Remote inventory for a Northern Temperate Forest Integrating Waveform Lidar with Hyperspectral Remote Sensing Imagery

Jeanne E. Anderson, **Mary E. Martin**, **Lucie Plourde**, **Rob Braswell** — *Complex Systems Research Center, University of New Hampshire, Durham, NH 03824*

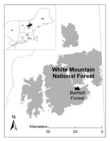
Marie-Louise Smith — *USDA Forest Service, Northeastern Research Station, Durham, NH 03824*

Ralph O. Dubayah, **Michelle A. Hofton** — *Department of Geography, University of Maryland, College Park, MD 20740*

J. Bryan Blair — *NASA, Goddard Space Flight Center, Greenbelt, MD 20771*

INTRODUCTION & DATA

Photo courtesy of Ken Dudzik



Introduction: The combined ability of waveform lidar metrics and hyperspectral data to estimate three common forest metrics (basal area (BA), above-ground biomass (AGBM) & quadratic mean stem diameter (QMSD)) and to discriminate the distribution and abundance patterns of several, common and often dominant tree species in a northern temperate mixed conifer and deciduous forest within the 1000-ha. Bartlett Experimental Forest (BEF) in central New Hampshire (USA) is described.

Lidar Data: Waveform lidar imagery was acquired in July 2003 using NASA's airborne Laser Vegetation Imaging Sensor (LVIS). LVIS is an airborne imaging laser altimeter that records the time and amplitude of a laser pulse reflected off target surfaces. Detail on LVIS capabilities can be found in Blair et al. (1999). LVIS records circular footprints of variable size; 2003 footprints had a nominal radius of 10 m. LVIS metrics used in this study were derived from the waveforms using an automated algorithm. The metrics of maximum canopy height (RH100), Height of Median Energy (HOME or RH50), RH75, and RH25 were calculated by finding the height (relative to the ground elevation) at which 100%, 75%, 50% and 25% respectively of the waveform energy occurs (http://lvis.gsfc.nasa.gov)

Hyperspectral Data: Cloud-free high spectral resolution imagery was acquired in August 2003 using NASA's Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) for a 11 km wide swath centered over BEF. AVIRIS captures upwelling spectral radiance in 224 contiguous spectral bands for wavelengths from 400 to 2500 nm with a 10 nm nominal bandwidth. Detail on AVIRIS capabilities can be found in Green et al. (1998). Nominal pixel size was about 16 m. In order to minimize a view-angle brightness gradient in the AVIRIS image, the mean and standard deviation of each column of raster data was normalized to the overall mean and standard deviation. The image was atmospherically corrected with ImSpec LLC's Atmospheric COrrection Now (ACORN) (v. 4.14) software (http://www.imspec.com) and geometrically corrected with a second order polynomial based on reference points collected from 1992 digital orthophotoquads (DOQ) with 1-m nominal spatial resolution acquired from the New Hampshire Geographically Referenced Analysis and Information Transfer System (NH GRANIT; http://www.granit.sr.unh.edu). The AVIRIS image was transformed with a forward minimum noise fraction transform (MNF) rotation (ENVI © v. 3.6, Research Systems, Inc. 2002) to reduce data dimensionality. Twenty-four bands with eigenvalues above 2.5 were retained for analysis (http://aviris.jpl.nasa.gov)

Forest Service Data: Sensor data were analyzed with field data from over 400 0.1 ha permanent plots from the USDA Forest Service Northeastern Research Station (USFS NERS) 2001-2003 inventory. Measurements tally species and dbh in 1-inch classes for trees greater than 2 inches (ca. 5 cm) in size. BA, QMSD, estimates of total standing AGBM and the relative fraction of biomass attributed to each tree species were calculated for each of over 400 plots. Estimates of aboveground woody biomass (AGBM) were calculated using established allometric equations specific to the northeastern region and inclusive of bole, branch and foliar biomass (Jenkins et al. 2004). Plots were separated into managed versus unmanaged classes by the Forest Service (Leak and Smith 1996).

DATA ANALYSIS, RESULTS and DISCUSSION

Integration: Individual LVIS circular footprints were converted to raster format using an inverse distance weighted algorithm (ArcGIS v. 8.3, ESRI 2003). Pixel size was set at 15.8 m to match the nominal resolution of the AVIRIS data. AVIRIS and LVIS imagery were aligned geometrically to establish coincident pixels. Values from each of the 24 AVIRIS MNF bands and 4 LVIS metrics were extracted and standardized (i.e. subtract the mean and divide by the standard deviation) from the locations of the USFS NERS inventory plots. Each plot (0.1 ha; roughly 30 by 30 m) encompassed portions of four to six pixels. Pixel data were aggregated and summarized as mean values.

	Forest Metric	adj. r^2	Press RMSE	N	Number of AVIRIS MNF 2003 and LVIS 2003 Model Predictors	VIF	Alpha	P
AVIRIS & LVIS	BA	0.47	7.51 $m^2 ha^{-1}$	406	7 AVIRIS MNF and 1 LVIS	< 3	0.05	< 0.0001
	AGBM	0.39	51.10 Mg ha^{-1}	406	7 AVIRIS MNF and 1 LVIS	< 2	0.05	< 0.0001
	QMSD	0.33	2.86 cm	406	8 AVIRIS MNF and 2 LVIS	< 3	0.05	< 0.0001
	BA - (unmanaged)	0.45	7.02 $m^2 ha^{-1}$	158	4 AVIRIS MNF and 1 LVIS	< 2	0.05	< 0.0001
	AGBM - (unmanaged)	0.55	41.03 Mg ha^{-1}	158	2 AVIRIS MNF and 1 LVIS	< 2	0.05	< 0.0001
	QMSD - (unmanaged)	0.32	2.61 cm	158	2 AVIRIS MNF and 1 LVIS	< 2	0.05	< 0.0001
	Forest Metric	**adj. r^2**	**Press RMSE**	**N**	**Number of AVIRIS MNF 2003 Model Predictors**	**VIF**	**Alpha**	**P**
AVIRIS ONLY	BA	0.39	8.08 $m^2 ha^{-1}$	406	11 AVIRIS MNF	< 3	0.05	< 0.0001
	AGBM	0.30	55.27 Mg ha^{-1}	406	13 AVIRIS MNF	< 2	0.05	< 0.0001
	QMSD	0.17	3.18 cm	406	10 AVIRIS MNF	< 2	0.05	< 0.0001
	BA - (unmanaged)	0.40	7.26 $m^2 ha^{-1}$	158	3 AVIRIS MNF	< 2	0.05	< 0.0001
	AGBM - (unmanaged)	0.45	45.27 Mg ha^{-1}	158	4 AVIRIS MNF	< 2	0.05	< 0.0001
	QMSD – (unmanaged)	0.19	2.84 cm	158	3 AVIRIS MNF	< 2	0.05	< 0.0001
	Forest Metric	**adj. r^2**	**Press RMSE**	**N**	**Number of LVIS 2003 Model Predictors**	**VIF**	**Alpha**	**P**
LVIS ONLY	BA	0.16	9.35 $m^2 ha^{-1}$	406	1 LVIS (RH25)	1	0.05	< 0.0001
	AGBM	0.27	55.52 Mg ha^{-1}	406	1 LVIS (RH50)	1	0.05	< 0.0001
	QMSD	0.25	3.00 cm	406	2 LVIS (RH25 and RH75)	< 2	0.05	< 0.0001
	BA- (unmanaged)	0.25	8.05 $m^2 ha^{-1}$	158	1 LVIS (RH50)	1	0.05	< 0.0001
	AGBM - (unmanaged)	0.36	48.75 Mg ha^{-1}	158	1 LVIS (RH50)	1	0.05	< 0.0001
	QMSD – (unmanaged)	0.29	3.00 cm	158	1 LVIS (RH100)	1	0.05	< 0.0001

Table 1 Relationships between 2003 AVIRIS MNF and LVIS metrics and selected measures of forest structure

Data Analysis: The relationships between the measured USFS NERS plot data for AGBM, QMSD, & BA and the mean values of 28 standardized LVIS and AVIRIS MNF metrics were explored through stepwise mixed linear regression techniques. Analyses conducted using only LVIS metrics were explored through simple linear regression or two-term multiple regressions, limited to the use of three pairs of less correlated LVIS metrics (RH25 & RH75; RH25 & RH100; and RH50 & RH100) as the independent variables (Table 1).

USFS NERS field measures of fractional AGBM (transformed as an arcsine square root value) specific to several tree species were also compared to the mean values of standardized 2003 AVIRIS MNF variables and LVIS metrics through stepwise mixed multiple regression (Figure 1). Relationships were explored between ground measures and sensor data only in those plots where the given species being modeled was present (AGBM fraction > 0 or 0.01). In addition, species-specific relationships between USFS NERS field measures of QMSD and the mean values of LVIS metrics were explored in only those plots where a given species was present at higher levels of abundance (EH > 0.3; RM > 0.33; SM > 0.1) and in the case of the maples, situated in relatively unmanaged conditions (Figure 1).

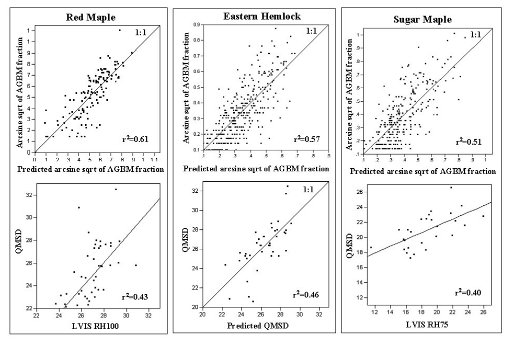


Figure 1. Scatter plots of predicted abundance patterns and QMSD relationships for selected species.

Results and Discussion: Results here suggest that the integrated data sets of hyperspectral and waveform lidar do improve the outcomes in evaluating BA, AGBM and QMSD for a given site over use of either data set alone (Table 1). Improvements of 8-9% across all forest conditions were seen in the coefficients of determination for measures of AGBM, BA, and QMSD through the use of the integrated data. Estimates of error dropped by 5-8% for the same measures.

The stratification of data based on broad patterns of management history (recently managed versus unmanaged conditions) was used as a tool to sharpen the predictive relationships explored through these regression analyses. Notably, AGBM coefficients of determination improved by 25% or more, while corresponding error levels decreased by over 25%, using integrated data sets stratified to reflect an absence of recent forest management when compared to results obtained using data from a single sensor (AVIRIS or LVIS) applied across all forest conditions.

The recognized ability of AVIRIS to predict levels of species-specific abundance was evident even in the mixed conditions of this forest for several of the dominant trees species. Of the three northern hardwoods species shown here, only red maple benefited appreciably from the integration of LVIS metrics into the analyses. The strength of AVIRIS data was apparent in this regard, explaining nearly all of the variance for the other two species and most of the variance in the red maple relationship.

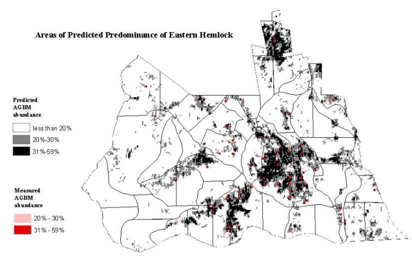


Figure 2. This model predicting areas of eastern hemlock predominance (AGBM fraction > 0.2) for BEF is derived from mixed stepwise regression of 25 standardized 2003 LVIS and 2003 AVIRIS MNF metrics that generated the following statistics: adj. r^2 = 0.57; Press RMSE = 0.12; p < .0001; N=337 for points where hemlock AGBM > 0, using 8 AVIRIS variables as predictors. An overlay of USFS NERS plot data indicating hemlock abundance measured in 2001-2003 is also presented.

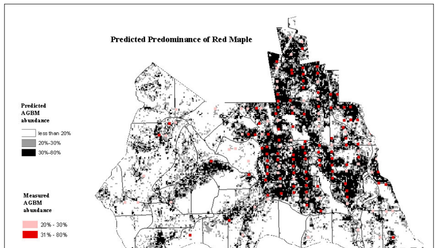


Figure 3: This model of predicted areas of red maple predominance in BEF is derived from the mixed stepwise regression of 24 2003 LVIS and 2003 AVIRIS MNF metrics and generated the following statistics: adj. r^2 = 0.61; Press RMSE = 0.13; p < .0001; N=138 for points where red maple AGBM > 0.01 in relatively unmanaged conditions, using 5 AVIRIS variables and 1 LVIS metric as predictors. An overlay of USFS NERS plot data indicating red maple abundance measured in 2001-2003 is also presented.

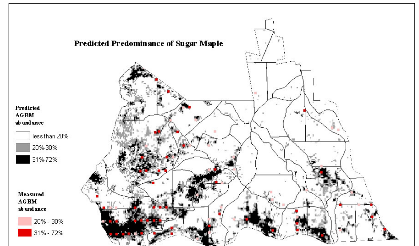


Figure 4: This model predicting areas of sugar maple predominance in BEF is derived from the mixed stepwise regression of 26 2003 LVIS and 2003 AVIRIS MNF metrics and generated the following statistics: adj. r^2 = 0.51; Press RMSE = 0.14; p < .0001; N = 256 for points where sugar maple AGBM > 0.01, using 10 AVIRIS variables and 1 LVIS metric as predictors. An overlay of USFS NERS plot data indicating sugar maple abundance measured in 2001-2003 is also presented.

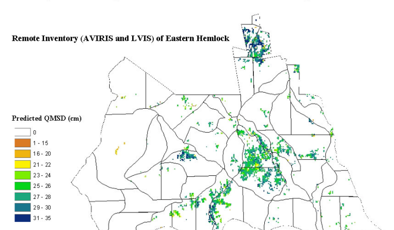


Figure 5. Two prediction models are combined in this map. Levels of predicted quadratic mean stem diameter (QMSD; cm) are shown within regions of the BEF that are predicted to encompass more than 30% Eastern Hemlock AGBM. The model predicting eastern hemlock abundance generated the following parameters: adj. r^2 = 0.57; Press RMSE = 0.12; p < 0.0001; N=337 for points where Eastern Hemlock AGBM > 0, using 8 AVIRIS variables as predictors. The model predicting QMSD (stems > 10 cm) generated the following parameters: adj. r^2 = 0.46; Press RMSE = 1.93 cm; p < .0001; N= 38 for points where Eastern Hemlock AGBM fraction > 0.30, using 2 LVIS metric as predictors.

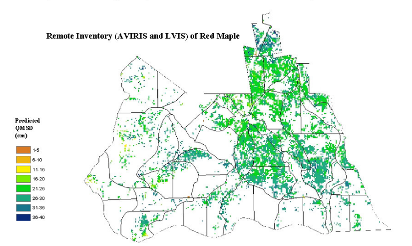


Figure 6: Two prediction models are combined in this map. Levels of predicted quadratic mean stem diameter (QMSD; cm) are shown within regions of BEF that are predicted to encompass more than 30% red maple AGBM. The model predicting red maple abundance generated the following parameters: adj. r^2 = 0.61; Press RMSE = 0.13; p < 0.0001; N=138 for points where red maple AGBM > 0.01 in relatively unmanaged conditions, using 5 AVIRIS variables and 1 LVIS metric as predictors. The model predicting QMSD (stems > 10 cm) generated the following parameters: adj. r^2 = 0.43; Press RMSE = 2.22 cm; p < .0004; N= 55 for points where red maple AGBM fraction > 0.33, using 1 LVIS metric as a predictor.

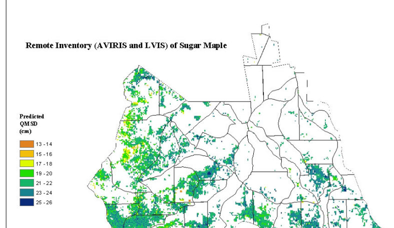


Figure 7: Two prediction models are combined in this map. Levels of predicted quadratic mean stem diameter (QMSD; cm) are shown within regions of BEF that are predicted to encompass more than 20% sugar maple AGBM. The model predicting suagr maple abundance generated the following parameters: adj. r^2 = 0.51; Press RMSE = 0.14; p < 0.0001; N=256 for points where sugar maple AGBM > 0.01, using 10 AVIRIS variables and 1 LVIS metric as predictors. The model predicting QMSD (stems > 5 cm) generated the following parameters: adj. r^2 = 0.40; Press RMSE = 1.85 cm; p < .0004; N= 27 for points where sugar maple AGBM fraction > 0.1, using 1 LVIS metric as a predictor.

CONCLUSIONS

The integration of waveform lidar with hyperspectral data did clearly enhance the ability to remotely describe a number of common measures of forest structure This level of improvement doesn't hold, however, for detection of the proportional composition patterns created by the common and dominant tree species of this northern forest. It is plausible that the predictive nature of these relationships could be improved further with the use of waveform lidar amplitude metrics such as ground energy and canopy energy (and the resultant relative measure of canopy closure derived from them) that were not employed in this study.

Nonetheless, results of value to traditional forest inventory efforts can be obtained in these northern forest tracts through separate analyses, as well as combined use of the two data sets (Figures 2 –7). AVIRIS data allowed species-specific patterns of abundance to be predicted that could be ultimately linked to other measures of forest structure better predicted through LVIS metrics (e.g. height, QMSD) or through the use of integrated LVIS and AVIRIS data (e.g. AGBM, BA).

Use of hyperspectral and waveform lidar data, in tandem, to create maps that explore landscape patterns that identify remnant areas of structural complexity and their attendant biodiversity in these northern forests are ultimately quite valuable. The ability to model such spatial patterns on a landscape scale could also be a more sensitive means of monitoring changes seen in the dynamics of individual species populations brought on by global warming and other environmental change over time.

REFERENCES and ACKNOWLEDGEMENTS

Lidar data sets were acquired through the Laser Vegetation Imaging Sensor (LVIS) team in the Laser Remote Sensing Branch at NASA Goddard Space Flight Center with support from the University of Maryland, College Park. Funding for the collection and processing of the 2003 Northeastern USA data was provided by NASA's Terrestrial Ecology Program (NASA Grant # NAG512112). Acquisition and processing of the AVIRIS imagery was made also possible by support from the NASA Terrestrial Ecology Program and the assistance of the Jet Propulsion Laboratory's AVIRIS Science and Instrument Teams. The first author received support from a NASA Space Grant to the University of New Hampshire, a Switzer Environmental Fellowship, and an Earth System Science Fellowship (NASA NGT5-ESSF/03-0000-0026). Portions of this research are based upon data generated in long-term research studies on the Bartlett Experimental Forest, funded by the U.S. Department of Agriculture, Forest Service, Northeastern Research Station

Blair, J.B., D.L. Rabine, and M.A. Hofton. 1999. The Laser Vegetation Imaging Sensor: a medium-altitude, digitization-only, airborne laser altimeter for mapping vegetation and topography. ISPRS Journal of Photogrammetry and Remote Sensing 54:115-122.

Green, R.O., Eastwood, M.L., Sarture, C.M., Chrien, T.G., Aronsson, M., Chippendale, B.J., Faust, J.A., Pavri, B.E., Chovit, C.J., Solis, M. 1998. Imaging Spectrometry and the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS). Remote Sensing of Environment. 65:227-248.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S., and Birdsey, R.A. 2004. Comprehensive database of diameter-based biomass regressions for North American tree species. Gen.Tech. Rep. NE-319. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 45 p. [1 CD-ROM].

Leak, W.B. and M.L. Smith. 1996. Sixty years of management and natural disturbance in a New England forested landscape. Forest Ecology and Management 81:63-73.