Using multi-sensor satellite imagery to map forest stand attributes in the Mackenzie Valley, NWT

[1]R.S. Skakun, [1]R.J. Hall, [1]E.J. Arsenault, [2]L. Smith, [2]A. Cassidy, [2]T. Lakusta, [3]A. Beaudoin, [3] L. Guindon

[1]Natural Resources Canada, Canadian Forest Service, 5320 122 Street, Edmonton, Alberta, T6H 3S5
[2]Government of the Northwest Territories, Department of Environment and Natural Resources, P.O. Box 4354, Hay River, NT, X0E 1G3
[3]Natural Resources Canada, Canadian Forest Service, P.O. Box 10380, Ste. Foy, Québec, G1V 4C7

ABSTRACT

Conducting vegetation inventories that describe the state of forests in the Northwest Territories (NWT) is challenging due to the large geographic extent of forest resources that are not easily accessible. A satellite land cover map depicting the spatial distribution of forests in the NWT was recently completed during the Earth Observation for Sustainable Development of Forests (EOSD) project. Demands for more detailed forest information necessitate the development of methods that can function within the framework of the EOSD land cover maps. A sampling approach was employed whereby a judicious collection of field plots in conifer stands were used to estimate stand attributes. These field-based attributes were subsequently correlated to the shadow fraction of conifer stands derived from a high spatial resolution Quickbird panchromatic image. The estimates of stand attributes on the Quickbird image were used to derive satellite sample plots that were subsequently scaled, using a k-Nearest Neighbour algorithm, to coarser resolution Landsat Thematic Mapper (TM) imagery. Stand height, crown closure, basal area, stand volume and aboveground biomass were estimated and mapped within coniferous land cover as defined by the EOSD land cover maps. Preliminary results near Fort Providence suggested that the stand attributes can be estimated to within 10 to 15 percent of the field plot measurements. This work is being undertaken in a region of the Mackenzie Valley that approximates 4.5 million ha of forested area within a footprint of three contiguous Landsat TM scenes.

Key words: Forest inventory, remote sensing, Landsat, Quickbird, volume, aboveground biomass

1. Introduction

The Northwest Territories (NWT) is approximately 128 million ha in size of which 33 million ha, or 25% is considered forested (Natural Resources Canada 2006). Attempting to complete a forest inventory over such a large area for use at local, regional and territorial scales is challenging given the relative lack of access and small amounts of detailed inventory data that presently exist (Smith 2002). In response, the federal (Natural Resources Canada, Canadian Space Agency) and territorial (Government of NWT) governments recently completed a satellite-based land cover map of the NWT. This map comprised a component of the Earth Observation for the Sustainable Development of Forests (EOSD) project that was completed for the forested areas of Canada, and was undertaken across the NWT with Landsat Thematic Mapper (TM) data (Wulder et al. 2003). To improve the informational value of these land cover maps for reporting on the state of NWT forests, generating additional knowledge about forest structure, volume and aboveground biomass is necessary.

The use of satellite remote sensing for inventory mapping from medium spatial resolution imagery has been widely explored but variable results have been reported (Ripple et al. 1991; Cohen and Spies 1992; Jakubauskas and Price 1997; Hall et al. 2006; Sivanpillai et al. 2006). Remote regions such as the NWT raise additional challenges because: 1) collection of field information is costly, 2) the forested landscape is diverse with multiple land use demands, and 3) relatively few remote sensing inventory-based studies have previously been conducted (Gerylo et al. 2002; Franklin et al. 2003). As a result, there is particular difficulty associated with scaling field measurements to medium spatial resolution satellite imagery such as Landsat, in remote northern regions. Alternative means of scaling stand attribute estimates between field and satellite image is a problem that has recently been investigated with high spatial resolution Quickbird satellite imagery (Beaudoin et al. 2005).

High spatial resolution images are able to distinguish small-scale features such as canopy foliage, gaps, and shadows that are generally undetectable on medium resolution imagery. It is the discrimination of these features that provide the basis for improved characterization of forest stand attributes that are of value in forest inventory (Wulder et al. 2000; Goetz et al. 2003). Previous work reported by Cohen and Spies (1992) suggest the spatial organization and quantity of tree shadows in mature and old-growth forest canopies facilitate improved estimates of stand structure variables. The process of extracting spatial properties from high spatial resolution images, however, requires the analysis of image pixels in a spatial domain (ex., pixel window), rather than from single pixel interpretation methods that are often employed with medium resolution sensors. The tradeoff with high spatial resolution sensors compared to medium resolution sensors, is that the footprint size is much smaller. As a result, this type of imagery is not, in itself, practical for mapping of large areas when many contiguous satellite scenes would be necessary. This study investigated the integration of field, high spatial resolution, and medium resolution image data for scaling estimates of forest stand attributes that could subsequently be applied over large areas.

This paper presents the use of Quickbird high spatial resolution imagery to estimate stand height, crown closure, basal area, stand volume and aboveground biomass as stand attributes from the shadow component of forest stands. Particularly in open stands, tree shadows can be detected spectrally on relatively flat terrain, and the presence of these shadows are enhanced at lower sun angles that are typically observed at more northerly latitudes. The image stand attribute estimates are then scaled to larger areas represented by Landsat TM imagery. This multi-sensor satellite image scaling approach was recently demonstrated in northern Québec to map aboveground biomass in open-canopy black spruce stands (Beaudoin et al. 2005; Guindon et al. 2005). Using the methods learned from these studies, this paper attempts to expand the scaling approach to include multiple forest stand structure attributes (i.e., height, crown closure, basal area) and volume to map within a range of coniferous stand types (jack pine, white spruce and black spruce) over a contiguous row of normalized Landsat TM imagery. This study also compares the regressive performance of Theil-sen (Fernandes and Leblanc 2005) to linear models for improving estimates of stand attributes from the shadow fraction analysis.

2. Study area

The study area consists of an approximate 4.5 million ha region of the Mackenzie Valley, NWT that is within a footprint of three contiguous Landsat TM images (Figure 1). Existing forest inventory information comprises less than 25% of the area of interest. The study focused on coniferous stands due to its predominance within the study region. Coniferous species mainly consisted of black spruce (*Picea mariana* (Mill) B.B.P.), jack pine (*Pinus banksiana* Lamb.) and white spruce (*Picea glauca* (Moench) Voss). The structural conditions of these stands can be characterized on a continuum from simple in young, even-aged stands to complex in mature stands, typical of the boreal forest within this region (Ecological Stratification Working Group 1995; Ecosystem Classification Group 2007). The simple structure stands generally have a single canopy layer of similar sized trees with few canopy gaps, whereas the complex structured stands commonly have multiple canopy layers with numerous gaps and variable tree sizes.

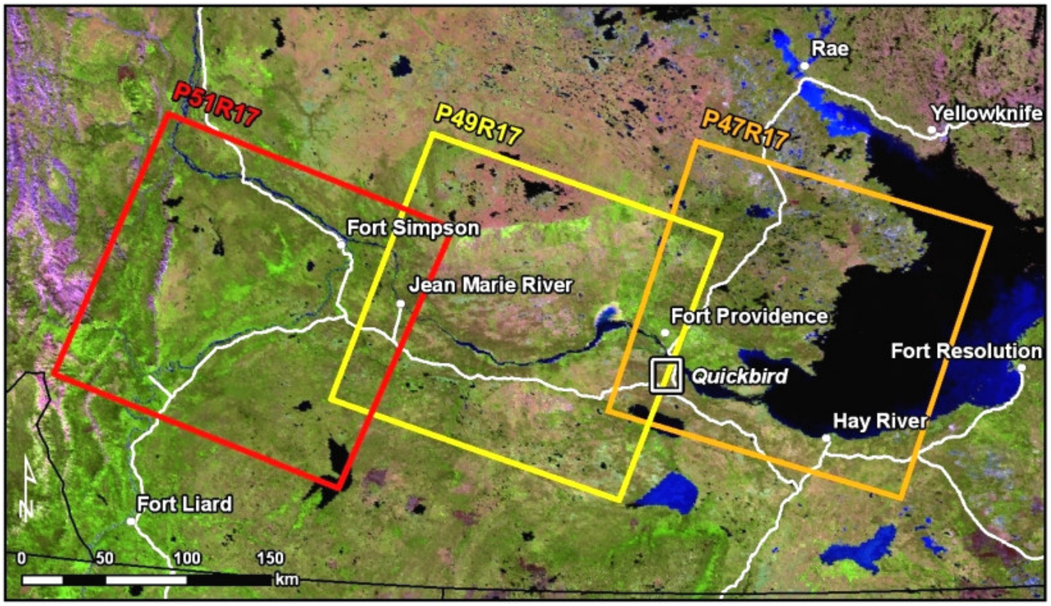


Figure 1. Study area location in the Mackenzie Valley as defined by the three coloured Landsat footprints. The backdrop is a MODIS 500m satellite image composite.

3. Data collection

3.1 Field sampling

Field data was collected during July 2005 within the Quickbird footprint located near Fort Providence (Figure 1). A total of 45 plots, $400m^2$ in size, were established in stands of jack pine, white spruce and black spruce. The data collection protocol included every tree within the plot that was at least 1.3 m in height, from which species type, tree height (m), diameter at breast height (cm), tree status (dead or alive), crown closure measurements, and a differentially corrected GPS coordinate at plot centre were collected. Approximately 6000 trees were recorded and entered into a digital database, followed by a quality assessment and error check for data entry errors.

Stand estimates of height, crown closure, volume, aboveground biomass, and basal area were computed from the field data. The stand height of each plot was calculated using Lorey's mean height (weighted by the basal area of each tree). Plot crown closure was derived from the average of nine spherical densitometer measurements taken within the plot boundary. Estimates of stand volume were generated by summing the computed individual tree volumes (Huang 1994), divided by the plot area and scaled to a total volume density measurement (m^3/ha). A generalized, allometric tree biomass equation ($AGB = a\mathrm{DBH}^b$) was used to generate tree level biomass[*], which was then summed for each tree and converted to a stand-level total aboveground biomass density (tonnes/ha). Basal area was also computed for each plot and converted to a basal area density measurement (m^2/ha).

3.2 Satellite imagery

A Quickbird panchromatic high spatial resolution satellite image was acquired on August 30, 2003 near Fort Providence (Figure 1). The image has a spatial resolution of 0.6m and a spatial extent of approximately 17 km (West-East) by 19 km (North-South). The image was orthorectified to ground control points collected along main roads through the image area. Canadian Digital Elevation Data at a scale of 1:250k was used for the elevation

---

[*] Case BS, Hall RJ Assessing prediction errors of generalized tree biomass and volume equations for the boreal forest region of west-Central Canada. Natural Resources Canada, Canadian Forest Service. *Manuscript under review.*

model. A first-order polynomial correction applied to 22 ground control points resulted in an average positional root mean square error (RMSE) of 0.73m.

Three Landsat TM images (30m spatial resolution) were acquired during late June to mid-August of 2004 and 2005 for generating large area estimates of the stand attributes (Figure 1). These images were orthorectified using ground control points and by image registration to the orthorectified Quickbird, resulting in RMSEs of approximately 5m.

4. Methods

4.1 Plot shadow fraction

Using the procedures described in Beaudoin et al. (2005) and Lebouef et al. (*in press*) for mapping aboveground biomass from Quickbird, this study applied a similar image analysis technique and extended its approach to multiple forest stand attributes from high spatial resolution imagery. The Quickbird panchromatic image was initially processed to isolate image tree shadows from other image objects such as standing trees by generating a threshold mask over tree shadow pixels. The spectral range of tree shadow reflectance was largely determined by manual interpretation of the image. Tree shadow reflectance was less than canopy foliage, but greater than water. This range of values was optimized through correlating and modeling its predictive performance to plot stand structure estimates.

Sampling areas that represent the size of a 30m by 30m Landsat TM pixel (50 by 50 Quickbird panchromatic pixels) were centered on each of the plot locations on the Quickbird panchromatic image. These sampling areas were then superimposed onto the tree shadow threshold layer to determine the proportion of tree shadow pixels at each plot location. This procedure is referred to as plot shadow fraction (plot SF), which was computed for each field plot as:

$$\text{Plot SF} = \text{Number of tree shadow pixels} / \text{Number of pixels in plot sampling area} \tag{1}$$

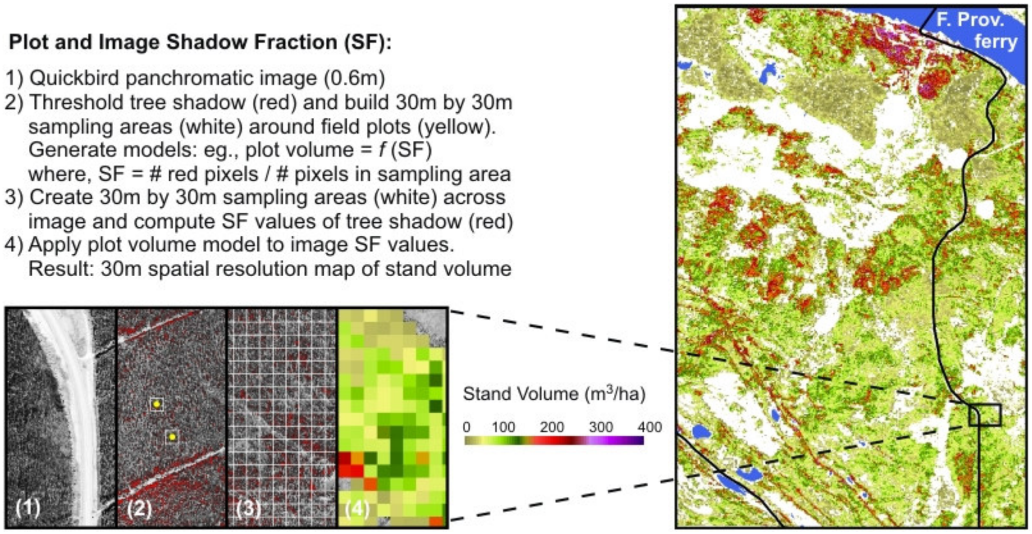
During this procedure, the 45 conifer plots consisting of jack pine, white spruce and black spruce compositions were combined and randomly stratified into model calibration (35) and image validation (10) samples. Stand attributes from the model calibration samples were regressed against the plot shadow fraction values using simple linear and Theil-Sen regression procedures (Fernandes and Leblanc, 2005).

4.2 Image shadow fraction

Shadow fraction for the panchromatic image (image SF) was determined by the proportion of tree shadow pixels within 30m by 30m sampling areas built across the entire image:

$$\text{Image SF} = \text{Number of tree shadow pixels} / \text{Number of pixels in image sampling area} \tag{2}$$

The regression form and parameters from the plot shadow fraction model for each stand attribute were then applied to the image shadow fraction to generate continuous estimates of the stand attributes on the image. The image was previously stratified by EOSD land cover (Wulder et al. 2003) to focus mapping of stand attributes in regions that were predominately conifer, as this accounted for approximately 85% of the forested land cover in the study area. The independent validation plot samples were used in a statistical analysis to assess the accuracy of the image stand attribute estimates. The plot and image shadow fraction procedures is summarized and illustrated in Figure 2 within a subset region of the panchromatic mage.



Plot and Image Shadow Fraction (SF):

1) Quickbird panchromatic image (0.6m)
2) Threshold tree shadow (red) and build 30m by 30m sampling areas (white) around field plots (yellow). Generate models: eg., plot volume = *f* (SF) where, SF = # red pixels / # pixels in sampling area
3) Create 30m by 30m sampling areas (white) across image and compute SF values of tree shadow (red)
4) Apply plot volume model to image SF values. Result: 30m spatial resolution map of stand volume

Figure 2. Example of the shadow fraction procedure to estimate stand volume.

4.3 Image normalization

A normalization of the Landsat TM imagery was performed to account for differences in radiometry and vegetation phenology. The objective was to generate consistent surface reflectance across the image scenes so the resulting stand attribute estimates would be consistent among the different image dates. The methods reported by Olthof et al. (2005) were modified to normalize the Landsat scenes to a MODIS 500m surface reflectance composite, and applied to image bands between the two sensors that approximately corresponded to the same portion of the electromagnetic spectrum. The MODIS composite image acquired was based on a 32 day collection period from July 12 to August 12, 2005. The normalized Landsat images were subsequently combined into a single image mosaic.

4.4 Scaling-up to Landsat TM

The image stand attribute estimates generated at 30m spatial resolution from the panchromatic image were randomly sampled to create surrogate sample plots to feed into a k Nearest Neighbour (kNN) algorithm to scale the image estimates to the Landsat TM mosaic. This procedure was implemented from Guindon et al. (2005) where surrogate aboveground biomass estimates were mapped by kNN over coniferous regions on a Landsat image. With the kNN algorithm, the value of a stand attribute at a given Landsat pixel location is determined by the inverse weighted average of the surrogate sample plots that fall within the k nearest neighbours as defined by the Euclidean distance in multispectral space (Franco-Lopez et al. 2001). A k value of 15 and Landsat bands 3, 4, 5 were used to define the multispectral space, where the band values at the surrogate sample plot locations were used to compute the Euclidean distance. The kNN algorithm was then applied under the coniferous component of the EOSD land cover.

5. Results and discussion

5.1 Field collected estimates of stand attributes

The number of plots that were predominantly conifer (i.e., >=80% of total species composition) was 36, of which 20 were in jack pine, 7 were in white spruce, and 9 were in black spruce stands. There were also 9 plots collected with a mixed conifer content (<80% of any conifer species type). Based on separating the plot data into species types, the white spruce plots had the largest estimate of any stand attribute, followed by jack pine and black spruce (Table 1). The mixed conifer plots consisted of all three species types thereby generating stand attribute estimates that tended to be the most variable among all species types (Table 1). Combining the plots into a single conifer sample allowed for greater distributions of the stand attribute values than with any of the species type alone. Because the Quickbird and Landsat TM imagery were stratified by the EOSD coniferous class, which is not a species-level classification, combining the plots was necessary for image modeling.

Table 1. Summary of the field plot stand attribute measurements by conifer species using live tree data.

Stand Attribute	Species type	Min	Max	Range	Mean	Standard dev.
Height (m)	Jack pine	6	16	10	11.8	2.8
	White spruce	16	21	5	18.3	1.6
	Black spruce	7	11	4	8.9	1.2
	Mixed conifer	7	16	9	10.8	3.7
Crown closure (%)	Jack pine	23	39	16	32.6	4.5
	White spruce	32	65	33	53.7	12.3
	Black spruce	18	36	18	24.4	5.8
	Mixed conifer	24	61	37	35.2	10.9
Volume (m^3/ha)	Jack pine	33	196	163	121.0	46.1
	White spruce	162	339	177	283.1	62.1
	Black spruce	23	80	57	52.2	17.9
	Mixed conifer	58	255	197	115.1	69.7
Biomass (tonnes/ha)	Jack pine	32	114	82	78.4	21.3
	White spruce	84	157	73	132.0	24.4
	Black spruce	20	64	44	42.6	12.8
	Mixed conifer	52	136	84	77.1	27.9
Basal area (m^2/ha)	Jack pine	11	31	20	22.8	5.0
	White spruce	24	45	21	38.4	7.2
	Black spruce	7	21	14	14.2	4.1
	Mixed conifer	16	43	27	23.8	8.6

5.2 Quickbird estimates of stand attributes

The optimal spectral range of thresholded tree shadow was between 100 and 176 for all the stand attributes, resulting in correlation R values >=0.80 and model predictive performances based on a linear regression >0.70 R^2_{adj}. Model function comparisons between linear and Theil-sen regression indicated that Theil-sen regression models generated a wider range of image estimates, thus increasing the range of modeled attribute values compared to what was generated from the linear regression models. This difference was demonstrated for stand height (Figure 3), where the intercept for the Theil-sen model is about half the value of the linear regression model and has a larger slope resulting in a perceptively steeper curve function. This can be explained, in part, by the insensitivity of Theil-sen to ~30% of outliers, as a few points that may be perceived as outliers do not influence the placement of the Theil-sen regression line (Fernandes and Leblanc 2005). By comparison to the independent validation samples, all the stand attribute estimates generated by Theil-sen regression were within 10 to 15 percent of field plot measured values.

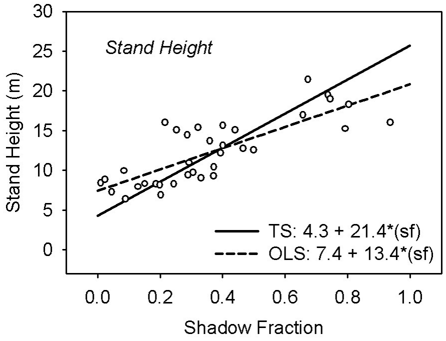


Figure 3. Theil-sen regression (TS) compared to linear regression (OLS) for estimating stand height.

5.3 Landsat TM estimates of stand attributes

A total of 600 pixels from the Quickbird stand attribute maps were extracted to serve as surrogate sample plots for the kNN scaling process. Illustrating the results for stand volume, estimates for the most part were less than 200 m^3/ha, with the exception of some areas scattered along the Mackenzie River valley and west of Great Slave Lake that presented higher values (Figure 4). These larger stand volumes were attributed to the taller and denser stands observed in these areas. Landsat image maps for the remaining height, crown closure, biomass, and basal area stand attributes were also generated. Validation of these image stand attribute maps will be undertaken in a future study using field plot data collected throughout the study area. While Figure 4 was presented for visualization purposes, from an application point of view, continuous estimates of stand attributes would be reclassified into the desired number of classes required by forest managers, or to the number of classes supported by the precision of the estimates. This is an important aspect of the remote sensing inventory approach because while continuous models are developed, this does not imply that these stand attributes can be mapped to this degree of precision. Reclassification of the remote sensing estimates into discrete classes would result in stand attribute maps that would be coupled with the forest cover classes defined by the EOSD land cover maps.

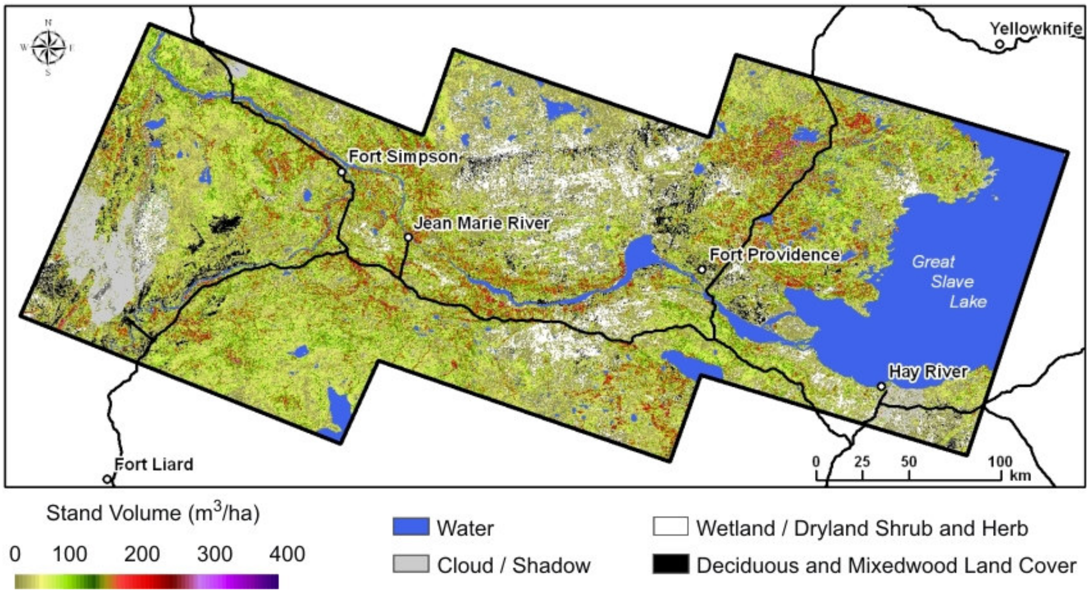


Figure 4. Stand volume estimates generated over coniferous forest land cover.

6. Conclusion

Generating forest inventory information in the NWT is challenged by its remoteness, relative lack of existing information, and large region over which such information is required. This study is developing a modeling and data integration approach that includes field, high spatial resolution Quickbird and Landsat TM data to generate forest stand attributes within the framework of EOSD land cover. Field estimates of stand structure, volume and aboveground biomass are correlated to the shadow fraction generated on a Quickbird image that is subsequently scaled to Landsat TM using a kNN procedure. Validation of these image-based estimates are in progress, and current work is extending this application to deciduous and mixedwood stands that comprises the other 15% of the forested land cover within the three Landsat scene study area.

7. Acknowledgements

The Canadian Forest Service would like to acknowledge the excellent working relationships, support and participation of GNWT Forest Resources Staff for establishing this project and for assisting in its execution. Several GNWT term staff and summer students are acknowledged for their assistance in collecting the field data (Kevin Mindus, Angela Desilets, Dallas Phillips). We acknowledge our Natural Resources Canada, Canadian Forest Service colleagues Joan Luther and Doug Piercey, and to Richard Fournier (University of Sherbrooke) for co-development of the EOSD biomass strategy. Review comments by Doug Piercey and Nicole Hopkins on an earlier version of this manuscript is gratefully acknowledged. Financial support provided by the Canadian Space Agency for the EOSD biomass project and the Mackenzie Gas Pipeline funds provided by Natural Resources Canada is greatly appreciated.

8. References

Beaudoin A, Leboeuf A, Guindon L, Fournier R, Luther J, Lambert M (2005) Mapping of Canadian northern boreal forest biomass using Quickbird high spatial resolution imagery. In Proceedings FORESTSAT 2005 workshop, May 31-June 3 2005, Borås, Sweden, 8b:66-70

Cohen WB, Spies TA (1992) Estimating structural attributes of Douglas-fir/western hemlock forest stands from Landsat and Spot imagery. Remote Sensing of Environment 41:1-17

Ecological Stratification Working Group (1995) A national ecological framework for Canada. Agriculture and Agri-food Canada, Research Branch, Centre for Land and Biological Resources Research and Environment Canada, State of the Environment Directorate, Ecozone Analysis Branch, Ottawa/Hull, Canada. Report and national map at 1:7,500,000 scale

Ecosystem Classification Group (ECG) (2007) Ecological Regions of the Northwest Territories – Taiga Plains. Department of Environment and Natural Resources, Government of the Northwest Territories, Yellowknife, NT, Canada

Fernandes R, Leblanc SG (2005) Parametric (modified least squares) and non-parametric (Theil-sen) linear regressions for predicting biophysical parameters in the presence of measurement errors. Remote Sensing of Environment 95:303-316

Franco-Lopez H, Ek AR, Bauer ME (2001) Estimation and mapping of forest stand density, volume, and cover type using the k-nearest neighbors method. Remote Sensing of Environment 77:251-274

Franklin SE, Hall RJ, Smith L, Gerylo GR (2003) Discrimination of conifer height, age and crown closure classes using Landsat-5 TM imagery in the Canadian Northwest Territories. International Journal of Remote Sensing 24(9):1823-1834

Gerylo GR, Hall RJ, Franklin SE, Smith L (2002) Empirical relations between Landsat TM spectral response and forest stands near Fort Simpson, Northwest Territories, Canada. Canadian Journal of Remote Sensing 28(1):68-79

Goetz SJ, Wright RK, Smith AJ, Zinecker E, Schaub E (2003) IKONOS imagery for resource management: Tree cover, impervious surfaces, and riparian buffer analyses in the mid-Atlantic region. Remote Sensing of Environment 88:196-208

Guindon L, Beaudoin A, Leboeuf A, Ung C, Luther JE, Côté S, Lambert M (2005) Regional mapping of Canadian subarctic forest biomass using a scaling up method combining QuickBird and Landsat imagery. In Proceedings FORESTSAT 2005: Operational Tools in Forestry Using Remote Sensing Techniques, 31 May - 1 June 2005, Borås, Sweden. pp 71-75

Hall RJ, Skakun RS, Arsenault EJ, Case BS (2006) Modeling forest stand structure using Landsat ETM+ data: Application to mapping biomass and stand volume. Forest Ecology and Management 225:378-390

Huang S (1994) Ecologically based individual tree volume estimation for major Alberta tree species. Report 1. Individual tree volume estimation procedures for Alberta: Methods of formulation and statistical foundations. Alberta Environmental Protection, Land and Forest Services, Forest Management Division

Jakubauskas ME, Price KP (1997) Empirical relationships between biotic and spectral factors of Yellowstone lodgepole pine forests. Photogrammetric Engineering and Remote Sensing 63(12):1375-1381

Leboeuf MA, Beaudoin A, Fournier RA, Guindon L, Luther JE, Lambert M A Shadow fraction method for mapping biomass of northern boreal black spruce forests using Quickbird imagery. Remote Sensing of Environment (*in press*)

Olthof I, Butson C, Fernandes R, Fraser R, Latifovic R, Orazietti J (2005) Landsat ETM+ mosaic of northern Canada. Canadian Journal of Remote Sensing 31:412-419

Natural Resources Canada (2006) The state of Canada’s forests 2005-06. Natural Resources Canada, Canadian Forest Service, Ottawa, Ont.

Ripple WJ, Wang S, Isaacson DL, Paine DP (1991) A preliminary comparison of Landsat Thematic Mapper and SPOT-1 HRV multispectral data for estimating coniferous forest volume. International Journal of Remote Sensing 12(9):1971-1977

Sivanpillai R, Smith CT, Srinivasan R, Messina MG, Ben Wu X (2006) Estimation of managed loblolly pine stand age and density with Landsat ETM+ data. Forest Ecology and Management 223:247-254

Smith L (2002) Forest resource inventory and analysis strategic plan. Government of Northwest Territories, Resources, Wildlife and Economic Development, Forest Management Division, Hay River, NWT.

Wulder MA, Niemann KO, Goodenough DG (2000) Local maximum filtering for the extraction of tree locations and basal area from high spatial resolution imagery. Remote Sensing of Environment 73:449-476

Wulder MA, Dechka J, Gillis M, Luther J, Hall RJ, Beaudoin A, Franklin SE (2003) Operational mapping of the land cover of the forested area of Canada with Landsat data: EOSD land cover program. The Forestry Chronicle 79:1075-1083