SPECTRAL MIXTURE ANALYSIS OF MONTANE FOREST BIOPHYSICAL PARAMETERS: A COMPARISON OF ENDMEMBERS FROM AIRBORNE IMAGERY AND A FIELD SPECTRORADIOMETER *

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ABSTRACT

Sub-pixel scale fractions computed from spectral mixture analysis (SMA) provide improvements over vegetation indices for extracting forest biophysical information such as LAI, biomass and NPP for use in forest inventories and regional scale carbon budget models. The acquisition of endmember spectra of forest canopy, ground vegetation and shadow is a critical input to spectral mixture analysis. In this paper, we compare the use of three sets of endmembers: image endmembers extracted directly from airborne imagery, reference endmembers measured in the field using a portable spectroradiometer, and an integrated set which combined both image and reference endmembers. Each set of endmembers was used in spectral mixture analyses of multi-scale airborne CASI imagery at 60cm, 1m and 2m resolutions acquired July 1998 over mountainous terrain in Kananaskis Provincial Park, Alberta. The scene fractions were validated using a sub-pixel multi-resolution classification strategy. To test their ability to predict biophysical variables, independent LAI measurements were first collected with LAI-2000 and TRAC instruments. Separate linear regressions were performed for each of the SMA fractions as well as for NDVI. The reference endmember set was the best predictor of TRAC based measurements of LAI, with $r^2 = 0.69$ and 0.67 for 1m and 2m imagery respectively. The integrated and reference endmember sets predicted effective LAI from the LAI-2000 with $r^2 = 0.62$ and 0.72 for the 1m and 2m data. NDVI results were $r^2 = 0.33$ and 0.34 for the TRAC and 0.45 and 0.44 for LAI-2000 measurements at 1m and 2m resolutions, respectively. These results suggest that the acquisition of reference endmembers is needed to achieve the best overall predictive ability using spectral mixture analysis, and that fractions from image endmembers also show significant improvements over NDVI without the need of reference spectra.

1.0 INTRODUCTION

Biomass, leaf area index (LAI) and net primary productivity (NPP) are important biophysical structural variables which are inputs to regional scale models of ecosystem processes (Running and Hunt, 1994; Bonan, 1993). Traditionally, vegetation index approaches such as the Normalized Difference Vegetation Index (NDVI) have been used to provide estimates of these parameters, however, new approaches such as spectral mixture analysis (SMA) have been shown to provide improvements (Hall et al., 1995, 1996; Peddle et al., 1997, 1999; Peddle and Johnson, 1999). SMA is used to determine the spatial abundance of sub-pixel scale scene components such as sunlit canopy,

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sunlit background and shadow. These component fractions can be separated and used to predict biophysical variables more accurately than vegetation indices. Changes in the forest structure result in different levels of scene component fractions, which serve as the basis for the stronger predictive capability for forest structure using SMA fractions. Although SMA has resulted in improved prediction of LAI over flat boreal forests, only limited tests have been done in mountainous terrain (Peddle and Johnson, 1999).

Building on the continued success using SMA in predicting biophysical variables, this paper focuses on a quantitative assessment of SMA endmember inputs (component reflectances), and their corresponding ability to make accurate estimations of sub-pixel scale fractions. The focus is on the validation of scene fractions produced using (1) reference endmembers measured in the field using a portable spectroradiometer (2) image endmembers extracted directly from multi-resolution airborne imagery and (3) an integrated image and reference endmember set. The results of the SMA analysis were then compared in terms of their ability to predict different sets of LAI measurements taken in the field using optical instruments (TRAC and LAI-2000)[1]. These results were compared to NDVI to determine the preferred approach at the different spatial scales of airborne imagery.

2.0 STUDY AREA AND DATA COLLECTION

2.1 STUDY AREA

The study area is centered at 115°4'20"W, 51°1'13"N on the eastern slopes of the Rocky Mountains and straddles Barrier Lake in Kananaskis Provincial Park, Alberta, Canada. This region covers approximately 77km^2 and includes a full range of terrain aspects with slopes ranging from 3° to 30°. The site is within the Montane Forest Region M.5 that is dominated by stands of lodgepole pine (*Pinus contorta* Lamb.), white spruce (*Picea glauca* [Moench] Voss), trembling aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.) on lower, more moist slopes, and some scattered mature Douglas-fir (*Pseudotsuga menziesii* var. glauca (Beissn.) Franco) (Rowe 1972). This study focused on 15 test plots of size 10 × 10m for which a detailed inventory of forest measurements was collected including tree locations, species, crown shape, tree height, crown closure, and diameter at breast height (DBH). The location of each plot was determined using differential GPS measurements for use with the airborne imagery. These plots were lodgepole pine and Douglas-fir stands which ranged in LAI from 1 to 8.8.

2.2 LAI MEASUREMENTS

LAI is defined here as half the total leaf area per unit ground surface area (Chen and Cihlar, 1996). Two optical instruments were used to estimate LAI in the test plots, the TRAC (Tracing Radiation and Architecture of Canopies)(Chen and Kwong, 1997), and the LAI-2000 Plant Canopy Analyzer (Welles and Norman 1991). The TRAC measures gap fractions as well as the gap size distribution (Chen and Cihlar, 1996) which enables the effects of non-random canopy architecture to be quantified for improved estimation of LAI. The LAI-2000 assumes a random leaf distribution and does not account for canopy architecture, and therefore provides an estimate of effective leaf area index (eLAI). This is not a true measure of LAI because foliage in plant communities are often not randomly distributed (Chen and Chilar, 1996). All optical LAI measurements were acquired in July and early August corresponding to the time of maximum photosynthetic capacity. Results from the spectral mixture analysis were compared in terms of the ability to predict the measurements of LAI and eLAI.

2.3 IMAGE DATASET

A multi-resolution CASI image data set was acquired at pixel sizes of 60cm, 1m and 2m by Itres Research of Calgary and with reference to Wulder et al. (1996). The data were acquired with a variety of spectral bands and provided as a geo-referenced image data set corrected to sensor radiance (Table 1). Ground based radiometric calibration spectra were collected during image acquisition at the southern parking lot near Barrier Lake, using an ASD FieldSpec FR (350 – 2500 nm) spectoradiometer (ASD, 1998). Calibration measurements were acquired over four 3 × 3 m calibration targets, as well as the asphalt parking lot. The calibration measurements were corrected to

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[1] The mention of trade names is for information only.

reflectance using calibrated irradiance measurements from a Spectralon white reference. These ground reflectance values were related to the CASI data using a linear spectral response function for each image band. These targets were located in the CASI imagery and used as pseudo-invariant targets to perform a linear atmospheric correction.

A high quality geometric correction was essential for proper overlay of the multi-resolution images used for validation of scene fractions produced from SMA. Careful examination of the geometric correction showed less than a single pixel variation between the 60 cm and 2 m resolutions (less than 2m absolute variation in alignment), which was acceptable for our multi-resolution analysis.

Table 1. CASI Image Band Set Collected at 60cm, 1m and 2m Resolution

Band	Wavelength (nm)	
Number	Start	End
1	450	500
2	540	560
3	610	640
4	640	680
5	690	715
6	730	755
7	790	810
8	850	875

3.0 METHODS

3.1 SPECTRAL MIXTURE ANALYSIS

Spectral Mixture Analysis is based on the fact that the reflectance value of a given pixel can be represented by a combination of reflectances of elemental radiometric components (Adams et al., 1993). In this research, three main scene components (or endmembers) were identified as sunlit canopy, sunlit background and shadow. In an earlier study in Kananaskis, which assessed a different study area and image data set (Peddle and Johnson, 1999), only the sunlit canopy and shadow endmembers were used. However, for this study area and image data set, crown closure in all of the plots sampled was insufficient to obscure the forest floor, therefore, all three endmember components were used in the SMA trials. Individual spectral measurements of each of these endmember components are an important input to the spectral mixture analysis. These endmembers were identified with care as SMA can be sensitive to these spectral values. Three methods of determining endmember spectra were tested: reference endmembers, image endmembers, and an integrated set of endmembers, as explained below.

3.2 REFERENCE ENDMEMBERS

Reference endmember spectra were collected using the ASD spectoradiometer (ASD, 1998). This instrument allowed for accurate and high spectral resolution measurements to be made in the field over a broad spectral range. The same instrument used to collect these spectra was also used for correcting the images to surface reflectance, thus providing a consistent calibration throughout the experiment. A set of spectral measurements was collected for each of the dominant forest canopy and groundcover species, following the procedures outlined in Peddle (1998). Each measurement was made by removing a sample to a clear area (e.g. a parking lot) to avoid unwanted reflected energy from adjacent vegetation. The samples were then arranged into optically thick stacks and all measurements were taken in a nadir orientation. Radiance measurements were performed under conditions of total and diffuse (sun-occulted) irradiance. These measurements were then corrected to reflectance using simultaneous spectra from a Spectralon white reference. For the shadow endmember, a measure of *apparent reflectance* was used to represent the shadowed target and was calculated by taking the ratio of a shadowed target measurement and an illuminated white reference measurement (Peddle, 1998).

Reference endmember spectra used in the SMA were selected from this set of measurements (Table 2). The canopy reference endmember was the reflectance obtained for lodgepole pine or Douglas-fir, depending on the composition of the plot. The reflectances from the main species present on the forest floor in these plots included pine grass (*Calamagrostis rubescens* Buckl.), step moss (*Shepherdia canadensis* (L.) Nutt.) and buffalo berry (*Hylocomium splendens* (Hedw.) B.S.G.). These reflectances were averaged and used as a single endmember to characterize the background. This does not account for the complexity of the forest floor as other species (e.g. juniper) were not measured, nor was the spatial abundance of each background component considered. The shadow endmember was chosen as the darkest apparent reflectance measure of the forest floor species (pine grass).

Table 2. Endmembers Used in the Reference Endmember Trial

Reference Endmember	Description
Sunlit Canopy	Reflectance measurement of lodgepole pine or Douglas-fir
Sunlit Background	Average reflectance measurement of dominant background species
Shadow	Apparent reflectance measurement of pine grass

3.3 IMAGE ENDMEMBERS

Image endmembers selected from all 8 bands of the 60cm image data were interpreted to represent pure samples of the scene components under investigation (Table 3). Image endmembers were selected based on spectral plots using the n-dimensional visualization capability available in the ENVI image analysis system (ENVI, 1998). The sunlit canopy endmember was selected based on the brightest canopy pixel value for either lodgepole pine or Douglas-fir in each band. The sunlit background endmember was selected from an adjacent clearing which had similar vegetation composition, and again the brightest image values were used. Three types of canopy shadowing were evident in the imagery, (1) infinitely dark, (2) transitional and (3) diffuse shadow, as outlined in Seed et al., (1997) and Peddle and Johnson (1998). The darkest image endmember was selected as the purest case of shadow. Preliminary sets of SMA results were produced and their Root Mean Square (RMS) error evaluated against what were deemed to be pure pixels in the image prior to the final image endmember selection.

Table 3. Endmembers Used in the Image Endmember Trial

Image Endmember	Description
Sunlit Canopy	Brightest canopy pixel from each band
Sunlit Background	Brightest background pixel selected from adjacent clearing for each band
Shadow	Darkest image value from shadow pixels

3.4 INTEGRATED ENDMEMBER SET

The integrated endmember set was created to take advantage of both the image and reference endmembers (Table 4). This integrated endmember set used the reference measure of sunlit canopy (Douglas-fir or lodgepole pine), to represent a more pure sample than could be identified in a 60cm image pixel. Image endmembers were selected for the sunlit background and shadow endmembers. The sunlit background image endmember more accurately represented the complex mixtures of background vegetation compared to combinations of individual reference endmember spectra. Both the image shadow and reference shadow endmembers were very similar to each other in Bands 1 through 5, however, the image endmember values were chosen since they were darker in Bands 6 - 8.

Table 4. Endmembers Used in the Integrated Endmember Trial

Integrated Endmember	Description
Sunlit Canopy	Reference measure of either lodgepole pine or Douglas-fir
Sunlit Background	Image background endmember
Shadow	Image shadow endmember

4.0 SCENE FRACTION VALIDATION

The validation of sub-pixel scale fractions is important when using the SMA approach in more complex environments such as mountainous terrain. If the sub-pixel fractions of scene components are to be used in predicting biophysical variables, it is important to first quantify their accuracy. The result of each SMA trial was a set of three fractions corresponding to sunlit canopy, sunlit background, and shadow, as well as an estimate of RMS error for each pixel. A quantitative validation of sub-pixel scale fractions at 1m and 2m resolutions was performed using a maximum likelihood (ML) classification of sunlit canopy, sunlit background and shadow at the 60cm resolution, and comparing that with the fractions obtained at coarser resolution 1m and 2m imagery. For example, a 10 × 10m test plot contains approximately 25 pixels at 2m resolution for which a set of scene fractions were produced and aggregated. These scene fractions were compared to the ML classification of the nearly 280 pixels at 60cm resolution that comprise that same plot area. This provided a way of validating the fractions produced using the three sets of endmembers. Potential error can be introduced into this analysis due to mixtures of materials that occur within a 60cm pixel as well as from errors in classification, however, this method provided a meaningful way of evaluating the SMA fractions prior to biophysical analysis, as in our previous work (Peddle and Johnson, 1999).

5.0 VALIDATION RESULTS

We first examined the RMS error produced for each endmember set as an initial test of the endmembers ability to represent the scene components. The RMS error was low in all trials with a maximum of only 0.02%, which suggested that the endmembers used in each case were representative of the spectral values in the scene.

Overall, there was good agreement between the fractions produced at the 1m and 2m resolutions with the ML classification at the 60cm resolution. The magnitude of error was evaluated for each of the three endmembers sunlit canopy, sunlit background, and shadow with respect to the ML classification (Table 5). The reference endmember case showed the closest agreement between SMA fractions and ML classification results. The difference ranged between 3 and 6 % for each scene component with the maximum variation observed with shadow. The image and integrated endmember cases showed a greater difference between the ML classification and SMA fractions. The image shadow endmember showed the greatest difference from the ML classification results with differences varying from 3 to 11% (mean = 6 %). The image sunlit canopy and background fractions ranged between 4 to 6% difference (mean = 4%). Image scale seemed to have little effect on the differences between the ML classification and SMA fractions as the results were within 2% for the reference, image and integrated endmember cases from the 1m and 2m CASI data. This result suggested that SMA trials were in fact producing representative scene fractions, which were suitable for LAI prediction. A previous study by Peddle and Johnson (1998) showed errors with the SMA model when differences in canopy composition within a plot were not accounted for (i.e. pine outliers in a spruce stand). These errors were accounted for in this study through image stratification, SMA trials and prior knowledge of the study sites based on fieldwork. This ensured the proper endmembers were used to characterize the canopy prior to unmixing. In larger area studies, this would be overcome using a per-pixel image stratification prior to deriving fractions, as in Peddle et al. (1997).

Table 5. Differences between the SMA Fractions at 1m and 2m Resolutions and Maximum Likelihood Classification at 60cm Resolution.

	Canopy fraction	Shadow fraction	Background fraction
Reference endmember set	3% to 6%	3% to 6%	3% to 6%
Image endmember set	4% to 6%	3% to 11%	4% to 6%
Integrated endmember set	4% to 6%	3% to 11%	4% to 6%

6.0 LAI ANALYSIS AND DISCUSSION

Linear regression analyses to predict LAI were performed using shadow fraction, sunlit canopy fraction, sunlit background fraction and NDVI. The ability to predict LAI was based on the magnitude of the regression coefficient of determination (r^2). A separate regression analysis was performed for each of the reference endmember, image endmember and integrated endmember sets for predicting each set of field-based LAI measurements from the LAI-2000 (Table 6) and TRAC instruments (Table 7).

Initial observations of these results show that SMA fractions consistently provided better results than NDVI for both the TRAC and LAI-2000 measurements. The reference and integrated endmember sets provided the best overall results. The best results were r^2 of 0.69 and 0.67 for the TRAC measurements and r^2 of 0.62 and 0.72 for the LAI-2000 measurements at 1m and 2m resolutions respectively. NDVI yielded a r^2 of 0.33 and 0.34 for the TRAC, with 0.45 and 0.44 obtained for LAI-2000 measurements at 1m and 2m resolutions. The improvements provided by SMA over NDVI are shown as differences in the far-right columns of Tables 6 and 7.

Table 6. Magnitude of the Regression Coefficient of Determination (r^2) using SMA Fractions and NDVI to Predict TRAC LAI for Three Endmember Sets at 1m and 2m Image Pixel Resolutions.
Best Result for Each Set Shown in Bold.

Image Spatial Scale	Endmember Set	Canopy Fraction	Shadow Fraction	Background Fraction	NDVI	TRAC LAI Measurement diff SMA-NDVI
1m	Reference	0.45	0.58	**0.69**	0.33	0.36
1m	Image	0.49	**0.61**	0.46		0.28
1m	Integrated	0.64	**0.68**	0.42		0.35
2m	Reference	0.22	0.39	**0.65**	0.34	0.31
2m	Image	0.11	0.30	**0.55**		0.21
2m	Integrated	**0.67**	0.50	0.27		0.33

Table 7. Magnitude of the Regression Coefficient of Determination (r^2) using SMA Fractions and NDVI to Predict LAI-2000 eLAI for Three Endmember Sets at 1m and 2m Image Pixel Resolutions.
Best Result for Each Set Shown in Bold.

Image Spatial Scale	Endmember Set	Canopy Fraction	Shadow Fraction	Background Fraction	NDVI	LAI-2000 eLAI Measurement diff SMA-NDVI
1m	Reference	0.21	0.33	**0.62**	0.45	0.22
1m	Image	0.23	0.34	**0.52**		0.06
1m	Integrated	**0.55**	0.43	0.20		0.10
2m	Reference	0.05	0.18	**0.62**	0.44	0.18
2m	Image	0.15	0.13	**0.53**		0.08
2m	Integrated	**0.72**	0.28	0.08		0.28

Overall SMA provided an average increase over NDVI of $\Delta r^2 = 0.33$ for the TRAC LAI and an average increase of $\Delta r^2 = 0.16$ for the LAI-2000. For each image spatial resolution there were some differences, however, there was no noticeable trend with changing resolution.

A multivariate regression analysis was performed using the best SMA fraction with NDVI to examine the possibility of using these two methods together. Although the NDVI results were significantly lower than the mixture fractions, we were interested to determine if NDVI provided any additional information to that already held in the SMA fractions, owing to the ease in computing NDVI and integrating it into our SMA analysis (Table 8).

Table 8. Improvements Provided by Multivariate Analysis to TRAC LAI and LAI-2000 eLAI Prediction

Image Spatial Scale	Endmember Set	TRAC LAI R^2 SMA and NDVI	Improvement over SMA Fraction Alone	LAI-2000 eLAI R^2 SMA and NDVI	Improvement over SMA Fraction Alone
1m	Reference	0.74	0.05	0.62	0.02
1m	Image	0.72	0.11	0.54	0.02
1m	Integrated	0.73	0.05	0.56	0.01
2m	Reference	0.72	0.07	0.62	0.00
2m	Image	0.67	0.12	0.54	0.01
2m	Integrated	0.67	0.00	0.73	0.01

In both cases, however, the multivariate analysis showed limited improvements in the prediction of LAI or eLAI. The inclusion of NDVI in the regression analysis showed improvements in R^2 values of between 0 and 0.12 in the prediction of TRAC LAI, with an average improvement of < 0.02 in prediction eLAI. The only notable improvement was with the image endmember set, for which an improvement of 0.11 and 0.12 was found when NDVI was used with image SMA fractions to predict LAI measured with the TRAC at the 1m and 2m scales, respectively.

7.0 CONCLUSIONS AND FUTURE RESEARCH

In terms of endmember spectra inputs to SMA, the reference endmember set from the field spectroradiometer was the best predictor of TRAC based LAI with r^2 values from 0.69 to 0.67 for the 1 and 2m data respectively. The integrated and reference endmember sets were the best predictors of LAI-2000 measures of eLAI with r^2 values from 0.62 to 0.72 for the 1 and 2m data. Using the SMA fraction from the image endmember set in combination with NDVI improved the prediction of TRAC LAI to a level similar to the reference endmember set when used alone. For the prediction of eLAI, the inclusion of NDVI provided only minimal improvements. It is therefore concluded that use of the reference and integrated endmember sets provided the best estimates of LAI and eLAI when used alone. The inclusion of NDVI with the SMA image endmember fractions can provide estimates of LAI that are comparable with the estimates provided by the reference endmember set. This would be an option if the collection of reference spectral data were not possible, however, the inclusion of NDVI did not provide any improvement to the prediction of eLAI using image endmembers.

Current attention and future work will address several issues. These include performing a more comprehensive atmospheric correction, incorporating optical reflectance models to account for the influence of terrain, and to provide a regional scale stratification capability with sub-pixel scale fraction output, as in Peddle et al. (1997). These will be important for our regional scale analysis of this mountainous environment using Landsat TM imagery acquired during the summer of 1998. In that work we plan to test field and CASI-based image endmembers and compare regional scale results with the significant improvements found here using spectral mixture analysis methods.

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9.0 REFERENCES

Adams, J.B., M.O. Smith and A.R. Gillespie, "Imaging spectroscopy: interpretation based on spectral mixture analysis," In Topics in remote sensing IV: remote geochemical analysis, Pieters and Englert, Editors Cambridge. pp. 145-166. 1993.

ASD, Analytical Spectral Devices Inc. FieldSpec FR User's Guide. Boulder, Colorado. Variously paged. 1998.

Bonan, G.B., "Importance of leaf area index and forest type when estimating photosynthesis in boreal forests," *Remote Sensing of Environment*, Vol. 43, pp. 303-314, 1993.

Chen, J. and J. Cihlar, "Retrieving leaf area index of boreal conifer forests using Landsat TM images". *Remote Sensing of Environment,* Vol. 55, pp.153-162, 1996.

Chen, J. and M. Kwong, Manual for TRAC: a new optical instrument for ground measurements of LAI and FPAR. Variously paged, 1997.

ENVI, The Environment for Visualizing Images: ENVI 3.1 and IDL 5.1 User's manuals. Research Systems Inc. Boulder Colorado USA. Variously paged, 1998.

Hall, F.G., Y.E. Shimabukuro, and K.F. Huemmrich, "Remote sensing of forest biophysical structure using mixture decomposition and geometric reflectance models," *Ecological Applications* vol.5, no.4, pp. 993-1013,1998.

Hall, F.G., D.R. Peddle and E.F. LeDrew, "Remote sensing of biophysical variables in boreal forest stands of *Picea Mariana," International Journal of Remote Sensing*, Vol. 17, No. 15, pp. 3077-3081, 1996.

Peddle, D.R., "Field spectroradiometer data acquisition and processing for spectral mixture analysis in forestry and agriculture". In, Proceedings, *First International Conference on Geospatial Information in Agriculture and Forestry.* ERIM International. Vol. II,. Lake Buena Vista, Florida, USA, pp. 645 - 652. June 1-3 1998.

Peddle, D.R., F.G. Hall, E.F. LeDrew and D.E. Knapp, "Classification of forest land cover in BOREAS. II: Comparison of results from a sub-pixel scale physical modeling approach and a training based method," *Canadian Journal of Remote Sensing.* Special Issue: BOREAS, Vol. 23, No. 2, pp. 131-142, 1997.

Peddle, D.R., F.G. Hall and E.F. LeDrew, "Spectral mixture analysis and geometric optical reflectance modeling of boreal forest biophysical structure". *Remote Sensing of Environment*, Vol. 67, No. 3, pp. 288-297, 1999.

Peddle D.R. and R. L. Johnson, "Spectral mixture analysis of airborne remote sensing imagery for improved prediction of leaf area index in mountainous terrain, Kananaskis Alberta". *Canadian Journal of Remote Sensing*; Special Issue: 20th Canadian Symposium on Remote Sensing, 1999.

Rowe, J.S., *Forest regions of Canada.* Environ. Can., Can. For. Serv., Ottawa, ON. Publication No. 1300, 172 pp.

Running, S.W. and E.R. Hunt jr., "Generalization of a forest ecosystem process model for other biomes, BIOME-BGC, and an application for global scale models," In *Scaling Physiological Processes: leaf to globe,* Ehleringer, J. and Field, C., Editors Toronto: Academic Press, pp. 141-157, 1994.

Seed, E.D. and D.J. King, "Determination of mixed boreal forest stand biophysical structure using large scale airborne digital camera imagery," *In, Proceedings GER'97: 9th International Conference on Geomatics / 19th Canadian Symposium on Remote Sensing*, Ottawa, Canada. Published on CD-ROM, 1997.

Welles, J.M. and J.M. Norman, 'Instrument for indirect measurement of canopy architecture," *Agronomy Journal* Vol. 83, No. 5, pp. 818-825, 1991.

Wulder, M., S. Mah and D. Trudeau, 'Mission planning for operational data acquisition campaigns with the casi". *2nd International Airborne Remote Sensing Conference and Exhibition,* San Francisco, CA., Vol. III, pp. 53-62, June 23-27, 1996.

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