

Modeling and Mapping Forest Biomass using Forest Inventory and Landsat TM Data: Results from the Foothills Model Forest, Alberta.

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Abstract - Forest biomass information is needed for reporting of selected indicators of sustainable forest management and for models that estimate carbon budgets and forest productivity, particularly within the context of a changing climate. In collaboration with the Canadian Space Agency, a strategy for mapping Canada's forest biomass has been developed as part of the Earth Observation for Sustainable Development of Forests (EOSD) project. This paper reports on the results derived from an application of this strategy to a pilot study area in the Foothills Model Forest, Alberta. Methods to estimate forest biomass have been developed using tree-level inventory plot data that is then extrapolated to the stand level by statistical relationships between biomass density and stand structural characteristics. These ground-based biomass estimates serve as source data that are related to stand structure derived from classified Landsat TM data. Models developed from inventory data to estimate biomass density attained adjusted R^2 values that ranged from 0.60 to 0.77 for 5 species groups, and tests with an independent validation sample compared favourably for all species (deciduous, lodgepole pine, mixed species, white spruce/fir), except black spruce/larch. Landsat-derived forest biomass was statistically and moderately correlated to the inventory-derived biomass with values of 0.63, 0.68, and 0.70 for conifer, deciduous, and mixed species, respectively. Research areas were identified from both inventory and remote sensing perspectives that will lead to incremental improvements in biomass estimation.

I. INTRODUCTION

Forest biomass is the dry mass of live plant material (trees and understory species) occurring in a forest ecosystem. The estimation of forest biomass is used in studies of ecosystem productivity, and in models for calculating and forecasting carbon budgets [1,2,3]. Accurate biomass estimation is important for assessing the contribution of Canadian forests to the global carbon (C) cycle [4,5]. The lack of accurate spatial forest biomass data has been

considered one of the most persistent uncertainties concerning the C budgets of global forests [6].

Field-based methods of biomass measurement and estimation are costly, time-consuming and location-specific. Extending these methods into maps of forest biomass across Canada is extremely challenging when factors such as ecological differences, variation in inventory systems, and scattered sources of biomass data are considered. There has been an increasing demand for spatially-explicit methods of forest biomass estimation that could be implemented nationally. Bonner [7] compiled Canada's first national forest biomass inventory from wood volume data reported in the 1986 forest inventory. Penner et al. [5] attempted to improve on this using the 1991 inventory data set. These efforts are the primary sources of biomass data reported at a coarse resolution (nominally 10 kilometre township units). There is, however, a demand for national forest biomass data at finer spatial resolutions. Such a demand exists for meeting Canada's commitment to the Kyoto Protocol, which allows for inclusion of forest carbon sinks as offsets to fossil fuel emissions of greenhouse gases. To meet these needs, methods developed will need to be robust, and independently verifiable.

The Earth Observation for Sustainable Development of Forests (EOSD) project, a joint effort between the Canadian Forest Service and the Canadian Space Agency [8], has been given the mandate to map Canada's biomass at the forest management stand level using Landsat Thematic Mapper (TM) data (30 metre pixel resolution). The EOSD strategy outlines a combined forest inventory-based method for biomass mapping, expansion of the method to several pilot regions, and implementation at the national level [9].

This EOSD method is being applied systematically across pilot regions in Newfoundland, Labrador, Quebec and Alberta. There are appreciable differences among these regions, not only in forest

composition and ecology, but also in the quality and structure of source data available for biomass mapping. The exploration of these differences provides important information relevant to national implementation. The objectives of this initial study were: (i) to estimate stand-level biomass using both Alberta Vegetation Inventory (AVI) and Landsat TM data, and (ii) to identify and explore data and method implementation issues relevant to their application to Alberta.

II. STUDY AREA

The EOSD Alberta Foothills pilot region, approximately 2700 km² in size, is located in west-central Alberta within the Foothills Model Forest. Ecologically, the study area consists predominantly of the Upper Foothills and Lower Foothills ecoregions [10]. Forest stands in this region are dominated by lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) and white spruce (*Picea glauca* (Moench) Voss). Pure or mixed stands of trembling aspen (*Populus tremuloides* Michx.) and balsam poplar (*Populus balsamifera* L.) occur in small amounts along with black spruce (*Picea mariana* (Mill.) B.S.P.) and tamarack (*Larix laricina* (Du Roi) K. Koch) in poorly drained areas. The study area has been mapped to the AVI standards that describe forest stands by moisture regime, crown closure, stand height, species composition, and stand origin [11].

III. METHODS

A. Stand-level Biomass from Inventory

Biomass data collected in the boreal forest regions of the Prairie Provinces and Northwest Territories [12,13], and in the Yukon [14] were pooled and used to develop allometric functions that related tree diameter at breast height (dbh) and height to above-ground total tree biomass (kg tree⁻¹) for four species groups. These functions were then used to estimate tree biomass in 1382 Permanent Sample Plots (PSP) located in the study area. Total tree biomass for each plot was subsequently converted to a stand-level biomass density (tonnes ha⁻¹).

For each PSP plot, mean tree height was calculated using measurements reported for all standing live trees. Crown closure class (A: 5-30%, B: 31-50%, C: 51-70%, D: 71-100%) was also obtained from the PSP database. Plots were classed as "pure" if the dominant species formed at least 80% of the stand by species composition: Decid (Deciduous: trembling aspen, balsam poplar), Pine (lodgepole pine), SbLt (black spruce/larch), and

SwFir (white spruce/fir), otherwise they were classed as Mixed (mixed species). Aggregations of these species groups were made for conifer (C), deciduous (D) and mixed (M) where mixed conifer was placed into the C category and M was comprised of mixed woods.

Thirty percent (316) of the total number of plots were randomly selected and withheld for model validation. Biomass density by species group, was then regressed on crown closure class (mid-value) and mean stand height for the remaining 966 plots, using both multiple linear and non-linear regression procedures. The models were assessed based on adjusted R² and Root Mean Square Error (RMSE) values and further validated by a paired t-test between predicted and "observed" biomass density using the validation data set.

B. Biomass Derived from Remote Sensing

The stand-level biomass equations developed from the inventory data were applied to a given set of forest strata to create a lookup table of values needed to estimate biomass from the satellite classifications. A stratum was defined as the combination of species group, crown closure, and stand height, and sixty strata were produced by combining the five species groups with two crown closure classes (A + B = Open, C + D = Closed), and six stand height classes (1-5m, 6-10m, 11-15m, 16-20m, 21-25m, 26m+). The crown closure and stand height attribute values for the 60 strata were input to the stand biomass function developed from the inventory to create a look-up table for biomass density.

A Landsat-5 TM image of the study area, acquired on September 8th, 1999, was used for our analysis. Top-of-atmosphere (TOA) corrections were applied to the image using an algorithm developed by the Canada Centre for Remote Sensing. The image was then orthorectified using National Topographic Data Base (NTDB) 1:50 000 vectors and a 25 m horizontal resolution digital elevation model derived from a provincial data set. Pre-processing of the imagery also included masking non-vegetated areas such as water and urban landscape using an NDVI thresholding procedure. Areas below a certain NDVI threshold value, which was arbitrarily set by visual assessment of on-screen results, were considered non-vegetated and masked out. A texture channel was also derived for classification from a 5 x 5 homogeneity filter on Landsat TM band 4.

Landsat TM bands 3, 4, 5 and texture were classified with the K-Means clustering algorithm available in PCI Image Works [15]. A training set of randomly sampled pixels within each species group

was used to derive the relationship between the inventory and the spectral cluster.

The accuracy with which spectral clusters could be labelled was compared for an output of 255 and 75 clusters. These labelled clusters were then used with the look-up table to derive an estimate of biomass density for the cluster. Biomass estimates derived from the 255 and 75 cluster outputs were compared to the biomass values derived from the inventory. This was accomplished by creating a validation dataset from a different set of randomly selected pixels than that used for cluster labelling to determine the classification accuracy and biomass correlation.

IV. RESULTS AND DISCUSSION

The five species groups were distributed across the pilot region as: Decid: 5%, Pl: 46%, Mixed: 19%, SbLt: 18%, SwFir: 11% (area fractions). Mean biomass densities calculated for PSP plots increased by species group in the order of SbLt < Mixed < SwFir < Pl < Decid (Table I). Biomass variability was relatively consistent in its distribution among all species, although data for SwFir were more positively skewed than for the other species.

Based on modeling results for relating biomass density (B) to stand height (H) and crown closure (CC), the overall best-fit model form was:

$$(B)^{1/3} = b_0 + b_1(\ln H) + b_2(CC). \quad (1)$$

TABLE I
DESCRIPTIVE STATISTICS FOR BIOMASS DENSITY (TONNES HA⁻¹) BY
SPECIES GROUP

Species Group	Descriptive Statistic				
	Range	Mean	Median	SD ^a	Skewness
Decid	0.00-362.23	131.74	133.00	86.14	0.34
Pl	0.00-359.91	108.30	96.60	77.51	0.50
Mixed	0.00-325.83	98.78	93.57	73.63	0.57
SbLt	0.03-230.81	63.30	58.09	47.69	0.51
SwFir	0.00-287.17	106.09	104.94	70.45	1.13

^a SD: standard deviation from the mean

The transformations of the B and H terms served to increase model fit and decrease heteroscedasticity of variance in the data. The model fits attained by species were (R², RMSE): Decid (0.77, 41.2), Pl (0.77, 37.1), Mixed (0.72, 38.8), SbLt (0.60, 31.7), and SwFir (0.62, 43.5). Paired t-tests between model fit and validation datasets suggest there were no statistical differences in estimations of stand-level biomass for Decid (p = 0.25), Pl (p = 0.35), Mixed (p = 0.42), and SwFir (p = 0.57). The only exception was for SbLt (p = 0.03). The stand models predicted

biomass density values that were statistically equivalent for 4 of the 5 species.

Image classification was less accurate by species group and for conifer, deciduous and mixed species when a maximum spectral cluster of 255 was used compared to 75 clusters (Table II). Specifying the maximum number of clusters likely results in more spectrally variable clusters than the inventory data that are suitable or available to label them.

Biomass estimates from these two sets of spectral clusters were statistically correlated to the inventory biomass (p < 0.05). Overall correlation improved for the 75 cluster set (C = 0.63, D = 0.68, M = 0.70) compared to the 255 cluster set (C = 0.59, D = 0.57, M = 0.67). Correlation coefficients for the 255 cluster set based on the use of spectral data alone without texture were C = 0.58, D = 0.55, M = 0.63. The addition of texture to the spectral data resulted in a very slight improvement to the mixed-wood (M) species correlation. Texture has been observed to be more sensitive to differences in stand structure in mixed-wood species stands than in pure conifer or deciduous stands, and may explain, in part, the slightly higher correlation for the mixed (M) species [16].

TABLE II
OVERALL ACCURACY OF CLUSTER LABELING

	Cluster Label vs Inventory Label	
	255 clusters	75 clusters
Species Group	46%	52%
C,D,M ^a	63%	68%

^aC (Conifer), D (Deciduous), M (Mixed)

Results of the paired t-tests suggest the stand-level models generally predict biomass well. These results express overall performance and did not address the variation in predictive performance of biomass estimation over the range of biomass values. In particular, greater variability is to be expected for high biomass stands because of the change in relationship between high biomass and stand structural attributes. The high biomass stands are more difficult to model relative to the lower biomass stands that tend to increment more linearly.

The labelling of the spectral clusters is sensitive to the number of maximum clusters set in the clustering routine and the intensity of the pixels sampled for overlay with the inventory. While it is difficult to establish what the maximum number of clusters or sample intensity should be for a given data set, we believe further work to define these procedures are justified. In this study, species classification accuracy was higher with a smaller number of clusters used in

the labelling process, and this translated into slightly improved biomass estimations.

V. CONCLUSIONS AND FUTURE WORK

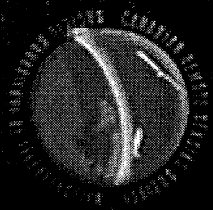
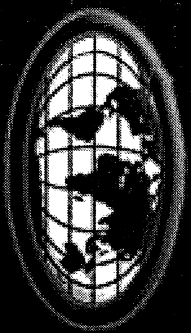
A stand model was developed to estimate forest biomass density for each species group. This model was then used to provide ground data for estimation of biomass by satellite remote sensing. The initial estimates for individual species groups and for aggregated conifer, deciduous and mixed species classes were modest at best but consistent with previous studies that have attempted biomass estimation from satellite remote sensing [17]. There remain many opportunities, however, to refine these estimates from both the biomass model fitting and validation process and from the remote sensing procedures utilized. Future work will address error validation and bootstrapping procedures [18] as methods of improving the allometric functions to estimate biomass at the stand level. Future remote sensing research will address spectral and spatial feature selection (including incorporating environmental and terrain measures into the classifier), image segmentation, mixture modeling [19], and methods of deriving classification parameters as approaches that will potentially lead to incremental improvements in biomass estimation from satellite remote sensing.

VI. ACKNOWLEDGMENTS

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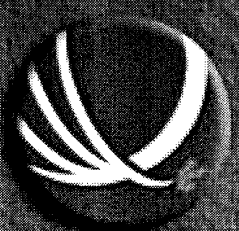
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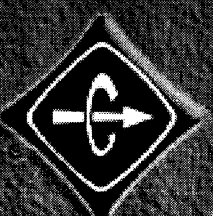
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