acquired at a lower sun elevation and had somewhat longer and darker shadows. This did not result in missing more trees, but the manual delineated polygons were generally smaller. For example, the average sizes of the ground reference delineations within the plots were 17 m^2 for the 1996 imagery and 20 m^2 for the 1998 data. The main difference between the images is due to the sun azimuth and direction of the cast shadow and different trees being shaded. Overall tree counts were similar, 163 for 1998 versus 157 for 1996. However, the differences are larger than this. There were 17 trees of the 1998 imagery that were not identified on the 1996 images, and 10 on the 1996 imagery not identified on the 1998 images. Therefore, 91% of the ground reference trees were the same between the two data sets. Not all trees were identifiable on the imagery; field counts indicated that there were 154 dominant, codominant, or intermediate trees, and 133 suppressed trees. Most trees not identifiable on the imagery were of the suppressed dominance class.

Three main species were present: western hemlock, amabilis fir (balsam), and western redcedar. Within the plots there were a few trees of other species visible on the imagery of either date (for the 1996 and 1998 data, respectively, there were four and three visible mountain hemlock, all in one plot, and four yellow cedar for both dates, several being unhealthy or shaded).

An examination of the spectral characteristics of the trees of each species (Leckie et al., 2003a) indicated variability within species. It was also determined that it was useful in the species classification process to have two internal spectral classes, termed bright and normal, to represent the hemlock and balsam trees. Thus, a bright and a normal class for each of hemlock and balsam was created. Shaded classes of each species were also found useful. The shaded classes did not classify species well, but permitted differentiation of the shaded trees from the better classified sunlit trees so that the shaded trees could be separated from the analysis or summaries of species composition for a stand. Unhealthy trees also had different signatures and species determination was not possible (Leckie et al., 2003a). Again, it was useful to include a general unhealthy class in a classification of species to separate these trees from any species analysis. In addition, approximately 10% of the trees in the plots were observed to have particularly uncharacteristic or odd spectral signatures or appearances on the imagery. They were often either very bright or had an irregular spectral shape. The uncharacteristic trees may be due to unobserved health problems, errors in the manual tree

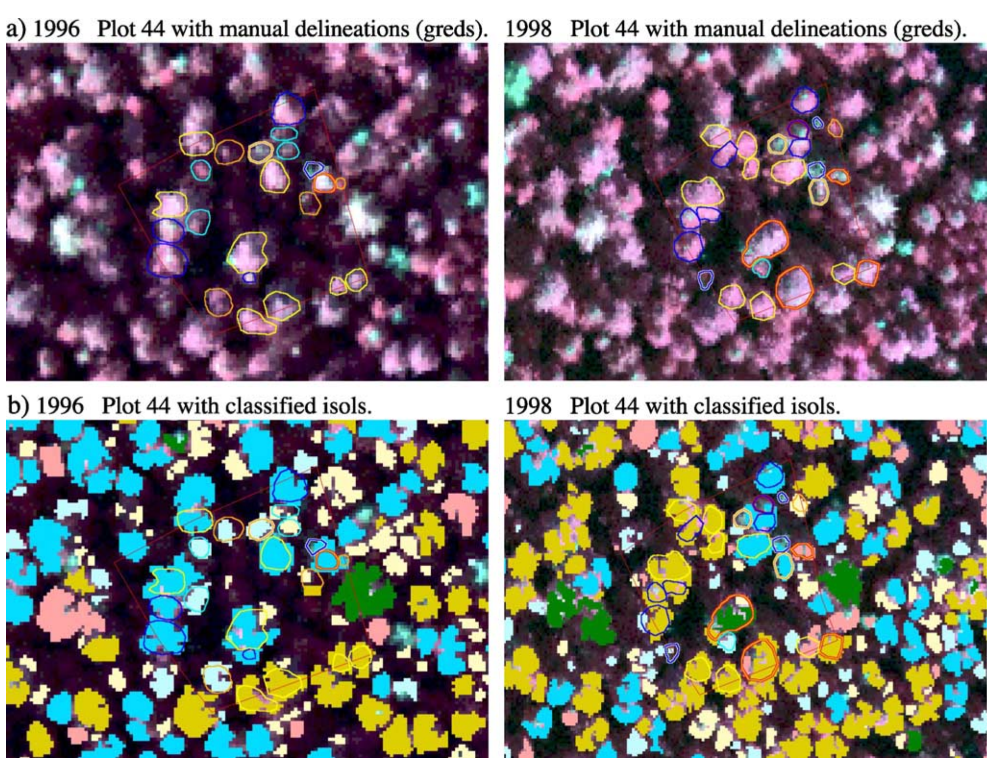

Fig. 2. Imagery, ground reference delineations with class designation, and automated isolations and classifications for plot 44 (1996 and 1998). Image bands displayed, scale and legend are the same as in Fig. 1. (a) Ground reference delineations within plot (i.e. test trees). (b) Isols and classification of the isols.

delineation, or illumination conditions (e.g., partially or weakly shadowed, or parts of crown obscured by others and therefore the full sunlit or normal shadow parts of the crown may not have been outlined). However, perhaps the most common cause was natural variability.

A species code was assigned to each manually delineated ground reference tree, they were also assigned to one of two internal classes of hemlock and balsam (bright and normal), shaded or unhealthy. Trees noted in the field to have a health problem were designated as unhealthy. However quite a number of additional trees were observed, through interpretation of the imagery, to be stressed or to have dead branches or other health problems. These trees were also labelled as unhealthy. The uncharacteristic trees were also designated as "odd" so that delineation and classification accuracy can be assessed with and without these trees.

Training trees for generating the classification signatures were generally created from a set of trees outside the plots used for testing. Approximately 120 trees were used for training each year. The "odd" trees were not used in the development of classification training signatures. In order to permit accuracy assessment that incorporated the accuracy of the automated delineation as well as classification capabilities, only the ground reference delineations within the plots were used as the test set of trees. All ground reference trees within the ground plots were used for testing. However, various classification accuracy analyses were conducted which alternately included or excluded the unhealthy, shaded and "odd" trees. Of the 157 ground-reference trees within the plots for the 1996 data, 129 were assigned to one of the eight classes used in the nominal classification (i.e., bright, normal, and shaded hemlock and balsam plus non-shaded cedar or non-shaded unhealthy). Seventeen were designated as odd (non-shaded and not unhealthy) and others were non-shaded mountain hemlock, shaded cedar, and shaded unhealthy trees. These trees not in the nominal classes are referred to as "other trees" or "other category trees" (Table 2). In total, 50 ground reference trees were shaded and 19 were considered unhealthy. Similarly, for the 1998 data, 127 of the 163 ground reference trees within the plots were in one of the nominal classes and 14 were odd (Table 3). Of these, 42 were shaded and 33 were unhealthy, including shaded unhealthy.

The data for the manually delineated ground reference trees were placed in a database. Each ground reference tree was referenced to its tree crown polygon and respective field observations. Field information in the database included species, dominance, diameter breast height, and health condition. Also specified was whether the tree was used for training or testing and its ground reference class (e.g., hemlock bright, hemlock normal, hemlock spectrally irregular, hemlock unhealthy, etc.). Once a classification was completed, the classification result for each tree was added to the database. Vector outlines of the trees can be colour-coded according to their ground reference or classified species. As well, one can point to each tree polygon on the imagery and the corresponding tree information is highlighted on the display of the database. Conversely, one can identify a tree in the database and its vector outline is highlighted on

Table 2
Automatically isolated and classified ground reference tree results (gred-centric, 1996)

Truth	Classification								
	Hemlock combined[a] (%)	Hemlock shaded (%)	Balsam combined[a] (%)	Balsam shaded (%)	Cedar (%)	Unhealthy (%)	Omissions (%)	Not good (%)	Total # trees
Nominal classes									
Hemlock combined	60	2	36	0	0	2	0	41	42
Hemlock shaded	11	53	10	21	0	0	5	32	19
Balsam combined	33	0.0	57	5	0	5	0	29	21
Balsam shaded	16	28	4	44	0	0	8	28	25
Cedar	25	0	12	0	38	25	0	38	8
Unhealthy	7	0	14	0	15	64	0	43	14
Other trees									
Mountain hemlock	50	0	25	25	0	0	0	25	4
Hemlock very bright	50	0	0	0	25	25	0	75	4
Hemlock odd	20	0	20	20	0	0	40	40	5
Balsam very bright	0	0	0	0	0	0	0	0	0
Balsam odd	50	0	50	0	0	0	0	0	4
Cedar odd	0	0	0	25	0	75	0	75	4
Cedar shaded	0	50	0	50	0	0	0	100	2
Unhealthy odd	0	100	0	0	0	0	0	0	1
Snag	0	0	0	0	0	0	0	0	0
Shaded odd and unhealthy	25	0	25	25	0	0	25	50	4

[a] Combined normal and bright classes.

Table 3
Automatically isolated and classified ground reference tree results (gred-centric, 1998)

Truth	Classification								
	Hemlock combined[a] (%)	Hemlock shaded (%)	Balsam combined[a] (%)	Balsam shaded (%)	Cedar (%)	Unhealthy (%)	Omissions (%)	Not good (%)	Total # trees
Nominal classes									
Hemlock combined	62	0	26	0	2	10	0	48	40
Hemlock shaded	24	18	6	6	23	23	0	53	15
Balsam combined	36	0	61	0	0	3	0	46	27
Balsam shaded	8	34	0	50	0	8	0	17	12
Cedar	0	0	11	0	89	0	0	89	9
Unhealthy	21	0	26	0	16	37	0	58	19
Other trees									
Mountain hemlock	100	0	0	0	0	0	0	33	3
Hemlock very bright	100	0	0	0	0	0	0	100	2
Hemlock odd	40	0	0	0	20	20	20	60	5
Balsam very bright	0	0	0	0	0	0	0	0	0
Balsam odd	50	0	50	0	0	0	0	25	4
Cedar odd	0	25	50	0	25	0	0	75	4
Cedar shaded	100	0	0	0	0	0	0	100	2
Unhealthy odd	0	0	100	0	0	0	0	0	1
Snag	0	0	100	0	0	0	0	67	3
Shaded odd and unhealthy	8	8	8	9	17	42	8	67	12

[a] Combined normal and bright classes.

the image. This made a versatile database for detailed analysis.

5. Image analysis methods

Image analysis was conducted with the Individual Tree Crown (ITC) suite of programs developed by the Canadian Forest Service (Gougeon & Leckie, 2003). An automated routine for delineating individual tree crowns was run on the images of the MASS site. These crown isolations were then treated as separate objects. Spectral signatures for species classes were generated from the manually delineated tree crowns. These signatures were examined with regard to the variability within species, overlap between species, and the appropriate spectral bands and approaches for classification. A maximum likelihood classifier was used to classify the automatically isolated individual tree crowns. The classification accuracy was determined using the manually delineated ground reference trees within the field plots. The accuracy for the computer-generated crown delineations considering the combined effects of errors in delineation and classification (recognition accuracy) was assessed using a specialized approach designed for this purpose.

5.1. Individual tree crown delineation

Automatic crown delineation was conducted with the "valley following" approach of the Individual Tree Crown software suite (Gougeon, 1995a; Gougeon & Leckie, 2003). It is based on the premise that there are high image intensity values on tree crowns and lower intensity shaded pixels between crowns, thus forming peaks of brightness and valleys of lower intensity on the imagery. The approach first finds local minima in an illumination image and follows all possible valleys of shade in the image pixel-by-pixel until the valley ends or reaches a specified maximum illumination value. This results in a preliminary separation of potential tree crowns. The next step invokes a rule-based process, which follows the crown boundaries favoring clockwise motions trying to close the loop to end at the starting pixel. Higher-level rules identify small indentations in the potential crown boundary and permit the boundary to jump across the indentation if there are other valley pixels within a specified direction and distance (jump factor) from the indentation. In this way, individual objects representing possible tree crowns are outlined. These are referred to as "isols".

The method works best for dense stands where the gap between trees is shaded. In more open stands where sunlit understory material is visible, preprocessing can be used to eliminate (mask-out) non-shaded background material. Such a filter was applied to the imagery to eliminate roads and some larger open areas, but this filter did not impact the dense old growth stands of the study. For this study, the green spectral channel was selected as the illumination image and was smoothed with a 3×3 average filter before applying the valley following algorithm. Green spectral bands have been found to be effective in other studies (Gougeon & Leckie, 2003). There is a lower pixel value threshold below which all pixels are considered shaded and which forms a mask under which the algorithm searches for local minima. An upper threshold stops the valley from proceeding into bright areas. There is also a parameter, which defines how much greater adjacent pixel values must be to create a valley. A separate isolation with different parameter settings was determined for each flight line. A jump factor of one or two pixels was used to break down large isolations into several entities. Isols not having a contiguous area of 2×2 pixels within them were also eliminated; canopy trees will not be affected by this rule as they are larger than this limit.

5.2. Classification

The approach taken to classification was an object-oriented one in which each tree is treated as an entity represented by a single signature. This study used a purely spectral approach to classification; each tree was represented by one value for each band. What is termed the "mean-lit" signature was used; it is the mean value of all the pixels that have a value above the average value of all the pixels for that crown. It is meant to represent the signature from the brighter sunlit pixels of the tree. The mean-lit signature was found in the past to produce the best results (Gougeon, 1995b; Gougeon & Leckie, 2003; Leckie, Yuan, Ostaff, Piene & MacLean, 1992; Leckie et al., 2003a). Relative to using a full crown mean, it reduces variability due to incorporating different proportions of the shaded side of the crown and adds consistency to what pixels it captures on the sunlit side (the brightest pixels are near the position on the trees with highest reflectance for that sun angle and view direction).

A supervised classification with a maximum likelihood decision rule is used. Classes are represented by the mean and covariance of a set of training trees, with each tree contributing only one value per spectral band. The mean-lit signature of each tree in the image is then classified and the tree is labelled as the most likely class. Eight classes are specified hemlock bright, normal and shaded, balsam bright, normal and shaded, cedar non-shaded and unhealthy. There is no cedar shaded class as few cedars were shaded and the unhealthy class includes trees of all three species. Six spectral bands were used in the classification. Comparable bands were used for each date and consisted of bands 2–7 for the 1996 imagery and bands 1, 2, 4, 5, 7, and 9 for the 1998 data (Table 1).

5.3. Accuracy assessment

Accuracy of the classifications was assessed against a separate set of test trees. To facilitate testing of the complete system of tree isolation and species classification, the training trees were generally taken from trees outside but nearby the test plots and the test trees were those trees within the plot. Comparison of the 1996 and 1998 data provided a further consistency check of the methods and results.

In the case of automatically isolated trees, the correspondence of the isolated trees with the reference trees can vary in a continuum from nearly perfect, to partial, to none. This calls for a new approach to accuracy analysis. The combined accuracy of tree isolation and species classification is termed tree "recognition". The quality of the correspondence between ground reference delineations (greds) representing the tree crown outline on the imagery and the automatically generated delineation or isolation (isols) depends on the quantity of the overlap one has with the other and the number of isols overlapping with the gred or number of greds overlapping an isol. This goodness of fit must be considered from the point of view of how well the ground reference delineations are matched by isols (gred-centric analysis) and how well each isol is matched by ground reference delineations (isol-centric analysis). There are several possible configurations of overlap, which can be considered a good match plus others of particular interest. Special cases are: ground reference trees that are split into several isols, isols that have several greds grouped within, omissions, and commissions. A categorization of 20 overlap types has been developed (Leckie, Gougeon, Watsworth, Burnet & Kent, 1999b) and is summarized in Appendix A. A component of the ITC software suite, ITCMARA (Manual to Automatic Recognition Accuracy), has been developed to assist in the accuracy assessment.

6. Results

6.1. Crown isolation results

Total species classification accuracy using automated isolation and classification (tree recognition) will depend strongly on isolation accuracy. Lack of correspondence of automated isolations (isols) with trees as represented by the ground reference delineations will result in spurious additional isols, missing trees, trees split into several isols, isols incorporating several ground reference trees, or offset matches. In addition to isols not representing real trees adequately, poor isolation can lead to poor matching of signatures used in a classification to represent a class and those of the isols being classified (e.g., if an isol incorporates two ground reference trees of different species or is only half related to a tree and the rest related to ground vegetation). The objective is to achieve good tree recognition, that is, for the isols to have a good match with the ground reference trees and to be classified correctly. There are a number of different degrees and types of correspondence of isols and ground reference trees that are of interest when describing how well an automated isolation and classification are performing (Leckie et al., 1999b). Appendix A outlines these cases. Good matches are considered those where there is only one isol associated with the ground reference delineation and that isol has only one gred associated with it (1:1 correspondence). The overlap should be more than 50% of each with the other, or the isol is too big but occupies most of the ground reference delineation, or vice versa, the isol is small but most of it is covered by the ground reference delineation. Also considered as a good match is an isol and gred that have more than 50% overlap of each other but the gred also has minor associated secondary isols without large overlaps. Other cases where there is correspondence (overlap) of the isols and ground reference delineations but overlap is not considered “good” will be referred to as “not good” matches. These consist of correspondence types 3, 6, 8–11, 13, and 20 of Appendix A. It does not include omissions. Cases of no match or overlap (type 12, Appendix A) will be considered omissions. The good and not good matches plus omissions incorporate the full set of all ground reference trees.

For the 1996 data, 59% of the ground reference trees within the plot were considered a good match, as defined as types 1, 2, 4, 5, and 7 in Appendix A; 47% were good matches for the 1998 imagery. Only six trees in the 1996 data were missed altogether (type 12, Appendix A), four of these were shaded, and the other two had a visually odd appearance. Six trees were split into two or three isols and a seventh into four associated isols (type 9, 10, or 11 of Appendix A). Only two trees were omitted for the 1998 data, but there was more splitting of trees, with 20 trees split mostly into two isols. Apart from omitting shaded trees on the 1996 imagery, there does not seem to be a strong trend between species, health condition or spectral class and the ability of the algorithm to isolate trees. An exception was cedar in the 1998 image, which was isolated poorly. In addition, there were proportionately fewer (15–20% fewer) good matches for trees other than those of the nominal classes (e.g., very bright, visually odd, spectrally irregular, etc.). Despite some omissions, the shaded trees had a similar overall rate of good matches as the bright or normal species classes.

The relationship between tree isolation performance and tree dominance and size is complex. The dominant and larger trees are not necessarily the best isolated; splitting of crowns becomes a problem. For example, over the two dates approximately 37% of the dominant trees had a good match and an equal percentage were split into more than one isol. For trees of the codominant, intermediate, and suppressed dominance classes, there was not a strong trend in isolation with dominance, with nearly equal proportions of crowns of all of these dominance classes being good matches. For the 1996 imagery, except for the large crowns (>40 m^2) approximately equal proportions of crowns in different crown size classes showed good matches. The larger crowns suffered from splitting. For the 1998 data, the trees with small crowns (<10 m^2) had fewer good matches. On both dates of imagery, a greater proportion of suppressed trees and trees with crowns less than 10 m^2 were omitted than for the other dominance and size classes. There were no large or dominant ground reference trees that did not have an isol associated with them.

Commission errors, isols not associated with a manually delineated tree, were the most serious issue with the isolation process. Both dates of imagery had high rates of commission error (approximately 23% of all isols within the plots were not related to a manually delineated tree, that is were type 18 commission error in Appendix A). Most of these were associated with the shaded portion of the image and likely related to the choice of lower threshold in the valley following component of tree isolation. There is always a compromise in the isolation process between potentially missing shadowed trees and identifying too many isols in the shaded regions. Fortunately, in the case of this study, many of these spurious isols were classified as shaded hemlock or balsam (76% for the 1996 data and 45% with the 1998 imagery); thus, they did not cause a large error in the species composition as determined for the sunlit crowns. Therefore, from an isol-centric viewpoint, the number of good matches of isols with manually delineated trees versus the number of isols delineated in the plots is lower than when considering the number of good matches versus the number of manually delineated trees. Isol-centric good match rates were 46% for 1996 and 33% for 1998. If one eliminates the commission isols classified as shaded, then the good match rate is 55% for the 1996 data, 36% for 1998 data.

In both numerical and qualitative analyses, the 1998 data were not as well isolated as the 1996 imagery, with fewer good matches and more split trees. The 1996 isolation produced a total of 204 isols in the plots and the 1998 trial produced 231. Average size of isols within the plots on both dates was similar, approximately 17 m^2 for both 1996 and 1998.

6.2. Classification and recognition accuracy for automatically delineated tree crowns

Recognition accuracy of the fully automated tree isolation and classification depends on both how well the trees are delineated and then how well the signatures of each tree separate into different species classes. Accuracy is first analyzed in terms of how well the trees visible on the imagery (ground reference delineations) are represented by the isols and their classification (gred-centric accuracy). The accuracy will be assessed in terms of how well the good match trees only are classified and by what the accuracy is if the trees with a match that is not good are considered an error. However, in this latter case, there are isols that are most associated with the ground reference delineation and it is interesting to note how well their classification matches the class of that manually delineated ground reference tree. The product that the forester is ultimately using is the classification of each isol. Therefore, secondly, accuracy is assessed in terms of how well the whole suite of isols represents the ground reference delineations (isol-centric accuracy). In this case, the accuracy considering all isols including commission errors must be examined. Finally, it is also interesting to note how well the overall species composition derived from the automated process (i.e., all isols) matches that of (a) the ground counts and (b) the manual delineations for the plots irrespective of how well the isolation performed and individual trees matched.

6.2.1. Accuracy in terms of ground reference delineations (gred-centric)

Considering the nominal classes, classification accuracy of all good matches of ground reference tree outlines with isols was 72%, 60%, 40%, and 88% for non-shaded hemlock, balsam, cedar, and unhealthy trees, respectively, for the 1996 data. This contrasts with an accuracy of 85%, 90%, 63%, and 64% for a classification of the manually delineated trees using the same training signatures (Leckie et al., 2003a). The poorer accuracy can result from several causes, but there is a loss of accuracy due to the delineation process and transfer of signatures from the ground reference delineations to automatically generated isols. If not good matches and omissions are considered errors, then the accuracies are approximately 43% for both hemlock and balsam, 25% for cedar, and 50% for unhealthy. Equivalent accuracies for the 1998 data were somewhat erratic because the isolation was not as good and some species classes had high rates of not good isolations. For the good isolations, hemlock accuracy was 59% with most confusion due to normal balsam being classified as normal hemlock. Accuracy was halved to 31% when not good isolations were considered errors in species classification regardless to what species they were classed. The well isolated balsam trees were well classified at 80% accuracy, but this is reduced to 43% when the not good isolations are included as errors. The bright classes of either species were underrepresented in the classification. In the 1998 trial, cedar was not isolated well with only one tree having a good isolation. It was classed correctly as cedar, but combined accuracy counting the not good isolations as errors was only 11%. The unhealthy class accuracy was 50% (well isolated trees) and 21% when not good isolations were considered errors.

Next the accuracy of the not good matches was assessed by assigning the ground reference trees to a class the same as the classification of the isol most associated with it. Using this analysis, accuracies of the ground reference trees with a not good match for the 1996 data were 44%, 50%, 33%, and 33% for hemlock, balsam, cedar, and unhealthy trees, respectively, and 65%, 39%, 88%, and 27% for the 1998 data. If the accuracies of the not good cases and good cases are combined, then overall accuracy in terms of how well the nominal class ground reference delineations were classified was 60%, 57%, 38%, and 64% for hemlock, balsam, cedar, and unhealthy trees, respectively, in 1996 (Table 2), and 62%, 61%, 89%, and 37%, respectively, for 1998 (Table 3). Although the isolation was poorer for cedar in the 1998 data, the overall accuracy was very good, much better than for the 1996 trial. The classification of the unhealthy trees was poorer. The error structure in terms of confusion among classes and species indicated that hemlock and balsam were confused. Shaded trees were generally classed as one of the shaded species classes (73% for 1996 and overall lower shaded class accuracy (48%) in 1998 with the poor classification of shaded hemlock causing error). The trees outside the nominal classes (other trees) also tended to be classed similarly to the classification of the ground reference trees (e.g., Tables 2 and 3), although, as mentioned above, these trees were generally less well isolated than those of the nominal classes.

There were seven trees split into more than one isol (types 9, 10, and 11, Appendix A) for the 1996 data. Only two such trees had all their associated isols classified the same and the correct class; four had the most dominant isol correctly classified. Alternately, only two had none of the isols classified as the correct species. Splitting of tree crowns into several isols was more common in the 1998 data where 20 crowns were split, almost all into just 2 isols. Five had all isols classified correctly as to both class and species, 13 had the dominant isol classified correctly, and only 3 had none of the isols classed as the correct species or correctly as unhealthy.

Overall, for combined good and not good nominal and the other category trees, the accuracy was 55%, 48%, 25%, and 60% for the 1996 data for hemlock, balsam, cedar, and unhealthy, respectively, and 61%, 59%, 69%, and 35% for 1998.

6.2.2. Accuracy in terms of automated isolations (isol-centric)

The above analysis examined how well the ground reference delineations were isolated and classified (gred-centric analysis). The following examines how well each isol is classified (i.e., an isol-centric analysis). The isols that have a good match with the ground reference trees are the same matches that produce a ground reference delineation that has a good isol match. That is, the types 1, 2, and 7 matches (Appendix A) involve good correspondence of only one isol with one ground reference tree. Types 4 and 5 matches have several isols associated with the manual tree, but one isol has more than 50% of its area in the manual tree and covers more than 50% of the manual tree. Although these isols could overlap with a second manual tree, the majority of the isol is occupied by the first manual tree. Thus, the isol can be considered a good match with the manual tree. Accuracies of these isols in terms of sunlit hemlock, balsam, cedar, and unhealthy classes are therefore the same as accuracies of manually delineated trees with a good match (e.g., 72%, 60%, 40%, and 88%, respectively, for 1996 data). Considering all isols and counting as errors both isols that have no associated ground reference tree (isolation commissions) and those most associated with trees of non-nominal classes (other category trees), accuracies of the 1996 isols were 49%, 42%, 46%, and 42% for hemlock, balsam, cedar, and unhealthy trees, respectively, and 41%, 46%, 52%, and 30% for 1998. This is comparing the class of the isol with that of the most associated manual tree (i.e., the gred that occupies the largest proportion of the isol). If the trees of other categories are not counted as an error and not included in the analysis and isolation commissions are still considered an error, then accuracies for the 1996 data are 57%, 50%, 50%, and 61% for hemlock, balsam, cedar, and unhealthy trees, respectively, and 51%, 54%, 60%, and 35% for 1998. Of all the isols classed as one of the shaded hemlock or shaded balsam classes in the 1996 data, only 43% were most associated with either shaded hemlock or balsam trees (40% for the 1998 data). Most of the error for the shaded classes was from high commission error due to isols being created in shaded areas where no trees were identified from the ground plot stem map and image interpretation. If these were not included, accuracy of the isols classified as shaded was 79% for 1996 and 75% for 1998.

Similarly for hemlock, balsam, cedar, and unhealthy trees, if commission isolation errors were not included, classification accuracy of isols (good and other matches) considering isols most associated with trees of only the nominal classes was 66%, 52%, 56%, and 73%, respectively (55%, 44%, 50%, and 48%, if isols associated with trees of the other categories are counted as an error in classification regardless of their species; 69%, 56%, 50%, and 48%, if the other category trees are placed in the class corresponding to the species of that tree). Similar accuracies for the 1998 trial were 64%, 61%, 71%, and 55% for the nominal classes only; 50%, 51%, 60%, and 41% with trees of the other categories treated as an error; and 62%, 57%, 65%, and 44% if isols associated with trees of the non-nominal categories were designated as the closest nominal class. With commission isolations included as error, this latter accuracy (other class trees designated as their respective species) is 57%, 46%, 41%, and 39% for 1996, and 50%, 45%, 53%, and 36% for 1998.

Confusion of hemlock and balsam was the main source of error for both dates. Isols being classified as bright balsam that were really associated with bright hemlock trees was common for the 1996 imagery, and few isols were classed as the two bright classes on the 1998 data. Cedar was classified better on the 1998 data, but correspondence of isols classed as unhealthy with unhealthy ground reference trees was less.

Isols with several manual trees within them (grouping) were not a large isolation problem. For the 1996 imagery, only five isols were considered to be grouped, having several ground reference trees within them (i.e., have several greds strongly associated with them; types 16 and 17 in Appendix A). The 10 manual trees in these grouped cases matched the general isol species in only 3 out of the 10 cases. Similarly, four isols are grouped in the 1998 data, nine manual trees were involved, and four were the correct species. An additional two were the correct species but were shaded and one mountain hemlock was classed as western hemlock; two did not match at all the species class assigned to the associated isol.

6.2.3. Comparison of overall species composition from automated isolations, ground reference delineations, and field counts

It is also interesting to examine the total percent species composition of the plots based on automated techniques versus species percent for the manually delineated trees and the ground counts within the plots. Table 4 gives the percentage of trees in each species class for all the plots combined based on the field counts, manual delineations, and isols. The isol versus manual tree comparison shows close overall similarity in species composition. The manual trees represent trees visible on the imagery. Comparison of total species proportion with that from field counts is not as good but is also close. As mentioned earlier, there are more unhealthy trees tabulated from the manual delineations than the ground data (Table 4), as it was not always possible to properly discern health problems from the ground, especially when the top of the tree may not be visible. More unhealthy trees were observed for the 1998 versus 1996 imagery on the manual delineations and indeed more were classified. It must be remembered that these comparisons do not represent true correspondence between trees and isols, rather they just compare the total species percentages within the plots. It should also be noted that there can be quite a large difference between the trees visible on the imagery and field counts of trees depending on tree dominance and vertical canopy structure. Care must be taken in comparing automated tree isolation results to standard field observations and plot data, which can include suppressed and very small trees and trees underneath the canopy of other trees (e.g., Leckie, Gougeon, Walsworth & Paradine, 2003b). In this study, there were 125 more trees counted in the field than there were manually delineated greds. Nevertheless, in this particular case, the species composition that would be provided to the forester from the whole automated isolation and species classification process would be reasonably correct.

Table 4
Percent of trees in each class within the plots for: the field counts (suppressed dominance trees excluded), the greds (test trees, all trees in plot visible in the imagery), and the automated isolations

Case	Hemlock		Balsam		Cedar		Unhealthy		Other	
% Field counts	48.7		33.1		7.8		7.8		2.6	
Image data year	1996	1998	1996	1998	1996	1998	1996	1998	1996	1998
% Field class of greds	44.6	39.9	31.9	28.5	8.9	9.5	12.1	20.2	2.5	1.9
% Classified isols	51.4	42.4	29.4	31.2	6.2	9.3	13.0	17.1	–	–

7. Discussion

Automated individual tree crown analysis of high resolution imagery in old growth stands is complex. Tree isolation is aided by the typically large crown sizes and tree spacing in old growth stands. At the 60- and 70-cm resolution of this study, there were typically 10 to 70 pixels per delineated crown. However, there was still a considerable number of trees with touching and interlocking crowns which can be difficult to separate. Old growth stands commonly have variable tree heights with some very tall trees and other intermediate canopy trees, which are often shadowed by nearby taller trees. Stands are also characterized by gaps in the canopy. Because of the height of the trees and size of the crowns, these gaps are generally in shadow, often deep shadow. This is advantageous for the valley following tree isolation approach, which relies on shadow between trees. However, this shadowing can also shade canopy trees. In the isolation process, there is a compromise between choosing a lower image intensity threshold to represent shade which eliminates false detection of trees in treeless shaded open areas and choosing a threshold that is not so high as to eliminate some shaded trees. This issue is illustrated by the difference between the imagery for the two dates. The sun angle was lower for 1996 imagery (36° versus 41°) and shadows were larger and stronger. This difference and mainly the different shadow patterns due to the sun's azimuth can be seen in Figs. 1 and 2. Comparison of the two images shows that, both through manual and automated interpretation, different trees were detected (e.g., for the ground reference trees, 91% of all trees identified were the same). Manual tree crown delineations were often smaller on the 1996 imagery, but the automated isolations were of generally similar size for both dates. Figs. 1 and 2 give examples of these features. The illumination changes with sun elevation and azimuth and subsequent shadowing were an important effect on the visibility of trees and detection of trees with automated techniques.

Criteria and a system for determining spatial correspondence of automatically generated tree boundaries and ground reference delineations were developed. The rules for a good match are quite stringent and, for the two data sets for the same plots, approximately 50–60% of automated isolations match the greds. There were few omissions. There was no bias with regard to species; the trees that were omitted were either shaded or one of the trees that was deemed to be unusual in terms of visual appearance on the image or spectral characteristics. Commission errors at approximately 25% were the main problem; however, most were in shaded areas and were classed as shaded isols through the classification process. Grouping of adjacent trees into one isol was not an issue. In terms of tree dominance, most codominant, intermediate, and suppressed trees were isolated equally well. However, small suppressed trees were omitted more often. Splitting of large crowned trees into several isols did occur, but was not a large problem. This problem has been observed in another study examining automated single tree analysis of root disease damage (Leckie, Jay, Gougeon, Sturrock & Paradine, 2004). With image data similar to that used in this study, it was found that it was difficult to achieve a good isolation on sites with variable tree sizes. When good isolation was achieved on smaller crowned trees, the very large crowns tended to be severely broken up into several or many isols. Results of the isolation processes in any study will depend on the sun azimuth and elevation at the time of the imagery. For example, Andrew, Trotter, Höck and Dunningham (1999) and Culvenor (2002) showed that higher sun elevation resulted in better automated isolation. This is more important in old growth stands than in other types of stands due to the size of the trees, mix in heights, and characteristic presence of gaps and uneven stem distribution. In the analysis of overall species composition or tree counts to field plot data, one must be careful as standard field composition and counts can be quite different from that of the canopy trees and those visible on imagery. There are improvements that can be developed for the isolation process, especially in combining or reducing the number of split trees and in isolating trees in shaded zones, but the general approach seems viable and produces reasonable results for old growth.

Spectral characteristics, especially image intensity was variable within species and there was considerable overlap between the signatures of the different species (Leckie et al., 2003a). It was useful to use several internal class signatures in the classification to help account for the within species spectral variability of the hemlock and balsam. The use of shaded and unhealthy classes was generally successful at separating such trees from the healthy sunlit trees, thus facilitating species classifications. Species determination within the shaded and unhealthy classes as expected was not reliable.

The combined accuracy of tree isolation and species classification (tree recognition) is complicated. An analysis approach was developed and implemented. The overlap between automatically delineated tree crowns (isols) and manually delineated ground reference trees was quantified and 20 relevant situations defined. Accuracy of isolation and classification is then based on relevant groupings of the overlap situations. Accuracy can be considered from the point of view of how well each ground reference tree is represented by an isolation and the class of that isol (gred-centric), or how well each isol is classified relative to the class of associated ground reference trees (isol-centric). The analysis of combined isolation and classification accuracy offers an example of how such complex results and issues can be presented.

For the trees with isols considered to match well with the ground reference trees, accuracy was moderate, for example 57% on average for the three species with the 1996 data set. For ground reference trees with an isolation that is not a good match, species accuracy was erratic but for the 1996 data on average 15% poorer than those with a good match. Trees split into several isols or isols encompassing several ground reference trees (grouped) resulted in poorer classifications. For trees grouped into one isol, spectral signatures can be particularly confusing if the trees are not the same species and poor classification results can be expected. It is also interesting to note that classification of the manually delineated trees with the 1996 data was on average 20% greater than for those with a good match (Leckie et al., 2003a). Therefore, quality of isolation does have an influence on species classification. If one demands a good match before the trees are considered correctly recognized, then recognition can be quite poor (e.g., in the order of 45% for balsam and hemlock and 25% for cedar using the 1996 data). Similarly, if isolation commissions are considered an error, accuracies of the isols related to the gred they are most associated with (isol-centric accuracy) were in the order of 50% for balsam and hemlock and 61% for cedar). Average accuracies of the hemlock and balsam were similar between the 1996 and 1998 data sets but were more erratic especially the cedar accuracy for the 1998 data, since the isolation with the 1998 data was not as good as for the 1996 imagery.

8. Conclusion

Automated tree recognition (the process of isolating trees and determining their species) is difficult in old growth conifer stands. Isolation using the valley following approach produced good results in terms of correspondence with ground information and what can be seen visually on the imagery. The valley following approach is appropriate for these stands as it is based on using the shadow between trees to help locate and delineate their boundary. Results for 2 years of data over the same site indicate a robustness in methods. They also show that results will inevitably be different due to sun angle and elevation and to some extent sensor view angle. Isolation of shaded trees will be an issue as there is a fine balance in the isolation process between creating omissions and commissions in shaded areas. There is tremendous variability and overlap in the spectral signature of trees in old growth stands which makes species classification difficult. Nevertheless, simple spectral classification used with care and employing judicious use of classes (e.g., the two classes for hemlock and balsam in this study) produced useful individual tree information.

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Appendix A. Categories of isol-ground reference delineation overlap (after Leckie et al., 2004)

Notes:

- 1:1 means a gred only has one isol associated with (overlapping) it and that isol only has that gred associated it.
- 1:n means a gred has several isols associated with it.
- n:1 means an isol has several greds associated with it.
- a minimum percent area of overlap is required before an isol and gred are considered associated (this was set at 5%, but can be changed).

(a) Gred-centric and isol-centric perfect match
  (1) Perfect 1:1
    - only one isol overlapping the gred; that gred is the only gred associated with the isol; >50% of the isol's area is occupied by the gred and the isol occupies >50% of the area of the gred.

(b) Gred-centric (how well ground reference trees are isolated).
  (2) Good 1:1 (ITC too big)
    - as in (1) (perfect 1:1) except >85% of the gred is occupied by the isol and only 20–50% of the isol is occupied by the gred. A very good 1:1 overlap of an isol with the gred, but the isol is too big. Therefore, it is considered a good match.
  (3) Poor 1:1 (ITC too big)
    - as in (2) but not as much (only 50–85%) of the gred is occupied by the isol. It is considered a poor match as the coverage of the gred by the isol is not good enough to compensate for the poor coverage of the isol by the gred.
  (4) Gred-centric good 1:n (multiple minor)
    - a perfect 1:1 gred with other isols with a minor association with it (i.e., <20% of the gred is occupied by the secondary isols).
  (5) Gred-centric good 1:n (multiple major)
    - a perfect 1:1 gred with other isols, some with significant (major) overlap with the gred (i.e., between 20% and 50% of gred is occupied by the secondary isols).

(6) Poor 1:1 (ITC too small)
 – only one isol overlapping the gred; that gred is the only gred associated with the isol; but the match is poor with the isol only occupying 20–50% of the gred. Also 50–85% of the isol's area is occupied by the gred. Represents a case in which the gred mostly covers the isol, but the isol is too small to cover most of the gred.

(7) Good 1:1 (ITC too small)
 – as in (6) but the gred covers most of the isol (i.e., >85% of the isol's area is occupied by the gred).

(8) Poor 1:1 (spatial offset)
 – as in (6) but the gred only covers a small part of the isol (20–50%). This potentially represents an isol, which may be associated with the gred but is offset spatially relative to the gred.

(9) Gred-centric 1:*n* split
 – a gred that contains several isols within it; >20% of the gred must be occupied by each isol and >50% of each isol's area is occupied by the gred.

(10) Gred-centric 1:*n* split (many small)
 – a gred that contains many small isols within it; <20% of the gred must be occupied by each isol and >50% of each isol's area is occupied by the gred.

(11) Gred-centric split 1:*n* (one dominant)
 – as in (10) but one of the isols is not small (i.e., >20% of the gred is occupied by the dominant isol).

(12) GRED-centric omission (complete, pure; 1:0)
 – gred with no overlap with any isol

(13) Gred-centric omission (impure) (1:1 or 1:*n* omission)
 – gred with some isols that have only a small overlap with the gred; an almost 1:0 pure omission, but with one to three isols occupying only a small area (<20%) of the gred; the second and third most dominant isols must not have >50% of their area occupied by the gred.

(c) Isol-centric (how well isols represent ground reference trees)

(14) Isol-centric good *n*:1 (multiple minor)
 – a perfect 1:1 isol with other greds with a minor association with it (i.e., <20% of the isol is occupied by the secondary greds).

(15) Isol-centric good *n*:1 (multiple major)
 – a perfect 1:1 isol with secondary greds, some with significant (major) overlap with the isol (i.e., between 20% and 50% of isol is occupied by the secondary gred).

(16) Isol-centric *n*:1 grouped
 – an isol that contains several greds grouped within it; >20% of the isol must be occupied by each gred and >50% of each gred's area is occupied by the isol.

(17) Isol-centric *n*:1 grouped (many greds in an isol; severely grouped/under separated isols)
 – an isol that contains many small greds within it; <20% of the isol must be occupied by each gred and >50% of each gred's area is occupied by the isol.

(18) Isol-centric commission (complete, pure; 0:1)
 – isol with no overlap with any gred

(19) Isol-centric commission (impure) (1:1 or *n*:1 commission)
 – isol with some greds that have only a small overlap with the isol; an almost 0:1 pure commission, but with one to three greds occupying only a small area (<20%) of the isol; the second and third most dominant greds must not have >50% of their area occupied by the isol.

(d) Other matches

(20) Partial match (all others)
 – all other cases of overlapping isols and greds

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