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Remote Sensing of Environment 85 (2003) 355–369

Remote Sensing of Environment

www.elsevier.com/locate/rse

Stand delineation and composition estimation using semi-automated individual tree crown analysis

Donald G. Leckie*, François A. Gougeon, Nicholas Walsworth, Dennis Paradine[1]

Canadian Forest Service, Pacific Forestry Centre, Natural Resources Canada, 506 West Burnside Road, Victoria, BC, Canada

Received 24 June 2002; received in revised form 27 November 2002; accepted 1 December 2002

Abstract

Stand delineation and species composition estimation are cornerstones of forest inventory mapping and key elements to forest management decision making. Improved mapping techniques are constantly being sought in terms of speed, consistency, accuracy, level of detail, and overall effectiveness. Semi-automated analysis of high-resolution imagery at the individual tree crown level may offer such benefits. Methods, however, need to be developed and tested under a variety of forest conditions.

High-resolution (60 cm) multispectral airborne imagery was acquired over a predominantly young conifer forest and plantation test area on the west coast of Canada. Automated tree isolation algorithms were applied to the data in order to delineate tree crowns or clusters of crowns. An object-oriented single tree classification was conducted using a maximum likelihood classifier. Stands of similar species composition, closure, and stem density were defined through a sequence that first generated images of these parameters from the automated delineation and classification, used these as input to an unsupervised classification, and then filtered and smoothed the resulting classification clusters. Because of the dense nature of the stands and small crowns on the site, the isolation process often delineated clusters of several trees. Species classification accuracy was determined by comparing the average stand composition from the automated technique to that derived from ground transects or plots. Species classification was good, with average composition error (difference between field measured and automated composition) over all 16 test stands being 7.25%. Most errors for individual species in stands were below 20%, but a few were up to 30%. The automatically generated stand boundaries mimicked well those of known plantation and interpreted inventory boundaries. The automated technique created a few larger stands and some additional small stands in areas of complex forest structure. Overall, for the young fairly uniform stands of the site, both stand delineation and species composition estimation were of a quality suitable for operational use in inventory and forest management. Further development and testing is needed to extend results to situations covering large areas, multiple flight lines, varied topography, and different forest conditions.

Keywords: Semi-automated individual tree crown; Stand delineation; Forest

1. Introduction

Traditional forest inventory and management planning in Canada and many countries is based on stand maps at a scale of 1:10 000 to 1:20 000. Stands are forest units defined mainly by similar species composition, density, closure, height, and age. Stand boundaries and attributes are estimated through air photo interpretation. Common requirements are to assign species composition to the nearest 10%, closure in four classes, height to the nearest meter or in 3–5 m classes and age in 10–20-year classes or in broad maturity classes (Leckie & Gillis, 1995). Increasingly, it is desirable to have information of a more precise and consistent nature and estimates of other attributes. At the same time, there is pressure to reduce the cost of producing inventories.

Semi-automated and computer-assisted interpretation of digital imagery offers a possible solution to acquiring more information, reducing time and costs, and increasing consistency. Because of the many possible stand structures and combinations of different attributes that can occur, automated analysis must operate at the individual crown level to successfully achieve the stand characterization required. Therefore, isolation of individual tree crowns and their

* Corresponding author. Tel.: +1-250-363-0624; fax: +1-250-363-0775.
E-mail address: dleckie@pfc.forestry.ca (D.G. Leckie).
[1] Formerly with Macmillan Bloedel.

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doi:10.1016/S0034-4257(03)00013-0

classification is a necessary component for the description of forest stands to the precision required for forest inventory. It also offers capabilities to extract new information such as canopy gaps, tree size, or numbers of snags. Delineation of stands is also a key component of forest inventory that may be possible to automate.

There are several approaches to automated tree isolation. Local maxima methods identify bright pixels within given sized windows in an image (Dralle & Rudemo, 1997; Gougeon & Moore, 1989; Niemann, Adams, & Hay, 1999). These methods do not delineate the boundary of the crown, but rather provide a location of each crown. However, local maxima have been used as part of other methods that do define crown boundaries. Pinz (1991) identifies local maxima and examines brightness changes in concentric circles out from each maximum to determine if it is a tree crown and estimate the crown radius. Walsworth and King (1999) use local maxima and cost surfaces to identify crowns. A valley following approach (Gougeon, 1995a) uses the fact that trees are often represented on high-resolution imagery by bright areas surrounded by darker regions of shade, in a way forming a hill top and valley topography in the spectral image. The algorithm follows the valleys to separate trees and applies a rule-based approach to further refine and outline tree boundaries. Using this same topographic structure, Culvenor (2002) identifies local maxima and grows them out to regions of minima representing shade to determine crown boundaries. Both these methods work best in dense canopies where there is shade between trees. Another suite of methods uses template matching (Larsen, 1997; Pollock, 1996) in which mathematical renderings of the appearance of trees of different size, shape, and viewing conditions are matched with the image brightness to locate trees and determine their crown size. Warner, Lee, and McGraw (1999) use directional texture to group pixels and adjacent groups of pixels into crowns in an algorithm specifically designed for a dense hardwood forest. Brandtberg and Walter (1998) find convex edges and combine them to locate tree crowns. These methods and variations have been applied in various situations (Andrew, Trotter, Höck, & Dunningham, 1999; Davison, Price, Mah, Gauvin, & Achal, 1999; Haara & Nevalainen, 2002; Leckie, Jay, Paradine, & Sturrock, 1999; Pinz, 1999; Pouliot, King, Bell, & Pitt, 2002; Quackenbush, Hopkins, & Kinn, 2000; Wulder, Niemann, & Goodenough, 2000). Subsequent species classification is less well developed, most methods making use of only spectral information (Gerylo, Hall, Franklin, Roberts, & Milton, 1998; Gougeon, 1995b; Key, Warner, McGraw, & Fajvan, 2001; Leckie & Gougeon, 1999; Preston, Culvenor, & Copps, 1999). A few studies have examined use of textural and structural information as well (Brantberg, 1999; Gougeon, 1995b). The final stage, stand delineation is even less developed. Leckie and Gillis (1993) examine the issues in using high-resolution imagery for forestry and Hill and Leckie (1999) provide a compendium of work regarding automated individual tree analysis. The applicability and effectiveness of each automated method is dependent on forest type.

This paper explores and demonstrates an end to end process of data acquisition, data preprocessing, tree isolation, classification, and finally stand delineation for a site representing young dense uniform conifer stands. The valley following tree isolation approach is used, as it works best in dense conifer stands and provides tree or tree cluster outlines that can then be used for species classification. An object-oriented spectral classification procedure is used for species classification and a stand regrouping or delineation procedure presented. The study concentrates on automated individual crown species classification followed by automated stand delineation. It deals with a simple case of a small site of low topographic relief and with image data from one flight line. The objectives are to determine the accuracy of species composition estimation at the stand level, present and test a stand delineation approach, and demonstrate a data processing stream for automated stand delineation and species classification. The study is part of a larger project to explore the use of high-resolution multispectral imagery from the airborne Compact Airborne Spectrographic Imager (CASI) sensor for providing data for forest inventory and management decision making. The overall project included methods for tree isolation, counts, closure, species composition, and root disease detection on a variety of forest conditions on Vancouver Island on the west coast of Canada (Leckie, Jay, et al., 1999).

2. Site

Data were acquired in a single flight line over a site that consisted of a series of plantations of different softwood species plus natural forest. The plantations are part of an experiment termed the "Nahmint Species Trial" (Dunsworth, 1990). The site is located along the Nahmint River south of Port Alberni, British Columbia, Canada on Vancouver Island (49°05′15N, 124°56′57W). It is in the coastal western hemlock very wet maritime submontane (CWHvm1) biogeoclimatic variant on a good growing site (site index 35 m at 50 years). The species trial was established to compare the height and volume growth of five coastal coniferous species: Douglas-fir (*Pseudotsuga menziesii* Mirb. Franco), grand fir (*Abies grandis* Dougl. ex Loud.), amabilis fir (*Abies amabilis* Dougl. ex Loud.), western red cedar (*Thuja plicata* Donn ex D. Don), and western hemlock (*Tsuga heterophylla* Sarg.). The trees were planted in 1979 and 1980 following logging of the area in 1977 and 1978. There was some natural regeneration in addition to the planted trees. Some thinning of specific plots occurred. Young trees of these species and especially hardwoods occurred along roads and trails adjacent to the plots. Fig. 1 shows imagery of the test area. The sites of interest for this study are outlined and are the young conifer stands. Aspen (*Populus* spp.) and other hardwood trees (e.g., cherry (*Prunus* spp.) and willow (*Salix* spp.)) were

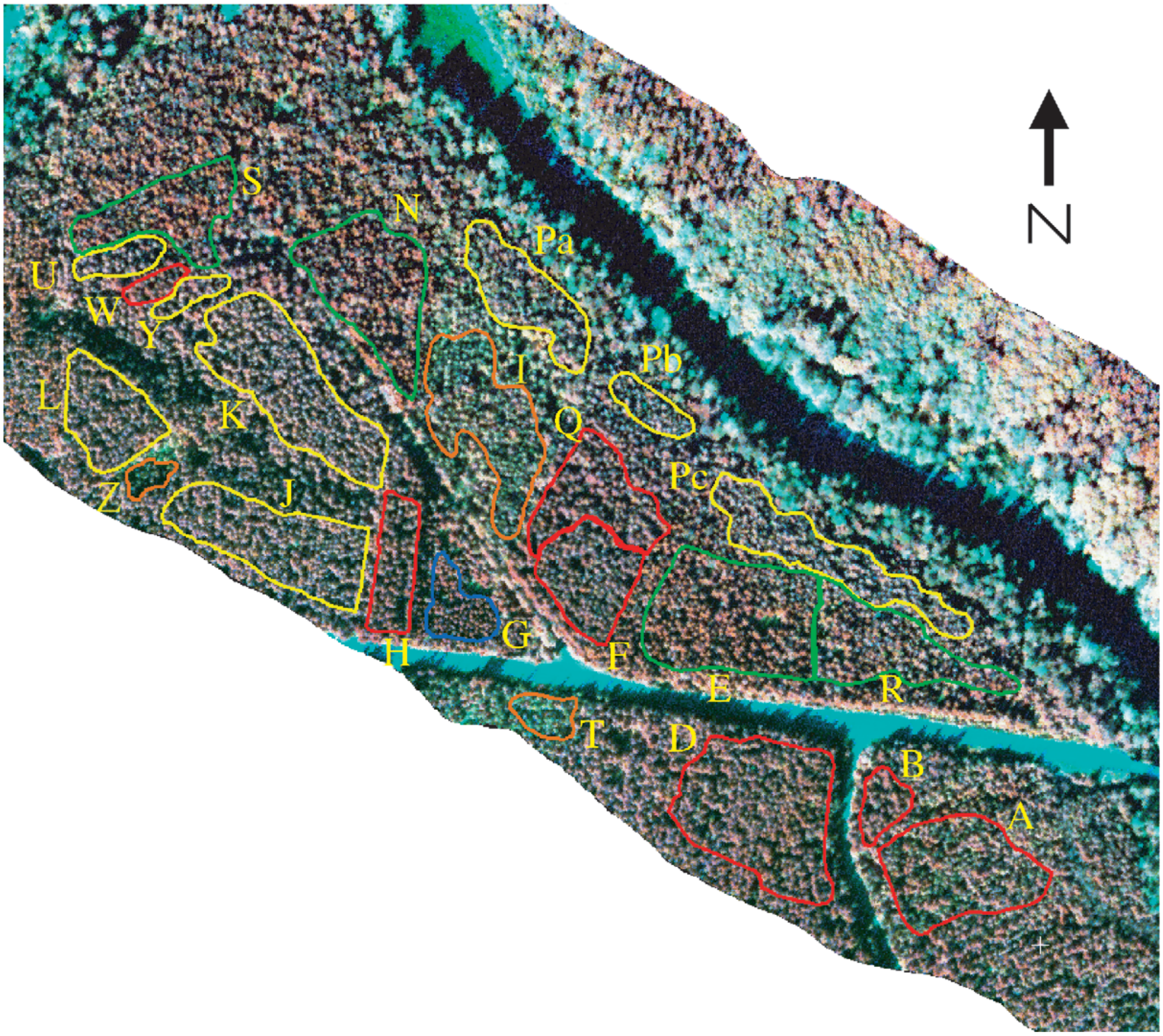

Fig. 1. CASI image of the test area (colour infrared combination of raw bands) with the outlines of the test sites (see Table 1 and text for test site description). The area represented by the outline of the figure is 620 × 550 m.

scattered within some of the young conifer stands and along the road and trail edges. Near the river and east side of the site, there were areas of mature trees and some large hardwoods. North of Nahmint River was a zone of predominantly young hardwood that was on a steep slope down to the river. This area was not part of the study. The area of interest south of the river was generally flat or rolling but had a few steep narrow valleys.

The study area and test sites are detailed in Fig. 1. There are 16 primary test sites for which there are field transects or plots (sites A, B, D through K, N, P, R, S, U, W). These were planted with single species, but some have had considerable natural regeneration and are now mixed species. In addition, five other sites of fairly uniform species were used as secondary sites, but have no ground plot information to confirm results. These were sites L and Y (predominantly hemlock), T and Z (cedar), and Q (Douglas-fir), and were a combination of planted and natural regeneration. For the test sites, tree height varied among stands, but generally ranged from 10 to 14 m. Diameter at breast height was typically between 12 and 20 cm. Tree dominance and size also varied. Several stands had suppressed trees or new regeneration in the understory. Stems per hectare and species composition depends on the dominance level of the trees one includes. Table 1 gives species composition and stems per hectare for dominant, codominant, and intermediate trees of the primary test sites used in the study (Fig. 1). For these trees, crown diameter was usually between 1 and 4 m, with most being 1.5–2.5 m. Stands were dense with high crown closures and tree crowns generally touching and interlocking.

3. Field data collection

The species composition and stems per hectare of stands were characterized through measurements along transects or within rectangular plots. Site I had both transects and plots. Those sites with transects had two to three transects from 30 to 50 m long (site B only had one transect). For each tree

Table 1
Classification error for each test stand and species

Test sites	Species composition	Douglas-fir	Grand fir	Amabilis fir	Western red cedar	Western hemlock	Hardwood	Unclassified	Stems per hectare	Average of absolute values (without unclassified)	Average of absolute values (softwoods only)
A	Transect/plot	8.6	10.9	0.0	53.7	26.8	0.0	0.0	1788		
	Classification	22.1	7.2	1.5	35.4	25.6	0.5	7.7			
	Difference	− 13.5	3.7	− 1.5	18.3	1.2	− 0.5	− 7.7		6.47	7.66
B	Transect/plot	62.5	0.0	0.0	25.0	6.3	6.3	0.0	1333		
	Classification	77.8	11.1	0.0	2.8	8.3	0.0	0.0			
	Difference	− 15.3	− 11.1	0.0	22.2	− 2.1	6.3	0.0		9.49	10.14
D	Transect/plot	73.9	0.0	0.0	8.6	17.1	0.4	0.0	1546		
	Classification	72.9	8.8	1.2	2.8	8.0	0.0	6.4			
	Difference	1.0	− 8.8	− 1.2	5.8	9.1	0.4	− 6.4		4.38	5.18
E	Transect/plot	0.2	62.4	0.0	2.4	33.4	1.7	0.0	1203		
	Classification	22.1	48.4	8.9	1.4	13.6	0.5	5.2			
	Difference	− 21.9	14.0	− 8.9	1.0	19.8	1.2	− 5.2		11.13	13.11
F	Transect/plot	84.4	0.0	0.0	0.0	13.3	2.2	0.0	1023		
	Classification	80.8	1.9	3.9	2.9	5.8	0.0	4.8			
	Difference	3.7	− 1.9	− 3.9	− 2.9	7.6	2.2	− 4.8		3.68	3.98
G	Transect/plot	0.5	0.0	88.0	0.4	10.8	0.4	0.0	1181		
	Classification	6.5	11.7	74.0	0.0	3.9	0.0	3.9			
	Difference	− 6.0	− 11.7	14.0	0.4	6.9	0.4	− 3.9		6.53	7.76
H	Transect/plot	96.0	0.0	0.0	0.0	4.0	0.0	0.0	1025		
	Classification	88.9	7.4	3.7	0.0	0.0	0.0	0.0			
	Difference	7.1	− 7.4	− 3.7	0.0	4.0	0.0	0.0		3.7	4.44
I	Transect/plot	5.4	0.0	0.0	68.8	18.3	7.5	0.0	1274		
	Classification	3.7	0.0	1.9	67.3	18.7	1.9	6.5			
	Difference	1.6	0.0	− 1.9	1.5	− 0.4	5.7	− 6.5		1.85	1.09
J	Transect/plot	0.0	0.0	0.0	3.5	95.4	1.2	0.0	1654		
	Classification	6.0	0.5	0.0	1.1	84.3	0.5	7.6			
	Difference	− 6.0	− 0.5	0.0	2.4	11.0	0.6	− 7.6		3.42	3.99
K	Transect/plot	2.2	0.0	0.0	0.4	96.4	1.0	0.0	1180		
	Classification	3.7	1.0	0.0	2.6	85.9	0.0	6.8			
	Difference	− 1.4	− 1.0	0.0	− 2.2	10.5	1.0	− 6.8		2.7	3.04
N	Transect/plot	1.3	47.4	0.0	2.6	30.3	18.4	0.0	1583		
	Classification	21.5	44.3	12.7	1.3	10.8	0.6	8.9			
	Difference	− 20.2	3.1	− 12.7	1.4	19.5	17.8	− 8.9		12.43	11.36
P	Transect/plot	0.0	0.0	13.3	3.3	66.7	6.7	0.0	2419		
	Classification	7.9	5.4	1.8	12.2	52.9	1.8	18.0			
	Difference	− 7.9	− 5.4	11.5	1.1	13.8	4.9	− 18.0		7.43	7.95
R	Transect/plot	0.4	46.5	0.0	3.0	48.6	1.5	0.0	2751		
	Classification	30.2	21.4	2.5	2.5	28.9	1.9	12.6			
	Difference	− 29.8	25.1	− 2.5	0.5	19.7	− 0.4	− 12.6		13.01	15.53
S	Transect/plot	6.4	46.8	0.0	0.0	42.6	4.3	0.0	1703		
	Classification	17.0	47.5	11.4	2.8	12.8	0.0	8.5			
	Difference	− 10.6	− 0.7	− 11.4	− 2.8	29.8	4.3	− 8.5		9.93	11.06
U	Transect/plot	0.0	0.0	0.0	0.0	100.0	0.0	0.0	1313		
	Classification	8.3	8.3	2.8	0.0	72.2	0.0	8.3			
	Difference	− 8.3	− 8.3	− 2.8	0.0	27.8	0.0	− 8.3		7.87	9.44
W	Transect/plot	66.7	0.0	0.0	0.0	33.3	0.0	0.0	750		
	Classification	60.0	20.0	16.0	0.0	4.0	0.0	0.0			
	Difference	6.7	− 20.0	− 16.0	0.0	29.3	0.0	0.0		12.00	14.40
Average of absolute values (differences)		10.06	7.68	5.74	3.91	13.27	2.85	6.57		7.25	8.13

Error is the difference between composition based on the ground transect and plots versus that of the classification. Also given (first row of data for each test site) is the field measured species composition and total stems per hectare based on trees with crown size class of 4 or larger and dominance 1, 2, or 3 for stands described through transects, and trees with dbh>3.8 cm for stands represented by plots.

within 2 m of each side of the transect line, a series of attributes was recorded. This included:

- species,
- dominance rating,
- crown size category, and
- distance along transect.

Dominance rating was related to tree visibility from above, but generally followed the normal inventory description of dominance. Table 2 describes the dominance and crown size classes.

The plots were 15 × 30 m permanent sample plots established and measured as part of the Nahmint species trial growth experiment. Sites represented by plots generally had two to four plots per site. The species, diameter at breast height, and height of each tree were measured. Dominance rating was inferred from species, height, and dbh. The plots were measured in February 1996 and the transects in August 1997.

4. Image acquisition and data preprocessing

Imagery was acquired with the CASI sensor in a twin-engined aircraft by Itres Research (Anger, Mah, & Babey, 1994; Babey et al., 1999). The imaging spectrometer was operated in spatial mode and eight spectral bands were programmed (Table 3). Data was recorded in 12-bit resolution, then calibrated and converted to 16-bit data. One flight line was flown at 535 m above ground level with an azimuth of 280°, centred along the test sites. Resolution along and across track was 65 cm and with a detector array of 512 elements across the image, swath width was approximately 330 m. The segment of the flight line corresponding to the test site was 800 m long (Fig. 1). Imagery was acquired September 25, 1996 at 1514 hr PDT. This gave a sun azimuth and elevation of 218° and 33°, respectively. Sky conditions were clear. Ground vegetation was still green, but a few hardwood trees had minor senescence.

Imagery was geometrically corrected to 60-cm resolution by way of aircraft position from differential GPS, aircraft attitude data, and digital elevation and control point data. A nearest neighbour resampling kernel was used. Because the acquisition resolution was somewhat larger, there was some duplication of pixels. The data were also radiometrically normalized for the effects of sun–object–viewer geometry. Sun azimuth was near perpendicular to the flight line direction and sun elevation fairly low. Thus, on the southwest side of the imagery, the sensor is viewing the shaded side of trees and, on the northeast side, the sunlit side of the crowns. The across image radiometric normalization was done in an empirical object-oriented approach. Since it is the trees or tree clusters that are being classified, the correction was applied such that the signatures for the trees would be uniform across the imagery. The results from an automated tree isolation applied to the imagery before across track radiometric normalization were used and a preliminary classification of conifer versus broadleaf was conducted. Then the mean values of each spectral band for the automatically delineated isolations that were classified as conifer were plotted versus position across the image and a second or third order polynomial fit. An additive offset equal to the difference between the curve value at each position across the image and the curve value at nadir was calculated. This offset was then applied to each pixel of the image dependent on its position. The fits of the correction curve polynomials for each band were good with coefficients of determination (r^2 values) in the order of 0.81–0.92. Examination of the residuals after correction indicated that this procedure successfully minimized the bidirectional reflectance effect. Classifications of species without this correction were clearly biased. For example, no Douglas-fir was classified near the edge of the image and the stand delineation showed a tendency towards stands elongated in the along track direction in zones away from the centre line of the image.

Table 2
Crown size and dominance classes used

Dominance code	Interpretation	
1	Dominant visible, easily separable, distinct	
2	Dominant or co-dominant, separable	
3	Co-dominant, may be difficult to separate	
4	Suppressed, but possibly visible	
5	Suppressed, of significant size but not visible	
Crown size	**Crown diameter (m)**	**Interpretation**
1	>3.5	very large
2	2.5–3.5	large
3	1.5–2.5	average
4	< 1.5	small

Table 3
Spectral bands

Band	Wavelength (nm)	Width (nm)
1	437.5	27.4
2	488.5	24.8
3	550.2	25.0
4	601.0	25.1
5	656.0	25.2
6	715.0	25.4
7	795.4	25.5
8	860.7	25.6

5. Analysis methods

5.1. Tree crown isolation

Crowns of trees or clusters of trees were delineated using the valley following approach of Gougeon (1995a, 2000). This method treats the spectral values of the imagery as topography with the shaded and darker areas representing valleys (valley material) and bright pixels of the tree crowns (crown material). The highest valued pixels generally correspond to a location on the crown where the sun orientation, viewing angle, and tree geometry create a bright area on the crown. This is on the sunlit side of the tree usually near the crown apex. The valley following algorithm starts in low value areas and follows any valleys in image brightness. There is a lower threshold setting on the algorithm where pixels below this value are considered valley material regardless of topographic shape. Another threshold (valley roughness) is applied as the valley grows. It determines how large an increase in pixel value to each side of the current valley is considered part of the valley. For example, a threshold of two would require pixels on each side of the pixel at the current head of the valley to have values two or more than that of the valley head pixel in order for the valley to proceed. An upper threshold prevents valleys from progressing too far into bright tree crown material. Thus, the valley following method permits valleys between tree crowns even if there is no shade between them. It produces a bitmap of segments of valley and crown material. Masks can be created and applied before the isolation process to eliminate water, roads, and other non-treed zones from the processing.

Once the valleys and crown material are determined, a second rule-based system follows the boundary of each segment of crown material to create refined segments or isolations (isols), which are taken to represent tree crowns or clusters of crowns. The rules favour clockwise turns (i.e., check for clockwise moves first) and permit completion of valleys where an indentation in the segment shape can be

a

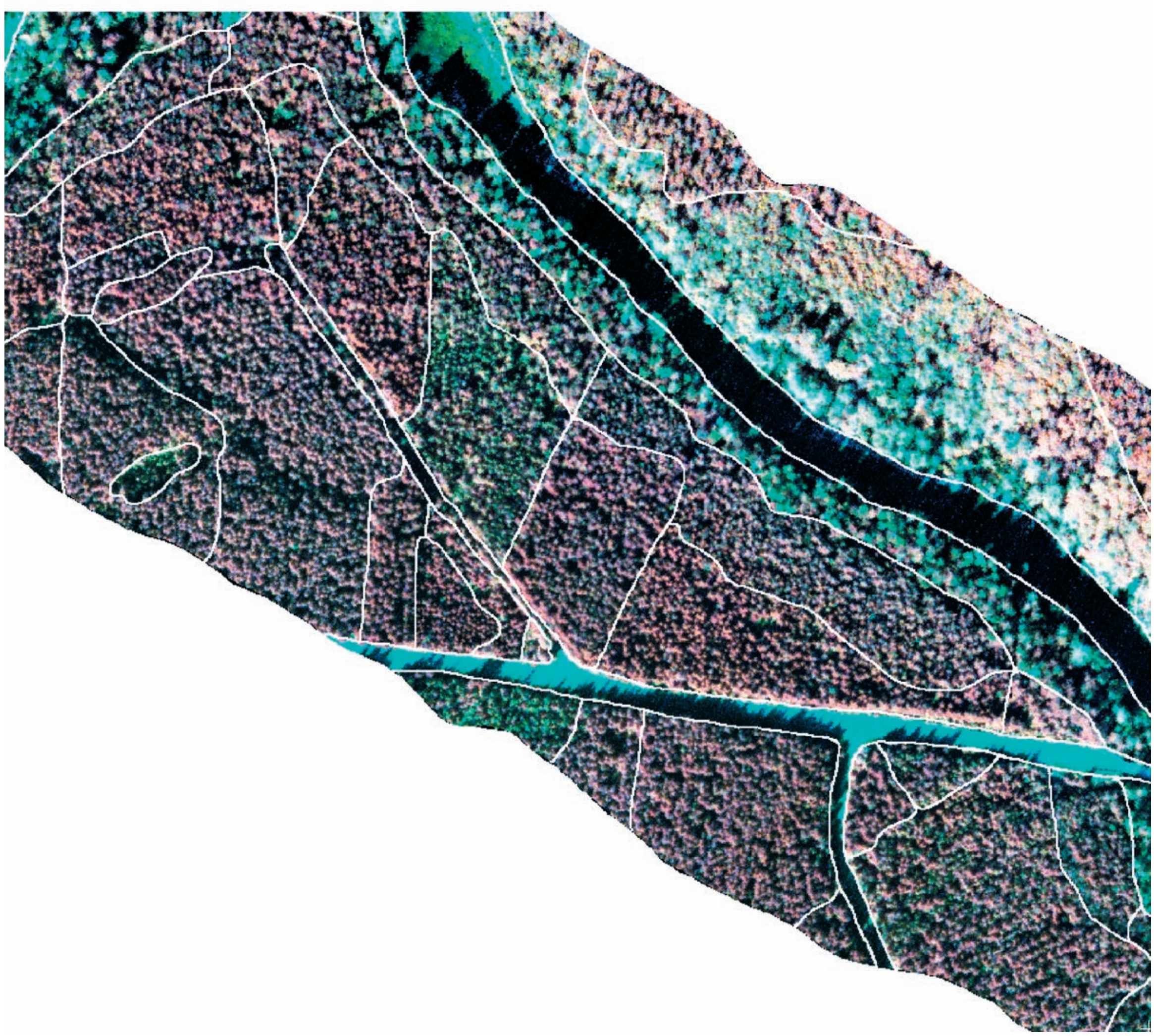

Fig. 2. (a) CASI image of test area with reference stand boundaries (colour infrared combination of raw bands). (b) Automatically isolated and classified tree crowns and crown clusters (isols) and automated stand delineations. Douglas-fir = red, grand fir = green, amabilis fir = blue, western red cedar = orange, western hemlock = yellow, hardwood = gray, and unclassified = white.

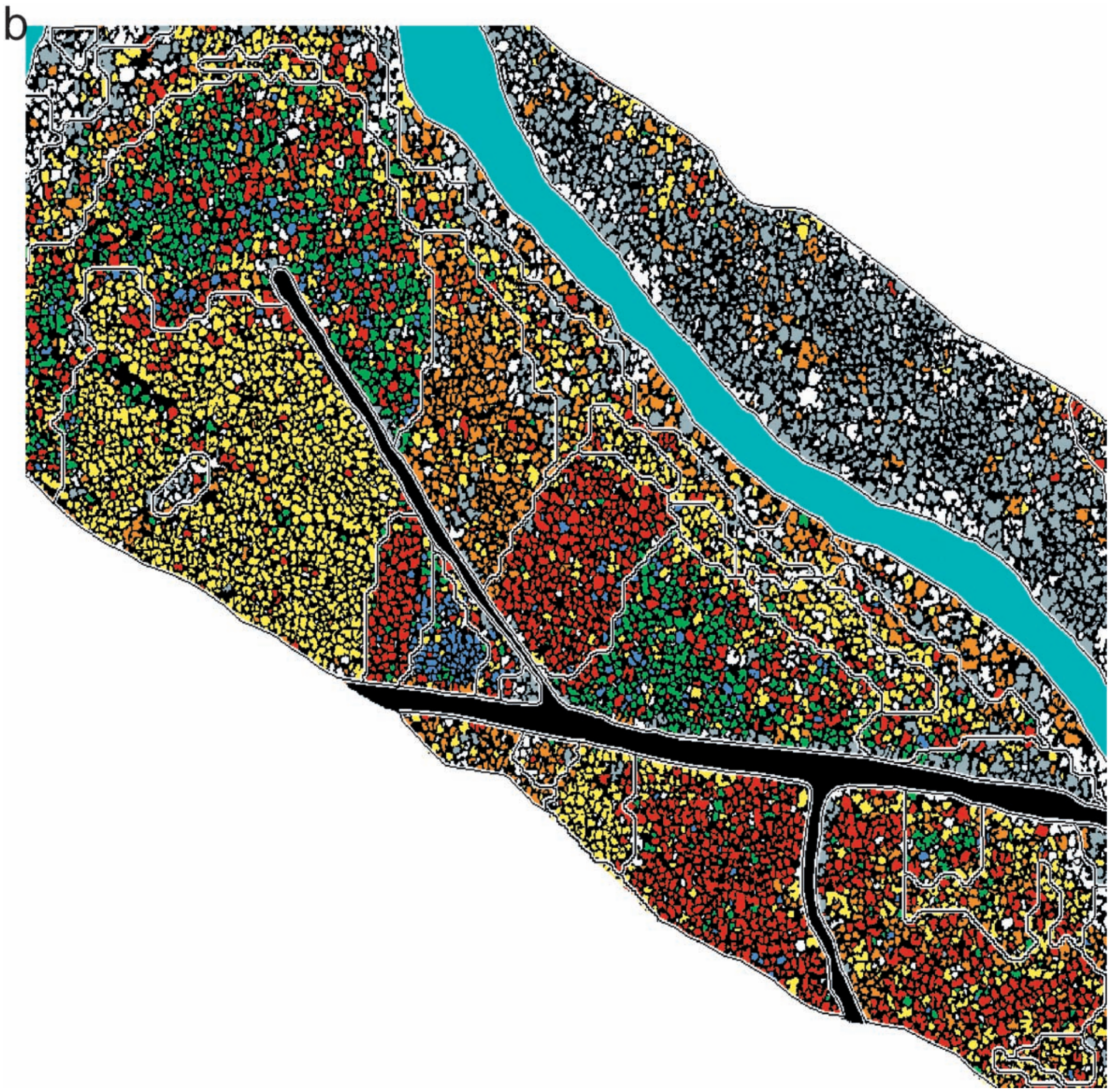

Fig. 2 (*continued*).

extended through to other valley material within a short distance in the direction of the indentation. This "jump factor" breaks larger segments into smaller isols.

An isolation was conducted on the imagery of this study (Fig. 2b) using established procedures for the valley following approach within the Individual Tree Crown software suite (Gougeon, 2000). The 795-nm band (before across image radiometric normalization) was used as the brightness image input for the isolation. A 3×3 averaging filter was conducted first. The isolation procedure was then applied with a lower threshold on the valley following of 500, no upper threshold, and a valley depth parameter of 60 pixel values. The "jump factor" used was one pixel or 60 cm.

5.2. Species classification

Species classification was done on an individual isol basis as opposed to a pixel by pixel approach. Each isol was described by a single multispectral vector. Several types of input signatures were tested. These were:

- mean intensity value of all the pixels in the isol,
- mean-lit value, which is the average of all pixels in an isol that have a pixel value above the mean intensity of all the pixels in the isol,
- texture, the standard deviation of the intensity of all pixels within the isol,
- mean and texture, and
- tree top value, the pixel value for the brightest pixel in the isol.

Signatures for five conifer classes and one deciduous broadleaf class were developed. They included: Douglas-fir, grand fir, amabilis fir, western red cedar, and western hemlock. All represented the young conifers from the plantation areas. The deciduous class was predominantly aspen and also young. Field data were collected for stands and were not on a tree-for-tree basis. Therefore, training isols for developing the class signatures (training trees) were selected by identifying, from field observation, areas of almost pure species composition and designating all isols contained within as one species. Several independent areas for each species were used to develop the signatures; an exception was the grand fir sample for which there was only one stand.

Fig. 3 shows the mean-lit signatures for the six classes. The hardwood had the highest values in all bands. Cedar

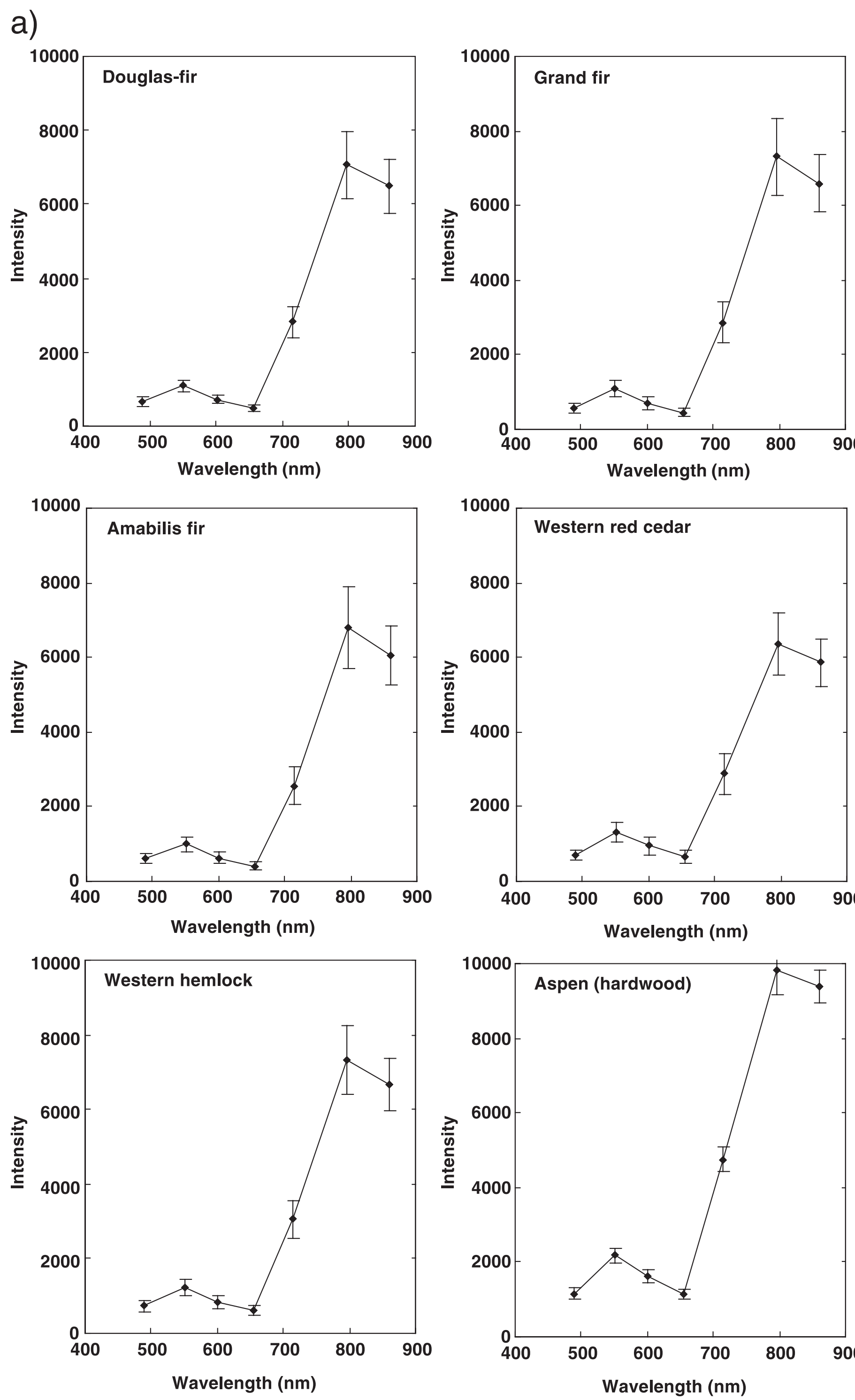

Fig. 3. Mean-lit spectral signatures for automatically isolated trees of different species. (a) Mean and standard deviation for each species class. (b) Mean for the six species classes.

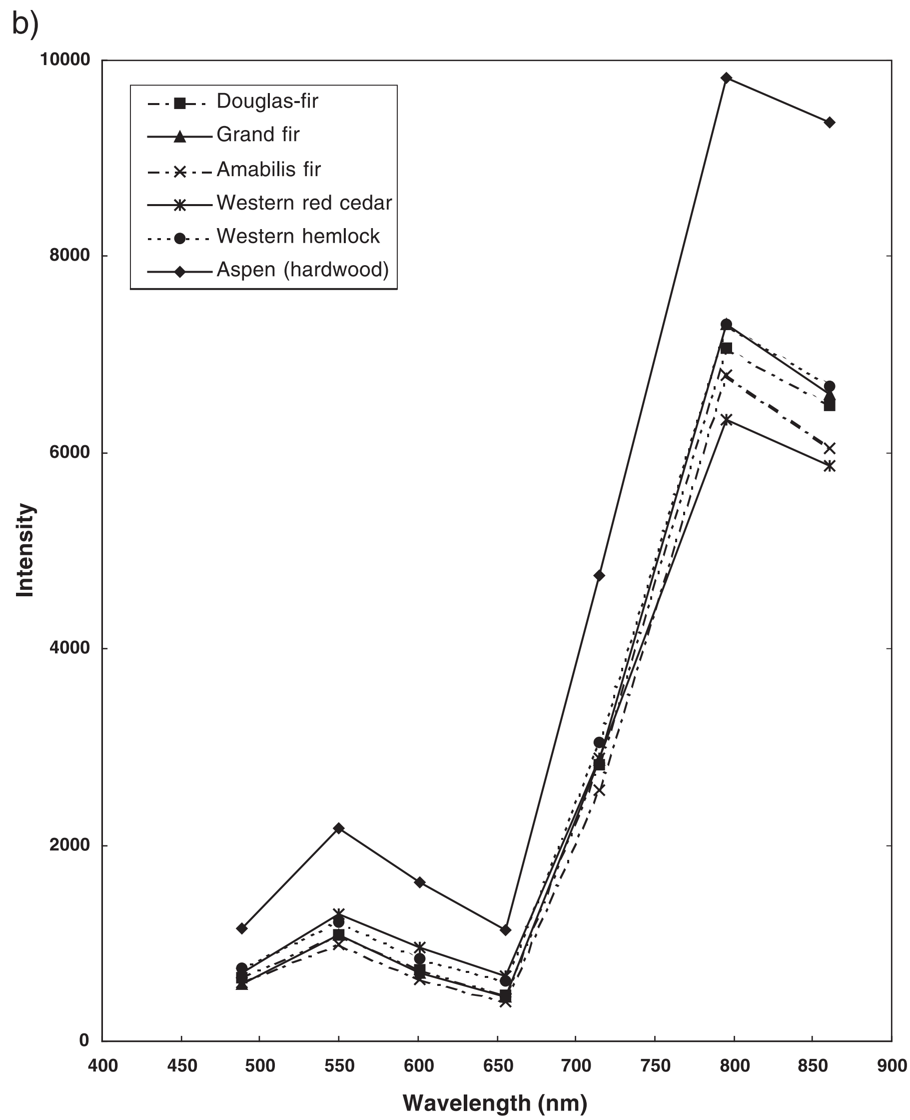

Fig. 3 (*continued*).

was characterized by high visible band reflectance and low near-infrared values. Hemlock had high values in all bands. There was little difference among the amabilis fir, grand fir, and Douglas-fir in the visible bands.

A supervised maximum likelihood classification (Richards & Jia, 1999) of species classes was conducted on all isols within the test site. This was done in an object-oriented approach with each isol representing one entity to be classified. The training isols of each species were used to generate the class signatures. An individual crown or crown cluster classification was therefore produced (Fig. 2).

Accuracy of the classification was tested by comparing the species composition of the test stands as determined from the ground transect and plot data with that from the classification of the isols within it. Only trees of dominance three or more and crown size four or larger were used to determine species composition from the ground data. As ground data were not on a single tree basis, it is the percentage of trees of each species from the ground truth versus isols that is compared. Errors can therefore be somewhat compensatory. For example, isols of Douglas-fir may be erroneously classified as hemlock but other hemlock isols within the same stand may in turn be classed as Douglas-fir.

Classifications and accuracy assessments were conducted with the different types of input signatures (mean, mean-lit, texture, mean and texture, and tree top value) in order to determine the best signature type to use. All spectral bands except the 438-nm band were used in these classifications. The mean-lit signature produced the best species classification accuracies of all the signatures tested. It was therefore used in subsequent analysis. The mean signature was slightly poorer, followed by the mean plus texture, texture, and tree top signatures, which had 1–3% lower average accuracy than the classification using the mean-lit signature. The mean-lit signature has also proven to be best in other studies (Gougeon, 1995b; Leckie et al., 1992; Leckie, Smith, et al., 1999).

The usefulness of the different spectral bands and performance of the classification with different numbers of bands were analyzed. Trials were also done with classifications using mean-lit signatures generated with different numbers and combinations of bands. An analysis of best band combinations was conducted using the mean-lit signatures and Jeffries-Matusita distance (J-M distance) between classes. J-M distance is a multivariate measure of the statistical difference between the signatures for two pairs of classes (Richards & Jia, 1999). It ranges from a value of zero for identical signatures to 2.0 for very widely separated classes. Values of 1.0 and greater are considered of moderate or better separability.

5.3. Stand delineation

A goal of this study was to automatically create stands that would be acceptable based on the concepts of forest inventory and compatible with stands of a standard forest inventory. Forest inventory stands are generally defined as spatially contiguous units of uniform species composition, stem density, crown closure, height, and age. For the bulk of the test sites, age is uniform. Stand heights are also uniform and there is no stereo imagery available with the sensor to estimate height. The approach taken is to regroup the

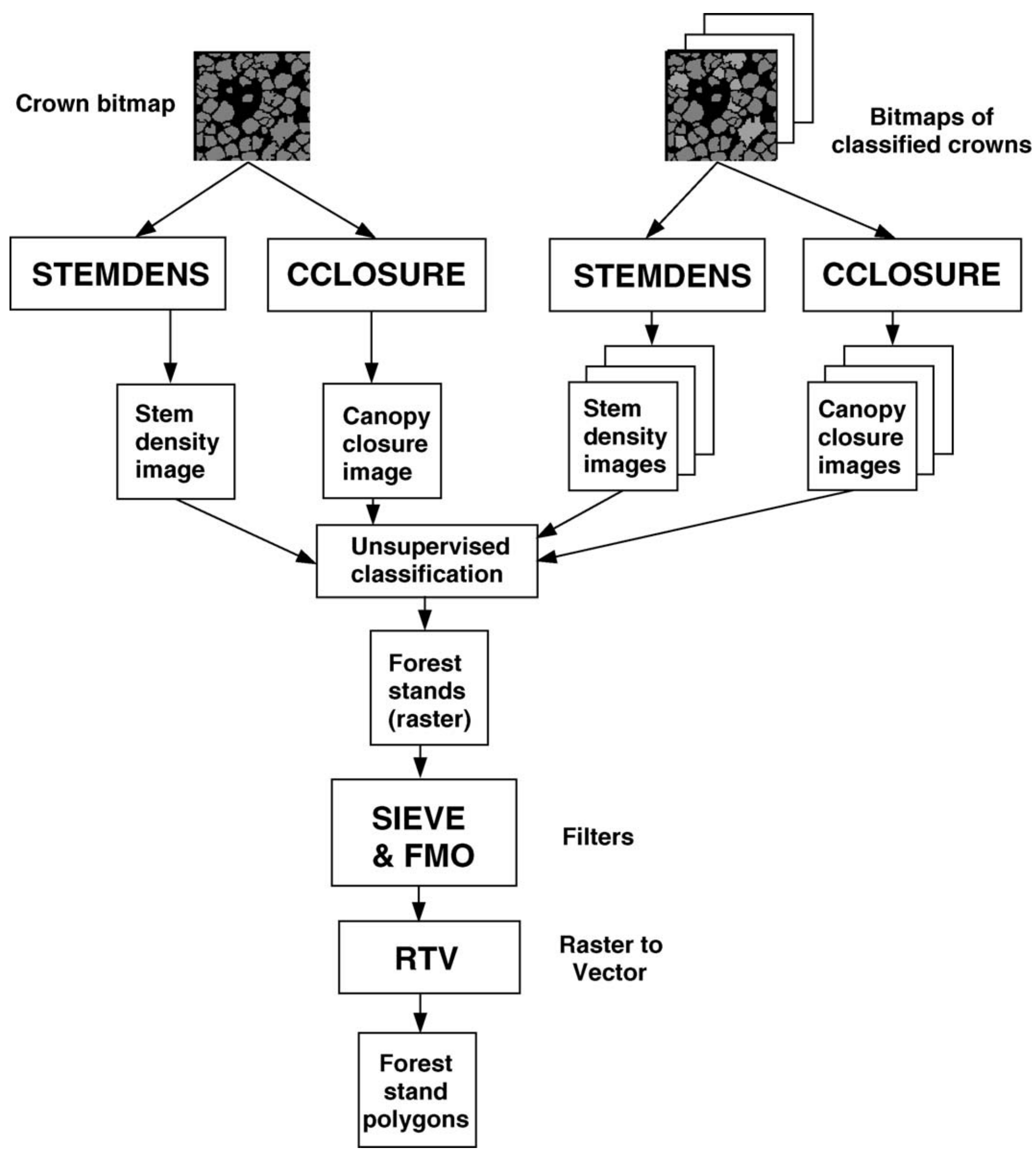

Fig. 4. Analysis stream for producing forest stand polygons. Rectangular boxes are software programs, the square boxes are inputs and outputs of the process (after Gougeon, 1997).

classified isols into forest stands using stem density, crown closure, and species composition. The isols were regrouped through a classification process using these parameters.

Fig. 4 outlines the stand delineation method. First stems per hectare and crown closure images were produced from all the isols. The classified isols were also processed to produce separate images of stem density and crown closure for each of the six species. The closure and stems per hectare images were generated by calculating average values within 51×51 pixel moving windows. The centre of the window was moved 10 pixels each calculation. These parameters were chosen based on the image resolution and expected stand sizes. Therefore, the resulting images were composed of blocks of 10×10 pixels of equal density or closure value. These images were then input into a pixel-based unsupervised classifier, much as spectral channels would be. An isodata classifier (Richards & Jia, 1999) was used. Several classifications inputting different numbers of requested classes were conducted until a good regrouping was achieved based on visual interpretation of the imagery. It was found that a good result was obtained using 9 requested classes and 20 iterations. Spatial units of less than 1000 (360 m^2) similarly classed connected pixels were removed and their pixels were assigned to spatially adjacent units through an erosion (SIEVE) process. A mode (FMO) filter with a 7×7 window size was then applied in three passes to help smooth the boundaries. The resulting spatial units were converted from raster to polygon format and input to a GIS. The stem density and closure images were generated from moving windows and were therefore influenced by the edge of the image and open areas such as rivers or roads. This created artificial stands along the image edges, the Nahmint River, and roads. The road and river boundaries were manually delineated and automatically delineated boundaries paralleling and within 15 m of the river, road, and image edges were eliminated. The results were polygons based on regrouping individual crown information into environmental strata or polygons approximating forest inventory stands.

Fig. 2a gives the stand boundaries that were used as reference for comparison to the automated boundaries. These reference stand boundaries were placed on the imagery based on the known boundaries of the plantations and interpretation of the natural stand boundaries based on the normal inventory criteria for stand delineation used by the B.C. Ministry of Forests, Weyerhaeuser, and others. No minimum stand size was applied. Interpretation of both the CASI imagery and stereo 1:19 000 scale colour photography (September 21, 1994) was used to define the boundaries, which are given in Fig. 2a. This was done independently from the automated interpretation by two interpreters, one familiar with the site and the other not. Discrepancies in line placement were resolved through discussion between them. If no clear consensus was reached, then at this point the automated boundaries were inspected and the interpreted boundary closest to the automated delineations was chosen. The final boundaries were then approved by a third interpreter. The automated boundaries were compared qualitatively with the reference stand boundaries.

6. Results

6.1. Tree crown isolation

Fig. 2 gives the results of the tree crown isolation procedure. The valley following approach, being based on the assumption of shade or lower intensity values between trees, works best in denser forest canopies such as those for the study area. The stands are, however, young and many tree crowns are small, closely spaced, and interlocking. Therefore, for this site, the procedure is expected to do well at isolating tree clusters or the larger dominant trees, but not all the individual trees themselves. This indeed is what happened, with smaller closely packed trees being combined in one isol. Total counts of the isols were typically one-half to one-fourth the number of trees in the stands (trees of dominance classes 3 and size classes 4 or larger for stands represented by transects and >3.8 cm diameter for stands with plots). Thus, some isols will represent several trees and these could sometimes be trees of different species.

6.2. Species classification

Average species error over the 16 test sites was 7.25%, ranging from 3% to 13% for each stand (Table 1). This accuracy was determined by first calculating for each stand, the difference between the percentage of trees of each species according to the ground measurements and the percentage of total isols in the stand of the same species. The ground reference species composition was based on crowns of dominance 1, 2, or 3 and crown size 4 or larger for the stands characterized by transects and on trees with dbh>3.8 cm for the stands represented by the permanent sample plots. The average absolute difference over the six species (five softwood species and a combined hardwood species class) was then calculated for each stand. These stand errors averaged by species were then in turn averaged over the 16 test stands. Unclassified isols are not included in this calculation. Average absolute error over all stands for each species was 10.1%, 7.7%, 5.7%, 3.9% and 13.3% for Douglas-fir, grand fir, amabilis fir, western cedar, and hemlock, respectively. Combined softwood species error averaged over the 5 species and 16 stands was 8.1%, while the hardwood class error was 2.9%, but over all the test sites there were few hardwoods (the average proportion of hardwood in each site was 3.2%). The one test site that did have considerable hardwood (N) had very few isols classed as hardwood. On average, 6.6% of the isols in each stand were unclassified. This typically ranged from 4% to 9%, but one hemlock stand had 18% unclassified isols. There was generally a

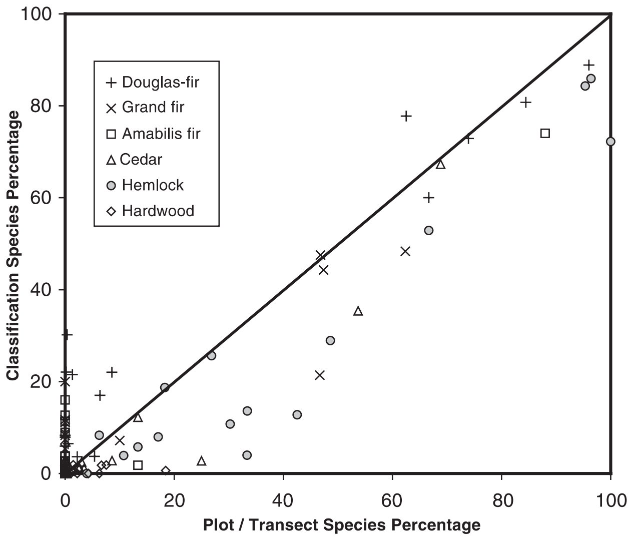

Fig. 5. Plot of percentage of each species in the stands based on the classification versus that from ground data.

tendency to underestimate species percentage, especially for cases of high species proportion (Table 1 and Fig. 5). This is partly due to presence of unclassified isols, so that the sum of the percentage of isols classed as each of the species often does not reach 100%. At low proportions of Douglas-fir, amabilis fir, and grand fir, there was an overrepresentation of these species. Hemlock was underestimated for most stands.

The average absolute error for the dominant species in a stand was 10.9%, with Douglas-fir being the best at 6.7% and hemlock having the highest error at 16.5%. The error at the individual stand level was 1–20%, with one hemlock site (U) at 28% (Table 1). The relative percentage error for the dominant species in each stand (species error/species composition percentage) averaged 15.1%, but ranged from 1% to 40%. For stands with a significant second or third species (>15% of the trees), average absolute error of these secondary species was 16.0% (range 0–30%). Two stands had species compositions that changed dramatically if different crown sizes and dominances were examined (i.e., dominance limit 3 and crown size limits of 2, 3, or 4). These were also two of the stands with the most extreme errors for specific species. For site S, using crown size 1, 2, and 3 instead of 1 through 4 along with dominance limit 3, reduced the percentage of hemlock and increased the grand fir component by 10%. The average absolute error for the species of the stand does not change much (9.3% versus 9.9%), but the extreme error in the hemlock at 29.8% was reduced to 19.7%. The lack of identification of cedar in site B (only 2.8% classified but 22.2% on the ground) may be due to the fact that the cedars in the stand had small crown sizes and may not be isolated well. For example, at dominance 1, 2, or 3 and crown sizes 1 and 2, there was no cedar and species composition was 87.5% Douglas-fir and 12.5% other.

Not all training sites were pure species and some had a small component of the other species within them. Therefore, the training set was not pure and this could lead to lower accuracies than might otherwise have been achieved. A trial was run in which the training areas were classified and isols classified as other species were removed from the training set. The classification was then rerun with this purified training set. This, however, did not improve results.

It is not possible to make a confusion matrix of the species accuracies since the true species of the trees represented by each isol is not known. Only the average species composition is estimated from the field data. However, a few observations can be made regarding the confusion among species based on the classification of nearly pure single species stands and some two species stands. Douglas-fir has minor confusion with grand fir and to a lesser degree with amabilis fir, whereas amabilis fir was somewhat confused with grand fir and Douglas-fir. Few trees of the other species were classified as western cedar. Misclassification of cedar as other species was also small. Percentage of hemlock in stands with a large hemlock component was underestimated with isols being unclassified or classed as Douglas-fir. These confusions were also reflected in the analysis of the statistical separation of the species classes as represented by the J-M distance (Table 4). For example, the low J-M distance between Douglas-fir and grand fir indicates difficult separability.

As an additional test, five sites for which there were no field transects were also assessed (sites L, Q, T, Y, Z of Fig. 1). The general species composition was known through inventory maps and field observations. In all cases, the classification resulted in the primary species of the stand to be identified correctly.

The above accuracies were for classifications using seven bands (i.e., all bands except the noisy 438-nm band). Table 5 gives the average species errors over all stands for different band combinations. There was a steady decrease in accuracy

Table 4
J-M distance of the five softwood species classes and aspen for classification training signatures using seven bands (i.e., 438 nm band not included)

	Douglas-fir	Grand fir	Amabilis fir	Western red cedar	Western hemlock	Hardwood
Douglas-fir	–	0.8543	1.5965	1.7086	1.6458	1.9944
Grand fir	0.8543	–	1.3277	1.7129	1.7315	1.9942
Amabilis fir	1.5965	1.3277	–	1.8780	1.9480	1.9998
Western red cedar	1.7086	1.7129	1.8780	–	1.5656	1.9454
Western hemlock	1.6458	1.7315	1.9480	1.5656	–	1.9823
Hardwood	1.9944	1.9942	1.9998	1.9454	1.9823	–

Table 5
Average species composition error over all stands for selected band combinations

Band list	Error of main stands (without unclassified)	Error without hardwoods
2, 3, 4, 5, 6, 7, 8	7.25	8.13
2, 5, 6, 7, 8	8.48	9.60
5, 6, 7, 8	9.24	10.50
2, 3, 5, 7	10.06	11.31
3, 5, 7	11.05	12.71

Band numbers correspond to band wavelength given in Table 3.

as the number of bands decreased, but a classification using four bands still gave good accuracies. Analyzing the average J-M distance between difficult to separate classes (i.e., class pairs with J-M < 1.0) also showed a small but steady decrease in separability between classes as the number of bands used decreased until only four or three bands were used. The best combination of different numbers of bands for separating the difficult to separate species pairs was determined through the following process. The sums of 1 minus the J-M distance ($\Sigma 1.0 - \text{J-M}$) for all class pairs with a J-M distance less than 1 were calculated to represent how well the difficult to separate class pairs are differentiated. In this process, larger sums represent a greater number of poorly separated species pairs and poorer separation between them. The sums were 0.146 (Table 4), 0.156, 0.275, 0.500, and 0.957 for seven through to the best three bands.

6.3. Stand boundary delineation

Assessment of stand boundary accuracy is a difficult task as there are quite often no definitive boundaries and several versions of stand boundaries, although quite different, can be valid. The automated stand boundaries were therefore mainly assessed qualitatively. Correspondence of the automated boundaries versus the boundaries of the distinct plantations was very close (e.g., the plantations of sites D, E and R, F and Q, G, H, and I). This was true whether the plantation was of single species, or of mixed species as in sites E and R, D and I. Of the total length of boundary of these six stands as determined from the manual delineation (Fig. 2a), 47% had a corresponding automated boundary within ± 5 m of the reference manual boundary, 70% within ± 10 m, and 87% within ± 15 m. This excludes boundaries adjacent to the roads. Most of the discrepancy was along the northeast border of site E and R, which abuts a naturally regenerating stand. The automated boundary was displaced approximately 10–17 m to the northeast. As well, the east side of the site for which the automated system created an additional stand was considered a complete boundary displacement error. For boundaries of these six sites that are adjacent to plantations including each other, the average displacement of the automated delineation from the manual boundary was 4.3 m and 69% of the length of the manual boundaries had a corresponding automated boundary within ± 5 m, 90% within ± 10 m.

Stands representing the area of sites N and S were combined into one stand by the automated procedures. Small plantation W was missed completely. Some discrepancies that did occur were related to subtle stand structure differences. The manual interpretation broke the large automatically delineated stand encompassing sites J, K, L, and Y into two stands. This was due to a height difference observed on the stereo photography rather than a species or crown closure difference. Other automated stands were split versus the manual delineations, especially in the natural (non-plantation) stands. For example, in some complex areas such as along the river, the area of site P, the northwest corner, and the southeast edge of the study area (Fig. 2), the automated procedure tended to identify a larger number of smaller stands. Inhomogeneities within stands related to species composition, density, or extent of shadow or unclassified isols also resulted in some small spurious stands being created. As well, roads, trails, and edges of imagery or forest cover caused anomalous stand boundaries. Recall that the roads and river boundaries have been added manually and automated boundaries altered to fit these and the image edges (i.e., any boundaries paralleling these features and within 15 m of their edges were eliminated).

7. Discussion and conclusion

This study represents a test of individual tree crown analysis, from data acquisition, preprocessing, isolation, and species classification through to stand delineation, for young dense conifer stands. It does not address the extraction of stand height, age, or other parameters. Research is ongoing regarding automatic extraction of other stand attributes, use of lidar or stereo data to determine tree and stand height, and integration of traditional photo interpretation methods with automated techniques. The test site is small and of fairly simple forest structure and topography. Results indicated that at 60-cm resolution individual trees were not isolated well, but the isolations were meaningful and provided a good basis for species classification. The valley following procedure used generally outlined many of the larger dominant tree crowns plus clusters of adjacent and closely packed smaller crowns.

Species classification produced accurate results at the stand level. They could not be tested on a tree-for-tree basis. The results were encouraging, especially since some training areas were not pure in terms of species and some isols were tree clusters and may have contained trees of different species. Therefore, results might improve if only isols known to be a given species are used for training. Average species composition error was less than 13%; the dominant species had an average error of 11% and the secondary species average error was 16%. Some stands did, however, have large errors on a per species basis.

Accuracies are well within the expected error for operational air photo interpretation for 1:10 000 to 1: 20 000 scale photography, which is generally considered 70–85% accurate for the main species of a stand but can be lower (Leckie & Gillis, 1995). Alternately, the stands tested were mostly plantations of a uniform nature. The species signatures except for the western red cedar were close to each other and had more of the stands contained larger mixes of species or been less uniform in terms of age, density, composition, and health, more confusion is to be expected. Leckie, Jay, et al. (1999), in a connected study with similar data, indicated reasonable crown isolation in old growth stands of hemlock, amabilis fir, and cedar, but poor species composition classification due to similarity of signatures and a wide range of signatures for trees of the same species resulting from different illumination factors, health conditions, and natural variability.

The sensor only sees the trees visible from above and therefore not many of the suppressed or intermediate trees. Thus, the composition estimated from the imagery is mainly that of the dominant and codominant trees. The ground data of this study emphasizes this issue. Several stands changed their species composition dramatically depending on tree dominance and crown size. Field data for such comparisons should record tree dominance and expected visibility from above as well as the traditional forest inventory information. This issue should be kept in mind when interpreting the composition results. The problem, however, is not unique to digital imagery and automated analysis, but also exists with traditional air photo interpretation for inventory mapping.

It appears that for young relatively simple structured stands, good estimation of species composition for the stand can be achieved with semi-automated crown isolation and classification techniques. This was true even though the crown delineation was often outlining clusters of trees.

The detailed information available from semi-automated individual crown analysis provides information that can be used for forest management directly. It can also be used to dynamically create forest units or strata to help address-specific environmental or timber production issues. However, most current forest management paradigms operate with forest inventory stands as the basic unit of management and therefore automated stand delineation is important.

The automated delineation procedure presented in this study uses as input representations of the basic parameters used for defining forest stands (closure, density, and species composition). However, height information is lacking. Results paralleled known independently determined stand boundaries remarkably well and could be used as a valid representation of the inventory stand boundaries. Spurious small stands need to be filtered out and problems arose at the edge of the imagery and along rivers and roads, and will also occur at the boundary between treed and open areas. Again, the stand boundary delineation was likely aided by the uniformity of the stands and distinctness of the boundaries. Gradational boundaries and delineation in more complex forest conditions will likely not be as good. As well, the test area was small with a limited number of stands and procedures need to be tested over larger areas and a greater variety of stand types.

Results show that a complete semi-automated process of tree crown delineation, species classification, and stand delineation may be achievable for at least young conifer stands of simple structure. The study is of a limited area and range of conditions, and has not addressed stand height, age, and other stand attributes. More testing and development is needed. Complex and older stands will present further challenges, as will terrain with more topographic relief and extending methods over large areas and multiple flight lines. The basic techniques, however, form a good foundation for further development and testing.

Acknowledgements

This work was supported by Forest Renewal of British Columbia under a project entitled “Development of Certified Forestry Applications Using Compact Airborne Spectrographic Imager (CASI) Data”. It was a joint initiative of MacMillan Bloedel (now Weyerhaeuser), Itres Research, and the Canadian Forest Service. The contributions of Dr. Nick Smith and Bill Wilson of Weyerhaeuser and of Dr. Doug Davison and others at Itres Research are acknowledged. Ian Scott and Trisalyn Nelson of the Canadian Forest Service also assisted with the project.

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