Estimation of Forest Cover Type and Structure from Landsat TM Imagery using a Canopy Reflectance Model for Biomass Mapping in Western Newfoundland

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Abstract - **Geometric optical canopy reflectance models provide an explicit physical-structural basis to the analysis of satellite imagery and represent an alternative approach to existing classification methods for obtaining forest cover type and structural information (density and height) for biomass estimation. The Multiple-Forward-Mode (MFM) approach applied with the GOMS canopy reflectance model (MFM-GOMS) was tested for labeling clusters generated from an unsupervised classification as part of the EOSD project. A reasonable level of correspondence was found between model-based cluster labels and independent descriptors of surface cover, density and height. Errors were found to be less severe in most cases and due in part to the inherent variability of individual clusters comprised of multiple cover types, density ranges and height classes. The next phase of this work involves MFM-GOMS to obtain forest landcover and structural information for direct input to biomass estimation routines, thus not requiring prior cluster analysis and the associated confounding variability.**

I. Introduction

Information on forest cover type and structure is needed to estimate above-ground forest biomass which, in turn, is important for carbon budget modeling, estimating forest productivity, meeting national reporting requirements, and in studies of global change. Satellite remote sensing is well adapted to complement existing strategies for mapping this type of information while also providing important advantages, particularly for large areas. This paper presents initial results for extracting the required cover type and structure information from Landsat Thematic Mapper (TM) imagery using a geometric optical canopy reflectance modeling approach applied to a study area in western Newfoundland. This work is part of an overall strategy to map the forest biomass of Canada [1] and was undertaken as part of the Earth Observation for Sustainable Development of Forests (EOSD) project aimed at monitoring the sustainable development of Canada's forest from space [2].

II. Canopy Reflectance Modeling

Geometric optical canopy reflectance models provide a powerful basis for understanding the interactions of solar radiation with forest stands as a function of the physical dimensions and structure of forest canopies [3]. These reflectance models simulate forest stands in terms of characteristic shapes of objects (trees) and the spectral properties of scene components which comprise pixel areas (sunlit canopy, sunlit background, shadow "endmembers"), and with reference to sun-sensor-view angle geometry.

In general, these models can be used in either forward or inverse mode. In standard forward mode, tree dimension and stand density information are input to the model, with modeled output consisting of multispectral pixel reflectance values and sub-pixel scale fractions (%canopy, %background and %shadow). Model inversion does the opposite – pixel values are input from which the model computes an estimate of tree dimension and stand density. In forestry, model inversion is highly desirable, however, this can be complex with sometimes non-exact or no solutions, as well as being computationally intense. Further, some of the more sophisticated models are not invertible due to their complexity, yet this level of complexity is often required.

The Multiple-Forward-Mode (MFM) approach to canopy modeling [4] was developed to address these issues in forward and inverse modeling. MFM essentially provides the physical structural information of inversion modeling, but does so using forward mode model runs. MFM works by performing a series of forward-mode model runs over a range of physical stand attributes, storing all the results in a structural look-up table (MFM-LUT), and then searching the LUT for matches between modeled image values and actual satellite image pixel values. In creating the MFM-LUT, all possible combinations of the different structural input values are modeled with respect to a specified increment or step. Once matches are identified, the corresponding tree dimension and stand density inputs constitute the physical-structural model output of interest. A key additional advantage to MFM is that, unlike standard forward mode, exact physical tree dimensions and density information is not required. The user need only supply a range of values for which no prior knowledge is required (e.g. theoretical minima and maxima can be specified for all inputs if necessary). The spectral reflectance of scene component endmembers are also required (as with standard forward-mode or inverse-mode).

III. Experimental Design

A. Study Area and Data Set

The 6000 km^2 study area in western Newfoundland encompasses moderate to high relief terrain in the Long Range Mountains, as well as low-relief and flat areas towards the coast. Forested areas are primarily Balsam fir (*Abies balsamea*) and black spruce (*Picea mariana*), with less frequent occurrences of various hardwood species, usually in valleys.

The remote sensing data consisted of a Landsat TM image acquired August 4, 1995 with a solar zenith angle of 39.57° and azimuth 133.33°. The image was atmospherically corrected to surface reflectance using the CRESTech-modified 5S software, geometrically rectified to national map coordinates, with a further topographic correction applied [5].

The Landsat image was subjected to a conventional unsupervised classification from earlier work [5] to generate spectrally distinct clusters using a K-Means clustering algorithm. For each cluster, the mean reflectance value for each TM band was used in the MFM approach to match with the modeled reflectance values.

Eight forest cover types (classes) defined in the provincial inventory were analysed (Table 1). These included two mixed classes defined according to dominant hardwood or softwood composition (HS/SH), with white birch and trembling aspen combined into a generic deciduous class (H). The two scrub classes contain non-productive forest land with tree or scrub growth and >10% crown coverage of the respective wood type (HSC, SSC). Treed bogs contain scattered trees (>10% cover) in wet areas of bog or marsh. Each productive class is further divided into structural classes defined by 3 crown density classes and 8 height classes (Table 1) to create a series of forest type-structural strata.

TABLE 1
FOREST COVER TYPES AND STRUCTURAL CLASSES FROM PROVINCIAL FOREST INVENTORY.

Forest Cover Classes	Structural Classes: Crown Density	Structural Classes: Height Classes
1. Balsam Fir (BF)		1. 0 - 3.5m
2. Black Spruce (BS)	1. 76%+	2. 3.6 – 6.5m
3. Hardwood (H)	2. 51-75%	3. 6.6 – 9.5m
4. Softwood/Hardwood (SH)	3. 26-50%	4. 9.6 – 12.5m
5. Hardwood/Softwood (HS)		5. 12.6 – 15.5m
6. Treed Bog (TBO)		6. 15.6 – 18.5m
7. Softwood Scrub (SSC)		7. 18.6 – 21.5m
8. Hardwood Scrub (HSC)		8. 21.6m +

B. MFM Modeling

In this work, the Li-Strahler Geometric Optical Mutual Shadowing (GOMS) model [3] was used. This model is well suited to the complex shadowing of northern forests, as shown in a comparison study by [6], and it is also suitable for use in higher relief environments. A set of input ranges (Table 2) was specified to parameterize MFM-GOMS with reference to knowledge of the area and GIS forest inventory data. The solar zenith and azimuth angles at the time of Landsat TM image acquisition were also input to the model.

TABLE 2
MFM-GOMS STRUCTURAL PARAMETER INPUT RANGES (ALL SPECIES). ALL POSSIBLE COMBINATIONS OF THESE PARAMETERS ARE MODELED. TREE HEIGHT = h+b.

PARAMETER	MIN	MAX	STEP
Density (D)	5	95	10
Horizontal crown radius (r)	0.5m	4m	0.5m
Vertical crown radius (b)	0.5m	6.5m	1m
Height to center of crown (h)	2m	20m	1m

Spectral endmember values for sunlit canopy, sunlit background and shadow were available in the red and NIR bands from field spectroradiometer measurements of balsam fir, black spruce and hardwoods converted to reflectance [7]. Where local measurements were unavailable, reference spectra from similar forests in the ECOLEAP project [8] in Quebec were used.

Model-based analysis of the Newfoundland data set involved generating MFM-LUTs for TM bands 3 and 4 for BF, BS and H using multiple-forward-mode runs of the GOMS model. Each entry in the MFM-LUT contained an individual structural parameter set (Table 2), the species label (according to the endmember set used) as retained from input, and the modeled output reflectance values and sub-pixel scale fractions. All entries were merged into a large MFM-LUT that was searched for matches between the mean reflectance value from each cluster, and the modeled reflectance values from MFM-GOMS. The modeled cover type, density and height values associated with each matching reflectance value were extracted from the MFM-LUT for further analysis and comparison with independent cluster labels. Multiple matches were retained in the MFM search-engine as this was deemed to be consistent with the inherent variability associated with the clusters being analysed. For example, the mixed cover types (SH,HS) were identified as multiple matches which included both softwood and hardwood endmembers. The magnitude of multiple matches determined the dominant (S or H) designation, with low density occurrences associated with the appropriate scrub class. The treed bog class was associated with instances of low density black spruce on characteristically moist to wet background surfaces. The assessment of modeled cluster labels was generated from comparisons with an independent inventory cluster table [5]. A number of cases involved multiple cover types in the cluster inventory descriptors and/or modeled output for a given set of matching reflectance values. In these cases, the full range of variability was considered in determining the final result, as a means to assess the modeling capability to correspond with internally heterogeneous clusters.

IV. RESULTS

A. Forest Cover Type

The results of cluster labeling of forest cover using MFM-GOMS are shown in Table 3. The overall level of agreement between MFM and the cluster inventory was 73% (Kappa=0.68), with reasonable individual accuracies obtained for most classes, with the exception of the three hardwood dominated classes. This may be due to the generality of the hardwood classes, issues with endmember spectra, or the model's representation of deciduous canopies. The five softwood dominated classes had an average accuracy of 83%. Errors were grouped into two levels of severity (ES1 and ES2) based on assessment of class omission. Errors amongst non-mixed classes (e.g. BF or BS confused with H) were considered to be more severe (ES1) than errors within general softwood or hardwood classes (e.g. BF vs BS; BF vs SH). Similarly, errors between mixed classes or scrub classes were regarded as less severe. Using this rubric, only 30% of the errors were deemed to be severe, with a concomitant expectation that with some refinement the remaining less severe errors might be reduced with improved modeling. It is also important to recognise that the cluster inventory data used in these assessments may have issues of quality that are introducing bias and error to the analysis, thus our assertion of agreement, but not absolute accuracy, in these trials.

TABLE 3
AGREEMENT BETWEEN MFM FOREST COVER TYPES AND INVENTORY CLUSTER LABELS (TABLE 1) SHOWING MORE SEVERE (ES1) AND LESS SEVERE ERRORS (ES2).

Cluster ID	MFM Cluster Label 1	2	3	4	5	6	7	8	n	%	Kc	ES1	ES2
1. BF:	**3**	1	1						5	60.0	0.52	1	1
2. BS:		**6**							6	100.0	1.00		
3. H:	1		**1**						2	50.0	0.47	1	
4. SH:		1		**7**					8	87.5	0.84		1
5. HS:				1	**1**				2	50.0	0.49		1
6. TBO:						**2**			2	100.0	1.00		
7. SSC:	1	1					**6**		8	75.0	0.68		2
8. HSC:	1						2	**1**	4	25.0	0.23	1	2
Total:	6	9	2	8	1	2	8	1	**37**	**72.9**	0.68	3	7

B. Analysis of Forest Structure

Crown density and stand height outputs from MFM-GOMS were assessed for clusters correctly identified in the forest cover stratification. In cases where there was a range of structural outputs for a set of matching reflectance values, measures of central tendency were used to place the structural cluster label into one of the predefined categories (Table 1) The contingency table for density (Table 4) reveals an overall agreement of 56%, with most of the model output into the low density class (3: <50%). That class had a high level of agreement, but this diminished at increasing densities. Many of the clusters contained multiple densities, however the dominant inventory value was used against the averaged MFM-density value. A more relaxed decision rule would increase the overall agreement found, though at a cost in terms of model precision. However, given the nature of the biomass estimation procedures these outputs are intended for, such a strategy may indeed be appropriate.

TABLE 4 (Density) and TABLE 5 (Stand Height)
AGREEMENT BETWEEN MFM MODELED AND INVENTORY CLASSES.

D Cls	MFM Density 1	2	3	n	%
1.			2	2	0
2.		**4**	9	13	31
3.			**10**	10	100
n:	0	4	21	25	56%

Hgt Cls	MFM Height 2	3	4	5	6	n	z%
2.						0	
3.	1	1				2	50
4.			11	4	1	16	69
5.				6		6	100
6.					1	1	100
n:	1	1	11	10	2	25	76%

Stand height results (Table 5) had higher individual and overall class accuracies compared to density, despite the larger number of height classes considered. Most of the MFM and cluster inventory labels ranged from height classes 3 – 5, with most errors contained to adjacent classes along this ordinal class structure of increasing height (Table 1). As with the density analysis, greater overlap could be achieved with a more general matching criterion.

V. Conclusion

The use of a geometric optical canopy reflectance model has been demonstrated for labeling clusters obtained from an unsupervised classification of forested terrain in western Newfoundland. Reasonable results were obtained for forest cover, density and height, with most errors being explainable and less severe within the context of agreement with a somewhat variable and therefore less than optimal validation product. The next phase of this work involves independent per-pixel MFM-GOMS analysis using a LUT approach. This circumvents the need for unsupervised clusters and represents a more direct and potentially more accurate approach for deriving key forest type and structural information for input to biomass estimation procedures.

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