Lidar Remote Sensing of Aboveground Biomass in Three Biomes

M.A. Lefsky
Oregon State University
Forest Sciences Laboratory
3200 SW Jefferson Way
Corvallis, OR, 97331
lefsky@fsl.orst.edu

Warren B. Cohen
USDA Forest Service, Forest Sciences Laboratory
3200 SW Jefferson Way, Corvallis, OR, 97331

David J. Harding
Goddard Space Flight Center, Geodynamics Branch
Mail Code 921, Greenbelt, MD 20771

Geoffery G. Parker
Smithsonian Environmental Research Center
P.O. Box 28, Edgwater, MD 21037

Steven A. Acker
National Park Service
909 First Avenue, Seattle, WA, 98104

S. Thomas Gower
Department of Forest Ecology and Management
University of Wisconsin, Madison, WI, 53706

Commission III, Working Group 3

KEY WORDS: Laser altimetry, lidar, forest, biomass

ABSTRACT

Estimation of the amount of carbon stored in forests is a key challenge for understanding the global carbon cycle, one which remote sensing is expected to help address. However, direct estimation of carbon storage in moderate to high biomass forests is difficult for conventional optical and radar sensors. Lidar (light detection and ranging) instruments measure the vertical structure of forests and thus hold great promise for remotely sensing the quantity and spatial organization of forest biomass. In this study, we compare the relationships between lidar-measured canopy structure and coincident field measurements of aboveground biomass at sites in the temperate deciduous, temperate coniferous, and boreal coniferous biomes. A single "simplified" regression for all three sites is compared with equations derived for each site individually. The simplified equation explains 84% of variance in aboveground biomass ($p<0.0001$) and shows no statistically significant bias in its predictions for any individual site.

INTRODUCTION

Accurate estimates of terrestrial carbon storage over large areas are required to determine its role in the global carbon cycle, estimate the degree that anthropogenic disturbance (i.e., land use / land cover change) is changing that cycle, and for monitoring mitigation efforts that rely on carbon sequestration through reforestation. Remote sensing has been a key technology involved in existing efforts to monitor carbon storage and fluxes (Cohen et al. 1996, Running et al. 1999), and has been identified as a likely tool for monitoring carbon related treaties such as the Kyoto protocol (Ahern et al. 1998).

Nevertheless, direct estimation of carbon storage in moderate to high biomass forests remains a major challenge for remote sensing. While remote sensing has had considerable success in measuring the biophysical characteristics of vegetation in areas where plant canopy cover is relatively sparse, quantification of vegetation structure where leaf area index (LAI) exceeds three has been less successful (Carlson and Ripley 1997, Turner et al. 1999, Waring et al. 1995). High LAI forests, which generally have high aboveground biomass, occur in the boreal, temperate and tropical regions. These forests cover less than 35 % of the Earth's terrestrial surface, yet account for 67 % of terrestrial NPP, and 89 % of terrestrial biomass (Waring and Schlesinger 1985). Given their prominent role in global biogeochemistry, and the likelihood that these high productivity areas will be prime areas for carbon sequestration efforts, better characterization of high biomass forests using remotely sensed data is desirable. One promising technique is lidar.

	Number of Plots	Mean	Minimum	Maximum
Canopy Cover (m^2m^{-2})				
Temperate Deciduous	112	0.853	0.607	0.938
Temperate Coniferous	21	0.696	0.285	0.876
Boreal Coniferous	16	0.312	0.168	0.472
Mean Canopy Height (m)				
Temperate Deciduous		28.6	9.7	39.5
Temperate Coniferous		35.6	15.3	53.2
Boreal Coniferous		7.3	2.2	11.0
Aboveground Biomass ($Mgha^{-1}$)				
Temperate Deciduous		312.5	11.4	716.3
Temperate Coniferous		602.0	135.6	1329.0
Boreal Coniferous		29.9	0.0	58.5

Table 1. Plot Characteristics

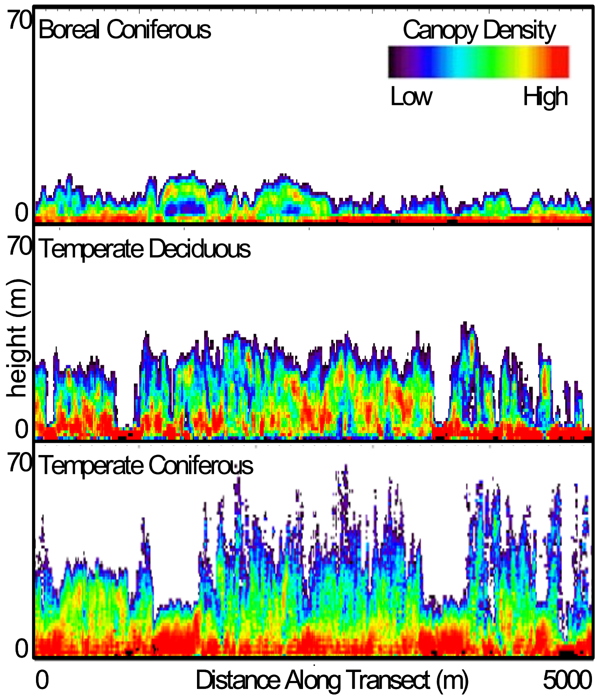

Figure 1. Measurements of canopy structure made using NASA's SLICER (Scanning Lidar Imager of Canopies by Echo Recovery) remote sensing device. SLICER operates by measuring the vertical distribution of energy returned to the sensor when a short-duration pulse of laser light is reflected off the forest canopy. Data are then transformed to correct for the occlusion of far surfaces by those closer to the instrument to create an estimate of canopy density (yellow and red indicate high canopy density, blue and black indicate low canopy density) . Top panel shows data from a boreal coniferous sites in northern Manitoba, with simple canopy structure and maximum heights of 18 m. Middle panel shows data from a temperate deciduous forest near Annapolis, MD., with regenerating gaps and complex canopy structure. Bottom panel shows data from a temperate coniferous forest on the western slope of the Cascades in Oregon, and shows both younger (shorter) stands with simple canopy structure, and an old-growth forest (middle third of panel) with extremely complex canopy structure and especially high diversity of canopy heights.

Lidar instruments directly measure the vertical structure of forests by estimating the distance between the sensor and a target through the precise measurement of the time between the emission of a pulse of laser light from the sensor and the time of detection of light reflected from the target. Waveform-sampling lidar systems, such as the SLICER device used in this work (Blair et al. 1994, Harding et al. 1994, Harding et al. 2001) and the VCL satellite (Dubayah et al. 1997) now scheduled for launch in 2003, employ multiple measurements of both distance to and amount of energy reflected from the many surfaces of a geometrically complex target. When this distribution of return energy, the lidar waveform, is measured over a vegetation canopy, it records the vertical distribution of light reflected back to the sensor from vegetation and soil surfaces from the top of the canopy to the ground. For forests, relating these waveforms to conventional, primarily non-spatial, measurements of forest structure, such as aboveground biomass and stand basal area, has been a primary research goal (Drake et al. 2001, Lefsky et al. 1999a, Lefsky et al. 1999b, Means et al. 1999). In this study, we compare the relationships between lidar-measured canopy structure and coincident field measurements of aboveground biomass at sites in the temperate deciduous, temperate coniferous, and boreal coniferous biomes. A single equation derived from regression analysis using data from all three sites is compared with equations derived for each site individually. The goal of the work is a simplified method to estimate aboveground biomass at all three sites. The existence of such a method could reduce the amount of fieldwork, with attendant effort and expense, required to develop global biomass estimates from satellite lidar data. We focus on the estimation of aboveground biomass because it is closely related to aboveground carbon storage, and allometric equations for its estimation are readily available. While belowground carbon pools are often as large or larger than aboveground storage, no existing remote sensing system can estimate their magnitude directly.

METHODS

Coincident field plots and lidar data were collected in three distinct sites in the boreal coniferous (Northern BOREAS study area), temperate coniferous (H.J. Andrews Experimental Forest) and temperate deciduous (Smithsonian Environmental Research Center) biomes. Estimates of aboveground biomass were calculated using established allometric equations using stem data collected using fixed or nested plot designs. Estimates of canopy height, canopy cover and a variety of canopy density weighted heights were calculated from the lidar data.

	Boreal Coniferous	Temperate Deciduous	Temperate Coniferous	ALL
Canopy Cover (%)	0.837	0.112 n.s.	0.633 †	0.372
Maximum Height (m)	0.665 †	0.765	0.909	0.885
Mean Canopy Height (m)	0.743 ††	0.792	0.92	0.868
Mean Canopy Height Squared (m)	0.701 †	0.79	0.929	0.914
Mean Canopy Profile Height (m)	0.781 †	0.746	0.774	0.812
Quadratic Mean Canopy Profile Height (m)	0.741 ††	0.804	0.825	0.841
Cover x Maximum Height (m)	0.853	0.744	0.921	0.839
Cover x Mean Canopy Height (m)	0.872	0.509	0.923	0.662
Cover x Mean Canopy Profile Height (m)	0.877	0.716	0.810	0.761
Cover x Quadratic Canopy Profile Height (m)	0.874	0.773	0.854	0.785

Unless otherwise noted, all relationships are significant at $P<0.0001$
† Denotes $P<0.01$
†† Denotes $P<0.001$

Table 2. Correlation coefficients (r) between height indices and aboveground biomass.

Study Areas

Field data for the temperate coniferous plots were collected in and near the H.J. Andrews Experimental Forest, located on the west slope of the Cascade Range in Oregon (Van Cleve and Martin 1991). Douglas-fir (*Pseudotsuga menziesii*) is the dominant species in these stands, contributing 90 % of all basal area in young stands, and 64 % in old-growth stands. Western hemlock (*Tsuga heterophylla*) in the second most important species, and occurs mostly in later succession, contributing 29 % of total basal area in old-growth stands (Lefsky et al. 1999a). Data from temperate deciduous plots were collected in and near the Smithsonian Environmental Research Center, located on the western shore of Chesapeake Bay, near Annapolis, MD. They are mixed deciduous forest with an overstory dominated by *Liriodendron tulipifera* (Lefsky et al. 1999b). Plots for the boreal coniferous type were collected at the Northern Old Black Spruce (NOBS) study area established as part of NASA's BOREAS study; plot data was collected as part of the BigFoot study (Cohen and Justice 1999). Major cover types at the site include muskeg, black spruce (*Picea mariana*) forest, and wetlands; infrequent patches of jack pine (*Pinus banksiana*) and aspen (*Populus tremuloides*) also occur.

Field Data Collection

Existing publications describe the field data collections for the boreal coniferous (Campbell et al. 1999), temperate deciduous (Lefsky et al. 1999b) and temperate coniferous stands (Lefsky et al. 1999a). Generally, fixed or nested plots were used to tally stems, and appropriate allometric equations were used to predict aboveground biomass. At the boreal coniferous site, the 25 x 25 m field plots put in as part of the BigFoot (Cohen and Justice 1999) study were used as a source of field data. The location of existing SLICER waveforms were compared to the locations of 107 field plot and any plot with more that 5 waveforms within its boundaries was considered as part of this analysis, a total of 16 plots.

SLICER Data Collection and Processing

SLICER data were collected at the temperate coniferous, boreal coniferous and temperate deciduous sites in September 1995, July 1996, and September 1997, respectively. To estimate canopy height profiles (CHPs, the vertical distribution of foliage and woody surfaces) from the raw SLICER waveforms, we adapted (Harding et al. 2001) the transformation method developed by MacArthur and Horn (MacArthur and Horn 1969). The resulting CHPs serve as a common measurement of forest canopy structure at the three sites. One key factor in the CHP algorithm is a coefficient calculated as the ratio of the average reflectance (at 0° phase angle) of the ground and canopy at the laser wavelength. For the temperate deciduous and temperate coniferous sites, the ratio of ground and canopy reflectance is assumed to be 2.0. Use of this assumption has been supported by fieldwork comparing lidar estimates and field measurements of canopy cover at these sites (Lefsky 1997, Means et al. 1999). At the boreal coniferous site, the existence of a high ground-level cover of herbaceous and fern species and a small dataset of coincident lidar and field measurements of cover imply that this ratio should be close to 1.0, the value used in calculations for this site.

Canopy structure indices used in this study were calculated from CHPs (Lefsky et al. 1999a). Measurements of mean canopy height are not available from the field measurements of canopy structure made at some of the temperate deciduous plots; a regression between quadratic mean canopy height and mean canopy surface height was developed using the another set of plots at the same site, and applied to these plots to predict mean canopy height.

RESULTS

Plot Characteristics

Mean canopy height at the sites follows the expected order, with boreal coniferous having the shortest maximum and mean heights, temperate coniferous having the tallest, with the temperate deciduous site in the middle (Table 1). Values for canopy cover for the temperate deciduous site occupy a narrower range than either of the coniferous sites due to the high cover associated with even the youngest of these sites, and the absence of significant disturbance. Mean, minimum and maximum cover are lowest in the boreal coniferous plots, as a consequence of the low productivity of this site, and the juxtaposition of closed forest and open forest / muskeg conditions. Site maxima for aboveground biomass range from 58.5 Mg ha^{-1} for the boreal coniferous plots to 1329.0 Mg ha^{-1} for the temperate coniferous forest; again the temperate deciduous plots occupy an intermediate position. Figure 1 illustrates characteristic transects of lidar measured canopy structure at each study site.

Correlation of Canopy Structure Indices and Aboveground Biomass

Nearly all the canopy structure indices were significantly correlated with aboveground biomass (Table 2), with the exception of canopy cover for temperate deciduous plots. This is likely due to the narrow range of canopy cover conditions observed in those plots. Otherwise, there were few patterns in the correlations that were consistent between all three biomes. For the boreal coniferous site, the product of cover and several of the height indices performed better than the height indices alone. At the temperate deciduous site, the reverse was true, again probably due to the low range of canopy cover, and the resulting non-significant correlation between cover and biomass. At the temperate coniferous site, no clear difference between the two sets of indices is clear. When all sites are considered together, mean height squared is the best overall predictor of aboveground biomass.

Regression Analysis

The correlation analysis identified the mean height squared as the variable with the highest correlation with aboveground biomass for all sites considered together. Analysis of the residuals of the resulting equation

$$AB = 0.378*MCH2, \quad (r^2=84\%, P<0.0001)$$

where:

AB is aboveground biomass (Mgha-1), and

MCH^2 is mean canopy height (m) squared.

Analysis of the residuals resulting from the equation indicates that product of Mean Canopy Height and Cover had the highest correlation (r=0.18) with those residuals, and this variable was added to the equation, resulting in

$$AB= 0.342* MCH^2 + 2.086*COVCHPX,$$

$$(R^2=0.84, P<0.0001)$$

where:

COVCHPX is the product of mean cover and mean canopy height.

Although the addition of the COVCHPX variable does not improve the overall fit of the model, it does improve the residuals associated with the boreal sites, and so it was left in. Regressions between the predicted values from this equation and the observed aboveground biomass were calculated separately for each site, and tested to see if the resulting regression lines were significantly different from an identify line (Figure 2). In all three cases, neither the slope nor intercepts were significant different (Table 3). Stepwise multiple regression was also performed for each site individually, and the resulting R^2 are presented in Table 3. Only in the case of the boreal coniferous site did the general equation predict considerably less of the overall variance than did the individual site equation.

DISCUSSION

The results of this study indicate that a single equation can be used to relate remotely sensed canopy structure to aboveground biomass in three distinctly different forested communities. Clearly, this result must be considered preliminary. Tropical systems are not discussed at all, and ultimately it would be necessary to have replicated studies from each climatic and physiognomic zone before the implied hypothesis-- that this result is applicable to forested ecosystems generally—could be accepted. The primary value of this work, in our opinion, is that it indicates that research into that hypothesis is reasonable. Forests of the type describe in this paper cover 16% of the global land surface, and 50% of the forested land surface. If the relationship between forest canopy structure and the aboveground biomass contained within are as consistent as suggested in this study, then the estimation of global forest carbon storage, and the monitoring of its change in time, may be greatly simplified. Adoption of a modeling approach would further improve the confidence associated with a simplified relationship. Simple models, starting with the known allometric properties of plants, and incorporating competition for light and space, have already demonstrated that they can reproduce emergent community level relationships (Enquist and Niklas 2001). Such an approach should be adaptable to this problem, and could provide the necessary confidence to interpret the global dataset anticipated from the Vegetation Canopy Lidar mission, with a minimum of additional fieldwork.

	Intercept (b_0)	Slope (b_1)	$P(b_0 \neq 0)$	$P(b_1 \neq 1)$	Simplified Equation R^2	Individual Site Equation R^2
Boreal Coniferous	10.11	0.75	0.09	0.19	56%	76%
Temperate Deciduous	11.10	0.93	0.62	0.29	65%	65%
Temperate Coniferous	61.55	0.98	0.30	0.81	87%	87%
All	-3.34	1.01	0.81	0.84		

Table 3. Slope and intercepts of general biomass equation applied to each site individually, Observed=B_0+ (B_1 x Predicted)

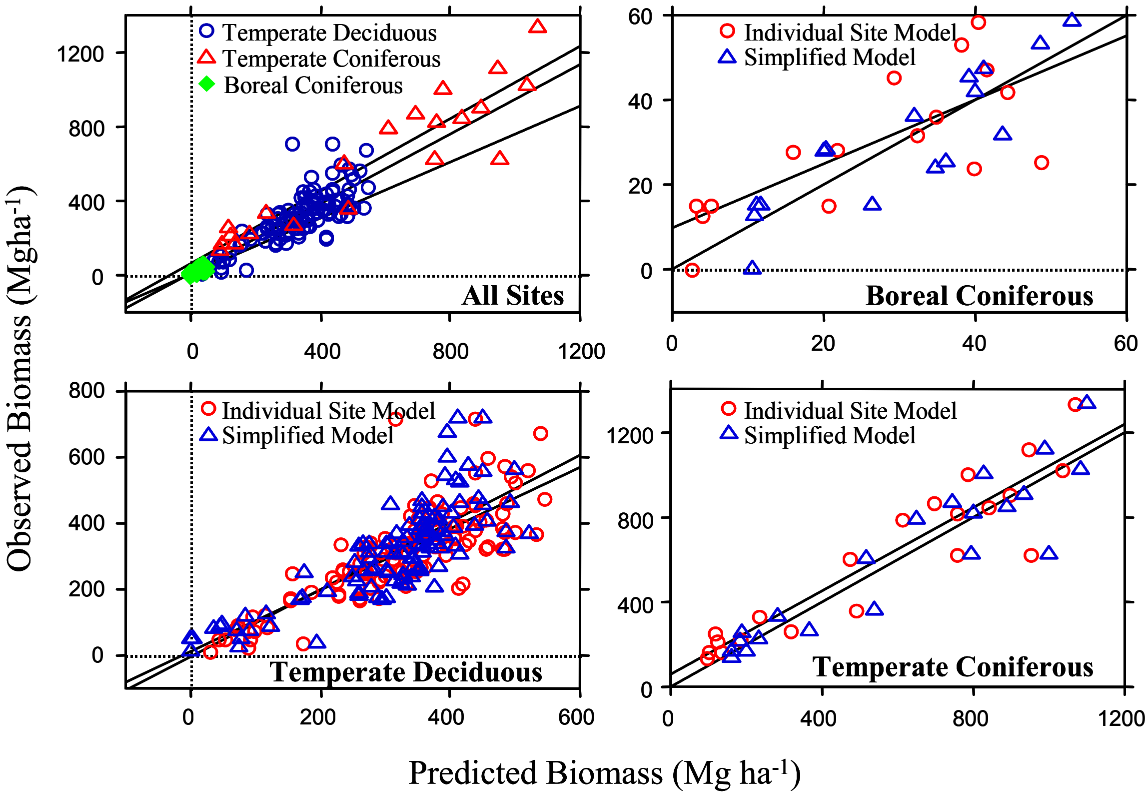

Figure 2. Comparison of predicted and observed aboveground biomass from simplified and individual equations for all sites (upper-left), and each site separately.

REFERENCES

Ahern, F. J., A. C. Janetos, and E. Langham. 1998. Global Observation of Forest Cover: one component of CEOS' Integrated Global Observing Strategy. Pages 1-5. *27th International Symposium on Remote Sensing of Environment*, Tromsø, Norway.

Blair, J. B., D. B. Coyle, J. L. Bufton, and D. J. Harding. 1994. Optimization of an airborne laser altimeter for remote sensing of vegetation and tree canopies. *Proceedings of IGARSS'94*.

Campbell, J., S. Burrows, S. Gower, and C. WB. 1999. Bigfoot: Characterizing land cover, LAI, and NPP at the Landscape Scale for EOS/MODIS Validation. Field Manual 2.1. Oak Ridge National Laboratory, Environmental Science Division.

Carlson, T. N., and D. A. Ripley. 1997. On the relation between NDVI, fractional vegetation cover, and leaf area index. *Remote Sensing of Environment* 62: 241-252.

Cohen, W. B., M. E. Harmon, D. O. Wallin, and M. Fiorella. 1996. Two decades of carbon flux from forests of the Pacific Northwest. *Bioscience* 46: 836-844.

Cohen, W. B., and C. O. Justice. 1999. Validating MODIS terrestrial ecology products: linking in situ and satellite measurements. *Remote Sensing of Environment* 70: 1-3.

Drake, J., R. Dubayah, D. Clark, R. Knox, J. Blair, M. Hofton, R. Chazdon, J. Weishample, and S. Prince. 2001. Estimation of tropical forest structural characteristics using large-footprint lidar. *Remote Sensing of Environment* In Press.

Dubayah, R., J. B. Blair, J. L. Bufton, D. B. Clark, J. JaJa, R. Knox, S. B. Luthcke, S. Prince, and J. Weishample. 1997. The Vegetation Canopy Lidar Mission. Pages 100-112. *Land Satellite Information in the Next Decade II: Sources and Applications*. ASPRS, Washington D.C.

Enquist, B., and K. J. Niklas. 2001. Invariant scale relations across tree-dominated comunities. *Nature* 410: 655-660.

Harding, D. J., J. B. Blair, J. G. Garvin, and W. T. Lawrence. 1994. Laser altimeter waveform measurement of vegetation canopy structure. *Proceedings of IGARSS'94*.

Harding, D. J., M. A. Lefsky, G. G. Parker, and J. B. Blair. 2001. Lidar Altimeter Canopy Height Profiles: Methods and Validation for Closed Canopy, Broaldeaf Forests. *RSE* 76: 283-297.

Lefsky, M. A. 1997. Application of lidar remote sensing to the estimation of forest canopy and stand structure. *Department of Environmental Science,*. University of Virginia, Charlottesville, Virginia.

Lefsky, M. A., W. B. Cohen, S. A. Acker, G. G. Parker, T. A. Spies, and D. Harding. 1999a. Lidar remote sensing of the canopy structure and biophysical properties of Douglas-fir western hemlock forests. *Remote Sensing of Environment* 70: 339-361.

Lefsky, M. A., D. Harding, W. B. Cohen, G. Parker, and H. H. Shugart. 1999b. Surface lidar remote sensing of basal area and biomass in deciduous forests of eastern Maryland, USA. *Remote Sensing of Environment* 67: 83-98.

MacArthur, R. H., and H. S. Horn. 1969. Foliage profile by vertical measurements. *Ecology* 50: 802-804.

Means, J. E., S. A. Acker, D. A. Harding, B. J. Blair, M. A. Lefsky, W. B. Cohen, M. Harmon, and W. A. McKee. 1999. Use of large-footprint scanning airborne lidar to estimate forest stand characteristics in the western Cascades of Oregon. *Remote Sensing of Environment* 67: 298-308.

Running, S. W., D. D. Baldocchi, D. P. Turner, S. T. Gower, P. S. Bakwin, and K. A. Hibbard. 1999. A global terrestrial monitoring network integrating tower fluxes, flask sampling, ecosystem modeling and EOS data. *Remote Sensing of Environment* 70: 108-127.

Turner, D., W. Cohen, R. Kennedy, K. Fassnacht, and J. Briggs. 1999. Relationship between leaf area index and Landsat TM spectral vegetation indices across three temperate zone sites. *Remote Sensing of Environment* 70: 52-68.

Van Cleve, K., and S. Martin. 1991. Long-term ecological research in the United States. Long-Term Ecological Research Network Office.

Waring, R. H., and W. H. Schlesinger. 1985. *Forest Ecosystems: Concepts and Management*. Academic Press, Orlando, Florida.

Waring, R. H., J. Way, E. R. Hunt, L. Morrissey, K. J. Ranson, J. F. Weishampel, R. Oren, and S. E. Franklin. 1995. Imaging radar for ecosystem studies. *BioScience* 45: 715-723.