ESTIMATION OF CROWN CLOSURE AND SPECIES COMPOSITION FROM HIGH RESOLUTION MULTISPECTRAL IMAGERY

R. J. Hall[1], S. E. Franklin[2], G. R. Gerylo[2] and A. Roberts[3]

[1]Natural Resources Canada, Canadian Forest Service, Edmonton, AB, T6H 3S5

[2]Department of Geography, The University of Calgary, Calgary, AB T2N 1N4

[3]Department of Geography, Simon Fraser University, Burnaby, BC V5A 1S6

ABSTRACT

In this study, airborne multispectral video camera images were acquired with 32 cm by 25 cm pixel resolution from approximately 150 m above a mature forest ecosystem near Barrier Lake in Kananaskis Country, southwestern Alberta. Alberta Vegetation Inventory (AVI) data, including species composition and crown closure, were collected at 22 plots scattered throughout several pure and deciduous and coniferous dominant mixed-wood stands. *Feature-based* methods of image analysis used a series of filtering, classification and spatial operations to separate individual features such as tree crowns, understory, and shadows resolved in the image data. There were no statistical differences between crown areas measured at the plot level when compared to similar measurements derived from the digital image. Species composition accuracy was higher for trembling aspen than for lodgepole pine and white spruce. A contextual classifier was used to construct a forest composition label similar to that employed by the AVI for species composition and crown closure. Additional work in developing estimates of stand volume using models based on image and AVI data (crown closure, stems/ha, species composition, stand height) is planned for softwood, hardwood and mixed-wood species.

Keywords: airborne multispectral video, feature-based image processing, vegetation, forestry, forest inventory.

RÉSUMÉ

ÉVALUATION DE LA FERMETURE DU COUVERT ET DE LA COMPOSITION DES ESPÈCES À PARTIR D'IMAGES MULTISPECTRALES À HAUTE RÉSOLUTION

Dans le cadre de cette étude, des images multispectrales ont été prises par caméra vidéo aéroportée avec une résolution de pixel de 32 cm x 25 cm à environ 150 mètres au-dessus d'un écosystème forestier adulte situé à proximité du lac Barrier dans la région de Kananaskis dans le sud-ouest albertain. Des données de l'Alberta Vegetation Inventory (AVI), y compris des données sur la composition des espèces et la fermeture du couvert, ont été recueillies dans 22 parcelles réparties sur plusieurs peuplements purs et décidus et peuplements mixtes à dominance résineuse. On a eu recours à des méthodes d'analyse d'images *basées sur les entités* mettant en œuvre diverses techniques de filtrage, de classification et de manipulation spatiale aux fins de la séparation des caractéristiques individuelles, notamment des houppiers, des sous-étages et des ombres extraites des données d'image. Aucune différence statistique n'a pu être constatée entre les mesures de projection des houppiers relevées à même les parcelles et les mesures semblables dérivées de l'imagerie numérique. On a déterminé avec plus d'exactitude la composition des espèces des peuplements de peupliers faux-trembles que celle des peuplements de pins tordus latifoliés et d'épinettes blanches. On s'est servi d'un classificateur contextuel pour

Automated Interpretation of High Spatial Resolution Digital Imagery for Forestry. Victoria, British Columbia, Canada, February 10-12, 1998. D.A. Hill and D.G. Leckie, editors. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, British Columbia. pp. 309-320.

réaliser une étiquette de la composition forestière semblable à celle utilisée pour l'AVI aux fins de la détermination de la composition des espèces et de l'évaluation de la fermeture du couvert. On prévoit également entreprendre des travaux supplémentaires pour l'évaluation du volume ligneux des peuplements résineux, décidus et mixtes à partir de modèles créés à l'aide de données d'image et de données de l'AVI (fermeture du couvert, tiges/ha, composition des espèces, hauteur des peuplements).

INTRODUCTION

The Alberta Vegetation Inventory (AVI) is an integrated inventory classification system that is based upon air photo interpretation of medium-scale aerial photographs to define forest stands based on species composition, height, crown closure, age, and productivity (Alberta Forestry, Lands and Wildlife 1991). The AVI provides very detailed spatial data that is utilized by Alberta forest managers who are required to manage the renewable resources on Crown forest lands in an ecologically sustainable manner (Alberta Forest Conservation Strategy 1997). They must also provide increasingly detailed estimates of the costs and effects of alternative management practices on tree and stand growth and yield, biodiversity, and conservation of wildlife habitat. AVI data alone are insufficient to meet these needs. The information required could be obtained by installing large numbers of ground-measured plots, but such plots are costly to establish, measure and maintain. The challenges to meet these information needs creates opportunities to investigate the potential role of and use in high resolution airborne or satellite remote sensing data that would complement AVI data acquisition.

Recent research has suggested traditional per-pixel image processing techniques will not be effective nor satisfactory for classification of high resolution data (Guindon 1997). A shift in analysis methods from *per-pixel* analysis (Treitz et al. 1985; Hughes et al. 1986; Franklin 1994) to *window-based operators* (Yuan et al. 1991) and *feature extraction* (Gougeon 1995a, b; St-Onge and Cavayas 1995; Hay et al. 1996; Gougeon 1997a, b) is evident in high spatial resolution image analysis. The image processing field is moving from a focus on *pixels* (picture elements) and *texels* (texture elements) to *mixels* (mixture elements) and *fexels* (feature elements). In this study, high resolution video images were acquired by the Multispectral Video (MSV) package (Roberts, 1995) in Kananaskis Country, with the objective of determining the extent that forest crown closure and species composition could be derived from existing *feature-based* image analysis methods.

STUDY AREA AND DATA COLLECTION

STUDY SITE AND FIELD DATA COLLECTION

The study site was located on a south-west facing slope near Barrier Lake, in Kananaskis Country, Alberta (51.02 N, 115.01 W) at an elevation of approximately 1400 m. This site is within the Montane Forest Region M.5 (Rowe 1972) that is dominated by trembling aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.), lodgepole pine (*Pinus contorta* Lamb.), and white spruce (*Picea glauca* [Moench] Voss). Archibald et al. (1996) provide detailed descriptions of the plant community types in the study area. AVI stand descriptors were determined on July 10, 1996, at 22 field plots located on 8 transects surveyed on an east/west gradient to sample the elevational and slope distribution in the area. Each plot measured approximately 10 m by 10 m. For every stem with a diameter at breast height (DBH) greater than 10 cm, tree height, DBH, and age were recorded, and understory species were noted in ocular quadrants with percent cover estimates. Percent species composition was determined for each species based on tree frequencies, and crown closure was measured with the aid of a spherical densiometer. Each plot was subsequently labeled with the appropriate AVI code. Plot centres were located with differentially-corrected, Trimble Navstar Global Positioning Satellite (GPS) observations.

MULTISPECTRAL VIDEO CAMERA IMAGERY

On July 11, 1996, under predominantly clear skies, three co-registered and calibrated Sony XC-75 CCD NTSC video cameras were flown from approximately 150 m above ground to yield a pixel size of 0.32 m by 0.25 m (Roberts, 1995). The video cameras were equipped with spectral filters whose effective bandwidths ranged from 490 to 565 nm, 585 to 660 nm, and 720 to 850 nm, respectively. Four overlapping lines at this altitude were flown, yielding thirty-four, 512 pixel by 486 line images that were frame-grabbed approximately every second, and downloaded immediately following the flight. Cardboard calibration panels of the three primary colours (plus a white reference) measuring 1 m^2 were placed at the beginning of the flight line and were constantly monitored for reflectance during the mission using the ASD Personal Spectroradiometer II. Reflectance calibration was not possible because the calibrated reflectance measurements showed significant saturation, and the calibration panels on the images appeared to contain significant 'blooming' (Roberts 1995). A companion study of the variability in pseudo-invariant object reflectance measured in the adjacent parking lot is described by Milton et al. (1997).

Markers placed at the beginning and end of each field transect were clearly visible on the images and were used to position the field plots on each frame. The field plots were later located more precisely with the aid of the on-board Loran-C GPS receiver which tagged each frame centre. The data acquisition mission was accomplished in less than 10 minutes of flying time, and no significant changes in extant environmental conditions were noted. To allow for multi-image comparisons, the auto-gain function of the digital video cameras was disabled.

METHODS

AERIAL IMAGE PRE-PROCESSING

Band-to-band registration was performed on each of the images from the three digital cameras to correct the camera mis-alignment that had occurred during image acquisition. The images were corrected for atmospheric aerosols using the dark object subtraction method (Chavez 1988) where histograms of each image were analyzed to find the lowest digital numbers. Radiometric matching of adjacent frames or frames located at different ends of flight lines was not necessary because of the short time period that elapsed between frames and the relatively constant environmental conditions that were noted during the data acquisition. In absolute radiometric terms, the images were not calibrated and only the raw digital numbers (DN's) were adjusted for dark-object reflectance (McCreight et al. 1994; Pellikka 1996).

FEATURE EXTRACTION FOR CROWN CLOSURE CALCULATION

Two tree crown delineation techniques were compared to determine which method was preferable for identifying individual tree crowns. The first technique employed an image classification approach to isolate tree crowns (Biging et al. 1995) by deriving 'pure' species signatures to classify individual tree species on the video images (Gerylo *et al* 1997; Fish *et al* 1995). Signatures of individual tree species were derived manually from the sunlit side of tree crowns (Hughes et al. 1986) using the ground survey information, and used in a per-pixel maximum likelihood classifier algorithm. The resulting classified image represented the dominant tree species. This technique is considered an effective technique for classifying tree species on MEIS high resolution images (Gougeon and Moore 1989; Gougeon 1995a; Gougeon 1997b). The classified image was subsequently recoded into one class to represent the areal extent of tree crowns.

The second tree crown delineation technique used a Laplacian 'second derivative' filter for isolating tree crowns. The Laplacian filter can be used to emphasize maximum values found throughout the images without any concern to edge direction because the filter highlights edges having both positive and negative brightness slopes. The second derivative is the rate of change in the measured value and has wide applicability in remote sensing feature extraction. Numerous uses of Laplacian operations are documented in other image processing applications. For example, Chavez and Gardner (1994) showed the importance of the second derivative in extracting spatial amplitude and variability information from sonar imagery. In this study, a second derivative filter was hypothesized to be an effective separator of the bright tree crowns from the darker (shaded) canopy understory and shaded side of the crown. A 9 pixel by 9 pixel Laplacian filter was passed across the image. This window size was determined after a series of iterations were run with various window sizes, whereby this window appeared to best emphasize maximum image values, and to separate tree crowns in known areas. All positive slope values thought to represent tree crown pixels, were then thresholded and written to a new image channel. These positive values were assigned a value of 1 (representing tree crowns), while the negative values received a value of 0 (representing non-tree crown space).

With both techniques crown closure was determined by calculating the percentage of pixels representing tree crowns that were found within a fixed area window. A 33 pixel by 33 pixel window was used for these calculations. Results of iterative tests suggested that this was a stable area over which the calculations could be made, and this window size was close to the 100 m^2 plots used in the field.

Crown closure (CC) accuracy was derived from each of the two feature extraction techniques by calculating the crown closure error for each plot relative to the field measurement. Crown closure in the field was measured at 5 point locations and averaged for each plot. The point locations included plot centre and one reading located 2 - 3 metres away from each plot corner along a diagonal towards plot centre to avoid the influence of vegetation from outside the plot. The CC error in percentage was calculated for each plot by subtracting the image based estimate of crown closure from its field observation, and dividing this value by the field observation, and multiplying by 100.

A one-way analysis of covariance design was implemented to determine if statistical differences in crown closure existed between crown closure measured in the field relative to the same trees estimated by image classification and Laplacian filter techniques. An important consideration is that crown areas of individual trees that make up the crown closure for a stand are species dependent. Differences in tree structure and crown area are particularly noticeable between hardwood and softwood species. A covariate term was therefore necessary to account for the influence of species on crown areas by grouping species composition into hardwood, softwood, and mixed wood. A hardwood or softwood stand was defined by the dominant species that comprised at least 80 percent of the stand, otherwise it was considered a mixed-wood stand. The response variable was percent crown closure measured within each of the plots. If there were significant differences among crown closure estimates, then the Bonferroni multiple mean comparison test (Neter et al. 1990) was employed.

FEATURE EXTRACTION FOR ESTIMATION OF SPECIES COMPOSITION

Stand species composition was estimated by combining the results of high pass filtering, image classification, and spatial operations. Individual trees often appear on high resolution digital images as bright regions, and the centre of a tree crown generally has a single bright pixel, relative to neighboring pixels that decrease slightly in intensity. Other work has shown (e.g., Eldridge and Edwards 1993; Fournier et al. 1995; Gougeon 1995b) that this bright pixel represents the highest part of the tree crown (crown apex) because it is not largely affected by shadows. Rather than identifying each tree stem location manually, a simple automated method based on a maxima filter (Gougeon and Moore 1989; Hay et al. 1996; Gougeon 1997b) was used to flag tree stem locations. While this filter is known to be effective for isolating a large portion of individual tree stems, for the purposes of this study, a rule-based maxima filter was designed to identify pixel locations where individual tree stems appeared on the DFC images with multiple maxima.

A 3 pixel by 3 pixel filter was built to 'flag' individual pixel locations. If the centre pixel value within the filter was larger than all of its 8 neighbors, it received a value of 1. If the centre pixel value was smaller than one or more of its immediate neighbors it received a value of 0. If one of the surrounding neighbours had the same DN value as the centre pixel, and all other neighbours had a lower value, then a second channel of image data was used to determine which pixel should receive the tree stem flag. This filter was applied to the NIR channel, because it was hypothesized to have the greatest contrast, and vegetation reflects most strongly in this portion of the electromagnetic spectrum. A Normalized Difference Vegetation Index (NDVI) image was then used to break the ties that occurred when multiple maximum values were found. The maxima filter was run across the entire image, flagging each individual tree, and writing the results to a new image channel. Local understory maxima may also be identified as tree stems in less dense regions. To eliminate this understory influence, a logical AND operation was performed with the tree crown image (from Laplacian filter) and the maxima filter tree stems image. This yielded a final image that depicted the spatial locations of individual tree stems (Figure 1).

To determine species composition, a species identifier was required for each of the tree stems. The image classification from the sunlit side of tree crowns was used to assign the species identifier for each stem. The tree stem image was multiplied by the species classification to assign each stem an appropriate species label. Species composition in percentage units was estimated by calculating the percentage of each tree species found within the fixed window. The 33-pixel by 33-pixel window was used to emulate the actual plot dimensions found in the field. The number of stems for each species was divided by the total number of tree stems in the window from which species composition was determined.

Species composition accuracy was measured by calculating the mean error of estimating species and the average percent accuracy for each species (lodgepole pine, white spruce, and trembling aspen). This method of accuracy assessment, described by Fent et al. (1995), has been shown to be an effective statistic for measuring the accuracy between actual and interpreted values. This test compared interpreted (image processing estimates) values to their actual field values (field estimates), resulting in a mean error of estimation (E) for each variable tested. Average (percent) accuracy from the image processing technique was then calculated as (100 - E). Correlation statistics were also examined to determine the strength of correlation between field and image processing estimates of species composition.

RESULTS AND DISCUSSION

CROWN CLOSURE ESTIMATION

Tree crown images were created from the image classification (Figures 1b, c) and Laplacian filter (Figure 1e) methods, from which a table that compared crown areas was created (Table 1). The image classification approach based on training signatures generated from the sun-lit side of tree crowns resulted in an average accuracy rate of 78% (Table 2). These results are consistent with other classification results of individual tree species based on high resolution images (Gougeon, 1995a; Meyer et al. 1996). Trembling aspen was classified most accurately with 97% of training pixels correctly classified. The lodgepole pine and white spruce classes had lower accuracy rates of 74% and 63%, respectively. The accuracy of conifers were lower because of the confusion between the lodgepole pine and white spruce class signatures. This confusion is a result of their similarities in crown structure and appearance. The three-band images did not provide sufficient multispectral data to distinguish between these two conifer species consistently. For improved classification of conifers, image dates at different phenological stages, and additional spectral bands of narrower band width, or, the addition of DEM data and image texture algorithms should be used to increase the separability between these two species.

Use of the tree species classification method for definition of tree crowns (Figure 1c) resulted in an average accuracy of 47.7% (Table 1). Crown closures were generally overestimated because of classification errors where understory species were misclassified as overstory tree species. These results are consistent, however, with a similar test conducted by Biging et al. (1995). The tree crown image generated by the Laplacian filter (Figure 1d) and thresholding the resulting image (Figure 1e) resulted in crown closure estimates that were more similar to their field estimates with an average accuracy of 86% (Table 1). The Laplacian filter constructed a crown-specific mask, whereby all understory vegetation were eliminated by virtue of the differences between bright and dark (shaded) portions of the canopy. An accurate representation of the spatial organization of tree crowns could be generated once all positive filtered values are thresholded into one class.

There was a significant difference in the crown closure methods based on the analysis of covariance design (Prob. > F = 0.0001). The species covariate term was also significant (Prob. > F = 0.0005), which suggested the analysis of covariance design was appropriate for this study. The Bonferroni multiple mean comparison test was necessary to determine which of the two methods for estimating crown closure were significantly different from the field measurements. At the 5% probability level, there was no difference between the field measured and Laplacian filter estimated crown areas. There was a significant difference between the crown areas derived from the image classification and crown areas from both the field measurements and Laplacian filter method. The Laplacian edge detector filter can be used as a simple and effective tool for delineation and separation of tree crowns from the canopy understory as expressed on the video camera images.

ESTIMATION OF SPECIES COMPOSITION

The first processing step in the calculation of species composition was to identify individual tree stems (Figure 1f). A qualitative visual analysis of results from the rule-based maxima filter suggested that the majority of tree stems appeared to be identified on the digital frame camera images. The use of the tree crown mask was effective in eliminating flagged values found within the understory, thereby exclusively isolating tree stems. The tie-breaking rule which was used to identify tree stem locations when two or more maximum values were present in the window was moderately effective in identifying the primary tree stem location. Ties were not broken in many cases because identical values were also found in the second image channel. The rule-based maxima filter was effective for identifying individual aspen trees, but identifying conifer stems proved more difficult. Increasing distances from nadir resulted in multiple conifer stems being identified due to radial displacement effects that increased the area of visible conifer needles. This served to flag more than one maximum value location under the small window. The isolation method is only considered an effective technique for identifying individual tree stems found at or near the nadir point of the image.

Species composition percentages were estimated with an average accuracy of 83% based on lodgepole pine, white spruce and trembling aspen (Table 3). The percentage of trembling aspen was estimated most accurately, while lodgepole pine and white spruce were estimated least accurately. Some plots exhibited lower accuracy rates because classification errors occurred between the two conifer classes. In some images lodgepole pine was classified as white spruce and vice-versa, while in other images, conifer stems were over-estimated (Table 3). The poor separability between conifer species was likely attributed to their similarity in spectral reflectance patterns at the time of year the data was flown. Subtle species spectral differences may not be detectable in July when conifer species are often at their maximum photosynthetic capacity. Additional data flown earlier in the year to represent a different phenological growth stage may be needed to separate these two species.

Some simple additional methods may improve these results. A modification of the rule-based maxima filter plus new rules such as how to handle three or more identical maximum values should aid in increasing species composition estimates by more accurately flagging all visible tree stem locations. Locating plots exclusively near image centres to reduce radial image displacement effects due to tree heights should also help to reduce the over-identification of conifer tree stems. Additional image bands and image acquisition dates should be explored to determine if stronger classification and species composition results could be achieved.

CONCLUSIONS

The results of feature extraction techniques (Laplacian filter, image classification, and a rule-based maxima filter) and logical image thresholding were evaluated to determine their effectiveness in performing an AVI classification on the available multispectral images. A supervised classification based on sunlit pixels and a Laplacian second derivative filter was compared for extracting tree crowns from the overstory canopy. A spatial operator was applied to the results of these operations to estimate percent stand crown closure. Tree crowns extracted by the Laplacian filter were statistically similar to field measurements based on a spherical densiometer. A rule-based maxima filter was employed for estimation of stand species composition. Trembling aspen was classified with higher accuracy (88.5%) when compared to lodgepole pine (75.6%) and white spruce (83.7%) (Table 3). Additional data at a different date such as early in the growing season to represent a different phenological stage is recommended to improve conifer species discrimination. Future work will employ estimates of crown closure and stems/ha density in models to estimate stand volume for hardwood, softwood and mixed-wood species.

ACKNOWLEDGMENTS

The authors thank Katja Bach (Simon Fraser Univeristy), Dr. Ted Milton (University of Southampton), and Medina Deuling, Nancy Merritt and Jenny Marshall (University of Calgary) for their assistance in this work. The research was partially funded by an Alberta STEP Grant, NSERC, the Canadian Forest Service, and The University of Calgary. Comments about the AVI were provided by Dave Morgan of Alberta Environmental Protection. Dr. Doug King (Carleton University) and Dr. François Gougeon (CFS - Pacific) provided many helpful comments on a more comprehensive discussion of this work submitted to the Canadian Journal of Remote Sensing in December 1997.

REFERENCES

Alberta Forest Conservation Strategy Steering Committee. 1997. *Alberta Forest Conservation Strategy: A new perspective on Sustaining Alberta's Forests.* Canada-Alberta Partnership Agreement in Forestry, Edmonton, Alberta.

Alberta Forestry, Lands and Wildlife. 1991. *Alberta Vegetation Inventory Standards Manual,* Version 2.1. Land Information Services Division, Resource Information Branch, Edmonton.

Archibald, J.H., G.D. Klappstein, and I.G.W. Corns. 1996. *Field guide to ecosites of Southwestern Alberta.* Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta. Special Report 8.

Biging, G.S., M. Dobbertin, and E.C. Murphy. 1995. A Test of Airborne Multispectral Videography for Assessing the Accuracy of Wildlife Habitat Maps. *Can. J. Remote Sensing* 21(3):357-366.

Chavez, Jr., P.S. 1988. An Improved Dark-Object Subtraction Technique for Atmospheric Scattering Correction of Multispectral Data. *Remote Sens. Environ.* 24: 459-479.

Chavez, P. S. and J. Gardner. 1994. Extraction of spatial information from remotely sensed image data - an example: Gloria sidescan sonar images. *Can. J. Remote Sensing* 20(4): 443-453.

Eldridge, N.R. and G. Edwards. 1993. Acquiring localized forest inventory information: extraction from high resolution airborne digital images. *Proceedings, 13th Can. Symp. Rem. Sens.*, Sherbrooke, Quebec, pp. 443-448.

Fent, L., R.J. Hall, and R.K. Nesby. 1995. Aerial Films for Forestry Inventory: Optimizing Film Parameters, *Photogramm. Eng.Remote Sensing* 61(3): 281-289.

Fish, A., R.A. Peart, and S.E. Franklin. 1995. Mapping montane forest structure using high spatial resolution CASI data. *Proceedings, 17th Can. Symp. Rem. Sens.*, Saskatoon, SK.

Fournier, R., G. Edwards, and N. Eldridge. 1995. A catalogue of potential spatial discriminators for high spatial resolution digital images of individual tree crowns, *Can. J. Remote Sensing* 21(3): 285-298.

Franklin, S. 1994. Discrimination of subalpine forest species and canopy density using digital CASI, SPOT PLA and Landsat TM data. *Photogramm. Eng. Remote Sensing* 60(10): 1233-1241.

Franklin, S., C. Blodgett, S. Mah, and C. Wrightson. 1991. Sensitivity of CASI data to anisotropic reflectance, terrain aspect and deciduous forest species. *Can. J. Remote Sensing* 17(4): 314-321.

Gerylo, G., S.E. Franklin, A. Roberts, E.J. Milton, and R.J. Hall. 1997. Hierarchical Alberta Vegetation Inventory (AVI) Classification Using Aerial Digital Frame Camera Data. *Proceedings, 19th Can. Symp. Rem. Sens..*, Ottawa, ON. Paper no. 4, Session E-7, 7 pp. CD-ROM.

Gougeon, F.A. and T. Moore. 1988. Individual tree classification using MEIS-II Imagery. in *Proceedings of IGARSS '88 Symposium*, Edinburgh, Scotland, 13-16 Sept., Ref. ESA SP-284. pp. 927.

Gougeon, F.A. 1995a. Comparison of Possible Multispectral Classification Schemes for Tree Crowns Individually Delineated on High Spatial Resolution MEIS Images. *Can. J. Remote Sensing*. 21(1): 1-9.

Gougeon, F.A. 1995b. A Crown-Following Approach to the Automatic Delineation of Individual Tree Crowns in High Spatial Resolution Aerial Images. *Can. J. Remote Sensing*. 21(3): 274-284.

Gougeon, F.A. 1997a. A Locally Adaptive Technique for Forest Regeneration Assessments from High Resolution Aerial Images. *Proceedings, 19th Can. Symp. Rem. Sens..*, Ottawa, ON.

Gougeon, F.A. 1997b. Recognizing the Forest from the Trees: Individual Tree Crown Delineation, Classification and Regrouping for Inventory Purposes. in *Third International Airborne Remote Sensing Conference and Exhibition*, Copenhagen, Denmark, July 7-10. Pp. II - 807 - II - 814.

Guindon, B. 1997. Computer-Based Aerial Image Understanding: A Review and Assessment of its Application to Planimetric Information Extraction from Very High Resolution Satellite Images. *Can. J. Remote Sensing* 23(1): 38-47.

Haddon, B.D. (Editor). 1988. Forest Inventory Terms in Canada. Canadian Forest Inventory Committee, Forestry Canada, Ottawa, Ont. 3rd Edition.

Haralick, R.N. and K.S. Fu. 1983. Pattern recognition and classification. In Manual of Remote Sensing, edited by R. N. Colwell. Falls Church, VA: American Society for Photogrammetry and Remote Sensing, pp. 793-804.

Hay, G.J., K.O. Niemann, and G.F. McLean. 1996. An Object-Specific Image-Texture Analysis of H-Resolution Forest Imagery. *Remote Sens. Environ.* 55: 108-122.

Hughes, J.S., D.L. Evans, and P.Y. Burns. 1986. Identification of two southern pine species in high resolution aerial MSS data. *Photogramm. Eng. Remote Sensing* 52(8):1175-1180.

Lowell, K., C. Gold, and G. Edwards. 1992. The next generation of digital spatial technologies: error utilization, thematic map and remote sensing integration, spatial operators, and data structures. *Proceedings GIS'92*, Vancouver, BC.

McCreight, R., R.H. Waring, and C.F. Chen. 1994. Airborne environmental analysis using an ultralight aircraft. *Proceedings, 1st International Airborne Remote Sensing Conference*, Strasbourg, France, Vol. 1, pp. 384-392.

Meyer, P., K. Staenz, and K.I. Itten, 1996. Semi-automated procedures for tree species identification in high spatial resolution data from digitized colour infrared-aerial photography. *ISPRS J.Photogramm. Remote Sensing* 51: 5-16.

Milton, E.J., K. Lawless, A. Roberts, and S.E. Franklin. 1997. The significance of unresolved scene elements on the reflectance of pseudoinvariant features intended as calibration targets. *Can. J. Remote Sensing*, submitted and in review.

Neter. J., W. Wasserman, and M.H. Kutner. 1990. *Applied linear statistical models*. Irwin, Boston, Mass. 3rd Ed. pp. 395.

Pellikka, P. 1996. Illumination compensation for aerial video images to increase land cover classification accuracy in mountains. *Can. J. Remote Sensing* 22(4): 368-381.

Roberts. A. 1995. Integrated MSV Airborne Remote Sensing. *Can. J. Remote Sensing* 21(3): 214-224.

Rowe, J.S. 1972. Forest Regions of Canada. Environ. Can., Can. For. Serv., Ottawa, Ont. Public. 1300. pp. 172.

St-Onge, B.A., and F. Cavayas. 1995. Estimating Forest Stand Structure from High Resolution Imagery using the Directional Variogram. *Int. J. Remote Sensing*. 16(11):1999-2021.

St-Onge, B.A., and F. Cavayas. 1997. Automated Forest Structure Mapping from High Resolution Imagery Based on Directional Semivariogram Estimates. *Remote Sens. Environ.* 61:82-95.

Treitz, P., P.J. Howarth, and D. Leckie. 1985. The capabilities of two airborne multispectral sensors for classifying coniferous forest species. *Proceedings, 19th International Symposium on Remote Sensing of Environment*, Ann Arbor, pp. 335-349.

Yuan, X., D. King, and J. Vlcek. 1991. Sugar maple decline assessment based on spectral and textural analysis of multispectral aerial videography. *Remote Sens. Environ.* 37: 47-54.

Plot #	Field Estimate	Image Classification	Laplacian Filter	% Error from Image Classification	% Error from Laplacian Filter	Accuracy (%) from Image Classification	Accuracy (%) from Laplacian Filter
1	61	80	50	-31.1	18.0	68.9	82.0
2	42	68	46	-61.9	-9.5	38.1	90.5
3	57	73	44	-28.1	22.8	71.9	77.2
4	41	78	51	-90.2	-24.4	9.8	75.6
5	32	49	40	-53.1	-25.0	46.9	75.0
6	38	83	51	-118.4	-34.2	-18.4	65.8
7	37	64	44	-73.0	-18.9	27.0	81.1
8	52	69	46	-32.7	11.5	67.3	88.5
9	39	50	40	-28.2	-2.6	71.8	97.4
10	40	86	50	-115.0	-25.0	-15.0	75.0
11	50	88	50	-76.0	0.0	24.0	100.0
12	49	61	43	-24.5	12.2	75.5	87.8
13	39	38	39	2.6	0.0	97.4	100.0
14	46	74	46	-60.9	0.0	39.1	100.0
15	43	56	42	-30.2	2.3	69.8	97.7
16	32	61	45	-90.6	-40.6	9.4	59.4
17	52	45	38	13.5	26.9	86.5	73.1
18	41	54	43	-31.7	-4.9	68.3	95.1
19	39	34	39	12.8	0.0	87.2	100.0
20	51	79	50	-54.9	2.0	45.1	98.0
21	41	61	44	-48.8	-7.3	51.2	92.7
22	36	62	45	-72.2	-25.0	27.8	75.0
					Average Accuracy	**47.7**	**85.8**

Table 1. Estimation of crown closure.

	Null	Pine	Spruce	Aspen
Pine	2.9	73.5	23.4	0.2
Spruce	1.8	35.1	62.8	0.3
Aspen	2.5	0.2	0	97.3
Average Classification Accuracy = 77.9%				

Table 2. Confusion matrix from the tree crown image classification.

Plot-Id	Field Estimates					Image Processing Estimates					Accuracy of Estimates (%)				
	Pine	Spruce	Aspen	Conifers	Deciduous	Pine	Spruce	Aspen	Conifers	Deciduous	Pine	Spruce	Aspen	Conifers	Deciduous
1	50	0	50	50	50	48	8	44	56	44	98	92	94	94	94
2	68	16	16	84	16	29	58	13	87	13	61	58	97	97	97
3	0	0	100	0	100	0	0	100	0	100	100	100	100	100	100
4	0	0	100	0	100	0	4	96	4	96	100	96	96	96	96
5	83	0	17	83	17	19	6	75	25	75	36	94	42	42	42
6	0	0	100	0	100	0	0	100	0	100	100	100	100	100	100
7	0	17	83	17	83	16	5	79	21	79	84	88	96	96	96
8	100	0	0	100	0	14	86	0	100	0	14	14	100	100	100
9	88	0	12	88	12	89	0	11	89	11	99	100	99	99	99
10	0	0	100	0	100	0	0	100	0	100	100	100	100	100	100
11	8	8	84	16	84	3	0	97	3	97	95	92	87	87	87
12	8	25	67	33	67	90	10	0	100	0	18	85	33	33	33
13	75	25	0	100	0	92	0	8	92	8	83	75	92	92	92
14	0	0	100	0	100	0	0	100	0	100	100	100	100	100	100
15	75	0	25	75	25	33	47	20	80	20	58	53	95	95	95
16	50	6	44	56	44	22	6	72	28	72	72	100	72	72	72
17	25	25	50	50	50	76	24	0	100	0	49	99	50	50	50
18	0	0	100	0	100	0	0	100	0	100	100	100	100	100	100
19	88	12	0	100	0	85	8	7	93	7	97	96	93	93	93
20	0	0	100	0	100	0	0	100	0	100	100	100	100	100	100
21	0	0	100	0	100	0	0	100	0	100	100	100	100	100	100
22	0	0	100	0	100	0	0	100	0	100	0	0	100	100	100
										Average accuracy (%)	**75.6**	**83.7**	**88.5**	**88.5**	**88.5**
										Overall accuracy (%)	**82.6**				

Table 3. Comparison of field and image processing estimates of species composition.

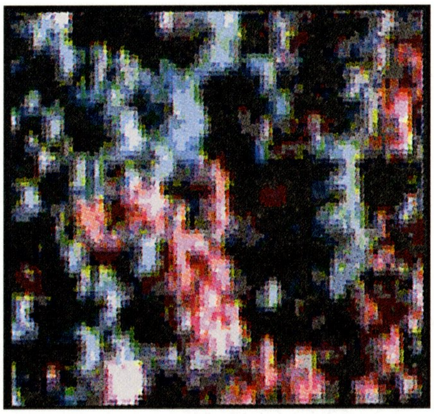

Figure 1a.
Sub-region of study area.

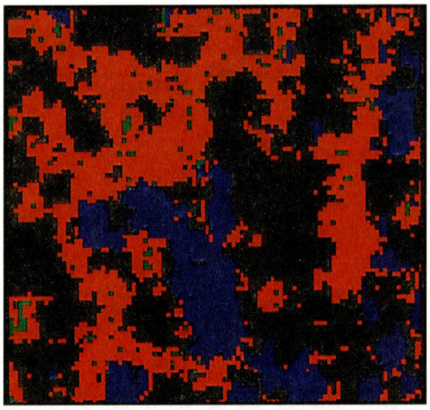

Figure 1b.
Image classification of tree species type; Red (Pine), Green (Spruce), and Blue (Aspen).

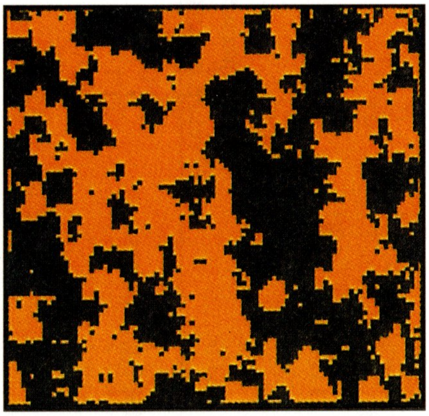

Figure 1c.
Tree crown image from the species classification image.

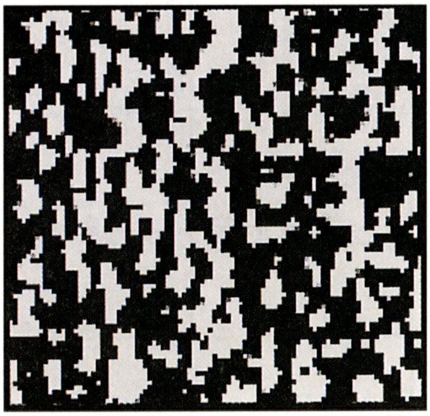

Figure 1d.
Results of the 9 by 9 Laplacian filter run over the NIR band.

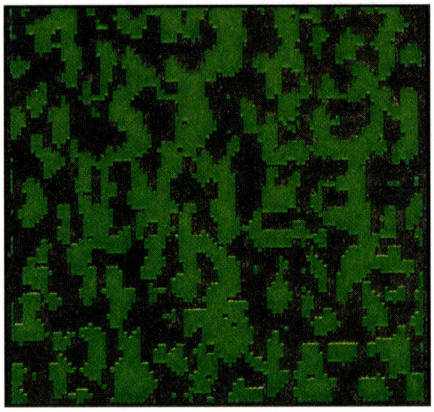

Figure 1e.
Tree crown image resulting from thresholding of the Laplacian-filtered image.

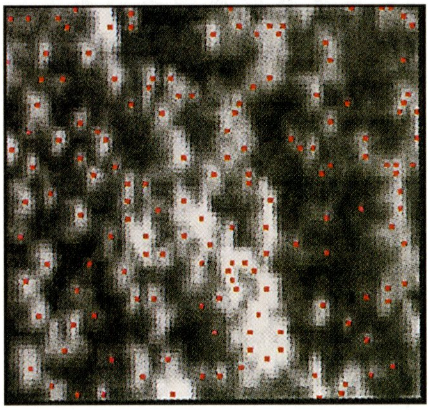

Figure 1f.
Individual tree stems, from the rule-based maxima filter, superimposed on the NIR image.

International Forum

Automated Interpretation of High Spatial Resolution Digital Imagery for Forestry

February 10-12, 1998
Pacific Forestry Centre
Victoria, British Columbia
Canada

Proceedings compiled and edited by
D.A. Hill and D.G. Leckie

Natural Resources Canada / Ressources naturelles Canada
Canadian Forest Service / Service canadien des forêts

Canada

Canadian Forest Service
Pacific Forestry Centre
506 West Burnside Road
Victoria, British Columbia
V8Z 1M5

Phone (250) 363-0600

Printed in Canada

Canadian Cataloguing in Publication Data

Main entry under title:

Automated interpretation of high spatial resolution digital imagery for forestry

Includes an abstract in French.
At head of title: International forum.
"February 10-12, 1998, Pacific Forestry Centre, Victoria, British Columbia Canada"
Sponsored by Natural Resources Canada, Canadian Forest Service
Province of British Columbia, Ministry of Forests
and MacMillan Bloedel Limited

ISBN 0-662-27659-0
Cat. No. Fo42-290/199E

1. Aerial photography in forestry – Canada – Congresses.
2. Image processing – Digital techniques – Congresses.
3. Forests and forestry – Canada – Congresses.
I. Leckie, Donald Gordon, 1953-
II. Pacific Forestry Centre.
III. British Columbia. Ministry of Forests.
IV. MacMillan Bloedel Limited.

SD387.A25H54 1999 634.9'2 C99-980138-4