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Chapter 4

LIDAR REMOTE SENSING FOR FOREST CANOPY STUDIES

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ABSTRACT

Remote sensing has facilitated extraordinary advances in modeling, mapping, and the understanding of ecosystems. Applications of remote sensing involve either images from passive optical systems, such as Aerial Photography and the Landsat Thematic Mapper, or, active Radar sensors such as RADARSAT. These types of remote sensors have proven to be satisfactory for many forest applications, such as mapping and classifying land cover into specific classes and, in some biomes, estimating aboveground biomass and Leaf Area Index (LAI). However, conventional sensors have significant limitations for ecological and forest applications. The sensitivity and accuracy of these devices have repeatedly been shown to fall with increasing aboveground biomass and LAI. They are also limited in their ability to represent the spatial patterns. They produce only two-dimensional (x and y) images, which cannot fully represent the three dimensional structure of the forest canopy. Ecologists have long understood that the presence of specific organisms and the overall richness of wildlife communities can be highly dependent on the three-dimensional spatial pattern of vegetation. Individual bird species, in particular, are often associated with specific three dimensional features in riparian forests. Additionally, aspects of forests, such as productivity, may be related to forest canopy structure.

Lidar (light detecting and ranging) is an alternative remote sensing technology that promises to both increase the accuracy of biophysical measurements and extend spatial analysis into the third dimension (z). Multi-return lidar sensors directly measure the

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three-dimensional distribution of forest canopies as well as sub-canopy topography, and therefore providing high resolution topographic maps and highly accurate estimates of tree height, cover, and canopy structure. In addition, lidar has been shown to accurately estimate LAI and aboveground biomass, even in those high biomass ecosystems, where passive optical and active radar sensors typically fail to do so. Estimation of forest structural attributes, such as LAI, is an important step in identifying the amount of water use in forest areas.

INTRODUCTION

Forests are often described in terms of their composition and structure. While composition typically refers to the presence and abundance of (floristic) species, structure is more broadly defined as "the physical arrangement and characteristics of the forest" Ecological function is an expression of and is affected by canopy vertical structure. Knowledge of canopy vertical structure is particularly important in assessing the potential value of forest resources for the production of public (water quality/quantity, recreation, fisheries and wildlife habitat, carbon sequestration) and private (wood, fiber, timber forest products) goods. Basic forest inventory procedures measure only a subset of the total composition and structure in a given area, as one might, for example, tally only trees of a certain species, of those that are larger than some threshold breast-height diameter. The resulting descriptors of forest composition and structure are essentially those that are (1) useful to forest managers and (2) relatively easy to obtain using basic field skills and tools.

For more demanding investigations and analyses, however, canopy vertical structure is typically measured using some combination of in situ and remotely sensed data. Remotely sensed data sources include digital photogrammetry, large footprint lidar sensors (Means et al. 1999), interferometric SAR, and small footprint lidar (Farid et al. 2008). Of these possibilities only digital photogrammetry and small footprint lidar data are both (i) widely available commercially, and (ii) suitable for structural analyses at the scale of management - stand or sub stand unit - on which silvicultural prescriptions (establishment, fertilization, thinning, release, and harvest) are made. Of these two data sources, small-footprint lidar data has become the most common.

LIDAR SENSORS

The basic measurement made by a lidar instrument is the distance between the sensor and a target surface, obtained by determining the elapsed time between the emission of a laser pulse and the arrival of the reflection of that pulse (the return signal) at the sensor's receiver. Multiplying this time interval by the speed of light results in a measurement of the round-trip distance traveled and dividing that figure by two, yields the distance between the sensor and the target (Bachman 1979). When the vertical distance between a sensor contained in a level-flying aircraft and the Earth's surface is repeatedly measured along transect the result is an outline of both the ground surface and any vegetation obscuring it. Even in areas with high vegetation cover, where most measurements will be returned from plant canopies, some measurements will be returned from the underlying ground surface, resulting in a highly accurate map of canopy height.

Key differences among lidar sensors are related to the laser's wavelength, power, pulse duration and repetition rate, beam size and divergence angle, the specifics of the scanning mechanism, and the information recorded for each reflected pulse. Lasers for terrestrial applications (topography and forest) generally have wavelengths in the range of 900 – 1,064 nanometers (nm), where vegetation reflectance is high. One disadvantage of working in this range of wavelengths is absorption by clouds, which impedes the use of lidar devices during overcast conditions. Bathymetric lidar systems (used to measure elevations under shallow water bodies) make use of wavelengths near 532 nm for better penetration of water.

The power of the laser and size of the receiver aperture determine the maximum flying height, which limits the width of the swath that can be collected in one pass (Wehr and Lohr 1999). The intensity or power of the return signal depends on several factors: the total power of the transmitted pulse, the fraction of the laser pulse that is intercepted by a surface, the reflectance of the intercepted surface at the laser's wavelength, and the fraction of reflected illumination that travels in the direction of the sensor.

The laser pulse returned after intercepting a vegetation canopy will be a complex combination of energy returned from surfaces at numerous distances, the distant surfaces represented later in the reflected signal. The type of information collected from this return signal distinguishes two broad categories of sensors. *Discrete-return or small-footprint* lidar devices measure either one (single return systems) or a small number (multiple return systems) of heights by identifying, in the return signal, major peaks that represent discrete objects in the path of the laser illumination. The distance corresponding to the time elapsed before the leading edge of the peak(s), and sometimes the power of each peak, are typical values recorded by this type of system (Wehr and Lohr 1999). *Waveform-recording or large-footprint* devices record the time-varying intensity of the returned energy from each laser pulse, providing a record of the height distribution of the surfaces illuminated by the laser pulse (Harding et al. 1994, 2001, Dubayah et al. 2000). The small-footprint systems identify, while receiving the return signal, the retention times and heights of major peaks; the large-footprint systems capture the entire signal trace for later processing. Conceptual differences between the two major categories of lidar sensors are illustrated in Figure 1.

Both small-footprint and large-footprint sensors are typically used in combination with instruments for locating the source of the return signal in three dimensions. These include Global Positioning System (GPS) receivers to obtain the position of the platform, Inertial Navigation Systems (INS) to measure the attitude (roll, pitch, and yaw) of the lidar sensor, and angle encoders for the orientation of the scanning mirror(s). Combining this information with accurate time referencing of each source of data yields the absolute position of the reflecting surface, or surfaces, for each laser pulse. One common misconception about lidar data is that they are raster data sets. This is untrue; the data as delivered are typically no more than an ASCII mass point file for each pulse-return combination containing the X, Y, and Z coordinates in the user-specified coordinate system, combining all returns from a particular area results in a point cloud.

There are advantages to both small-footprint and large-footprint lidar sensors. For example, small-footprint systems feature high spatial resolution, made possible by the small diameter of their footprint and the high repetition rates of these systems (as high as 100,000 points per second), which together can yield dense distributions of sampled points. Thus, small-footprint systems are preferred for detailed mapping of ground and canopy surface topography. An additional advantage made possible by this high spatial resolution is the ability to aggregate the data over areas and scales specified during data analysis, so that specific locations on the ground, such as a particular forest inventory plot or even a single tree crown, can be characterized. Finally, small-footprint systems are readily and widely available, with ongoing and rapid development, especially for surveying and photogrammetric applications (Flood and Gutelis 1997). The primary users of these systems are surveyors serving public and private clients, and natural resource managers seeking a cheaper source of high-resolution topographic maps and Digital Elevation Models (DEMs). Most current small-footprint instruments enable an absolute vertical accuracy of the elevation data of 15-20 cm or less, with horizontal position being on the order of tens of centimeters. A potential drawback is that proprietary data-processing algorithms and established sensor configurations designed for commercial use may not coincide with scientific objectives (Wehr and Lohr 1999).

The advantages of large-footprint lidar include an enhanced ability to characterize canopy structure, the ability to concisely describe canopy information over increasingly large areas, and the availability of global data sets. Examples of large-footprint laser altimeters include MKII (Aldred and Bonnor 1985) and a similar system described in Nilsson (1996), as well as a series of airborne devices developed at NASA’s Goddard Space Flight Center, starting with a profiling sensor described by Bufton and colleagues (1991) and including SLICER (Scanning Lidar Imager of Canopies by Echo Recovery; Blair et al. 1994, Harding et al. 1994, 2001), LVIS (Laser Vegetation Imaging Sensor; Blair et al. 1999), and VCL (Vegetation Canopy Lidar; Dubayah et al. 1997) satellite. One advantage of these large-footprint lidar systems is that they record the entire time-varying power of the return signal from all illuminated surfaces and are therefore capable of collecting more information on canopy structure than all but the most spatially dense collections of small-footprint lidar. Additionally, large-footprint lidar integrates canopy structure information over a relatively large footprint and is capable of storing that information efficiently, from the perspective of both data storage and data analysis.

The correspondence between data from each type of sensor is illustrated in Figure 2, using data collected with a small-footprint lidar at the Upper San Pedro River Basin, Arizona, USA. Figure 2a illustrates the three-dimensional distribution of small-footprint (first-return) data from within a 22 m × 26 m footprint centered on a cottonwood tree approximately 30 m tall. Figure 2b illustrates the distribution of these points as a function of height. Blair and Hofton (1999) and Farid et al. (2008) demonstrated that this vertical distribution of the small-footprint data is closely related to the large-footprint recorded by waveform-recording devices when certain conditions are met — the most important being a high density of samples collected using a very small footprint (on the order of 10-15 cm) so that elevation data can be collected from within very small gaps in the canopy structure. To completely simulate a large-footprint lidar waveform, the vertical distribution of the small-footprint lidar data would have to be corrected for the spatial and temporal distribution of energy within the lidar pulse and receiver response, as described in Blair and Hofton (1999).

APPLICATIONS OF LIDAR REMOTE SENSING

Only a few areas of application for lidar remote sensing have been rigorously evaluated. Numerous other applications are generally considered feasible, but they have not yet been explored; developments in lidar remote sensing are occurring so rapidly that it is difficult to predict which applications are dominant. Currently, applications of lidar remote sensing in ecology and forestry fall into three general categories: (1) Remote sensing of the ground topography; (2) Measurement of the three-dimensional structure and function of vegetation canopies; and (3) Prediction of forest stand structure attributes (such as Leaf Area Index (LAI) and timber volume).

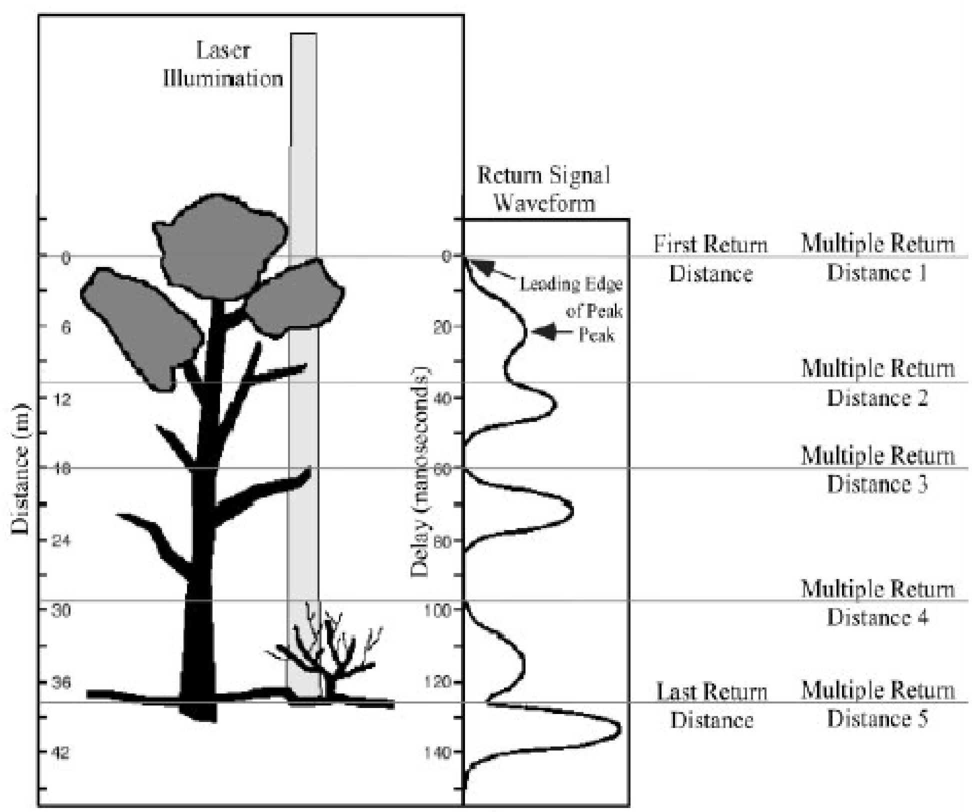
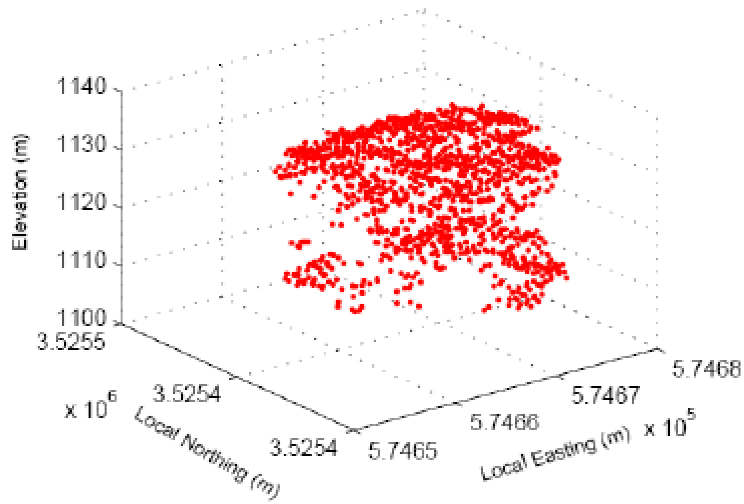


Figure 1. Illustration of the conceptual differences between large-footprint waveform recording and small-footprint discrete-return lidar devices. At the left is the intersection of the laser illumination area, or footprint, with a portion of a tree crown. In the center of the figure is a hypothetical return signal (the large-footprint) that would be collected by a waveform-recording sensor over the same area. To the right of the waveform, the heights recorded by three varieties of small-footprint discrete-return lidar sensors are indicated. First-return lidar devices record only the position of the first object in the path of the laser illumination, whereas last-return lidar devices record the height of the last object in the path of illumination and are especially useful for topographic mapping. Multiple-return lidar, records the height of a small number (five or fewer) of objects in the path of illumination. Figure adapted from Lefsky et al. (2002).

Measuring Vegetation Canopy Structure and Function

In general, the single most important step in lidar mapping of topography involves the deletion of data points returned from vegetation and, in urban areas, buildings.

a)



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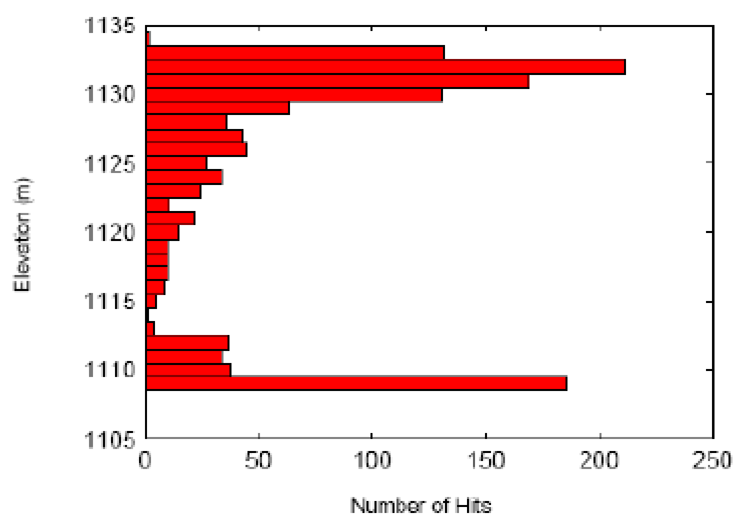

Figure 2. Illustration of the potential for creating synthetic lidar waveforms from small-footprint lidar data. Section a shows the three-dimensional distribution of small-footprint lidar data from within a 22 m × 26 m footprint. Section b shows the vertical distribution of these returns. Figure adapted from Farid et al. (2008), with permission from Elsevier Science.

However, for most forest applications, it is the returns from the vegetation canopy that will be of primary interest. Canopy structure contains a substantial amount of information about the state of development of plant communities (Lefsky et al. 1999a, 1999b) and therefore about canopy function (Hollinger 1989, Brown and Parker 1994) and vegetation-related habitat conditions for wildlife (Hansen and Rotella 2000).

The simplest canopy structure measurements are of canopy height and cover. Canopy heights have been compared with varying accuracy and strength of correlation, to maximum and mean tree height in temperate (Maclean and Krabill 1986), tropical (Nelson et al. 1997, Drake et al. forthcoming), boreal (Naesset 1997a, Magnussen and Boudewyn 1998, Magnussen et al. 1999), and riparian (Farid et al, 2006b) forests. In addition, Ritchie et al, 1995) found excellent agreement between lidar measurements of height in both temperate deciduous forests and desert scrub.

The latter finding is particularly important, as it indicates that vegetation height measurements can be made accurately even on vegetation of short stature, at least in low-slope environments. There are two general problems in determining vegetation height using lidar data. Determining the exact elevation of the ground surface poses difficulties for both small-footprint and large-footprint waveform-recording lidar. In complex canopies, elevations returned from what appears to be the ground level in fact may be from the understory, if the understory is dense enough to substantially occlude the ground surface. In addition, each type of lidar system presents difficulties in detecting the uppermost portion of the plant canopy. With small-footprint lidar, very high footprint densities are required to ensure that the highest portion of individual tree crowns is sampled. With large-footprint waveform sampling devices, a large footprint is illuminated, increasing the probability that treetops will be illuminated by the laser. However, the top portion of the crown may not be of sufficient area to register as a significant return signal and therefore may not be detected. In either case, the height of the canopy may be underestimated. Estimates of canopy cover have been made using both small-footprint (Farid et al, 2006b) and large-footprint waveform-recording lidar sensors. These estimates are made using the fraction of the lidar measurements that are considered to have been returned from the ground surface (Nelson et al. 1984, Ritchie et al. 1992, 1995, 1996, Weltz et al. 1994, Lefsky 1997), where the measurements are the number of small-footprint returns, or the integrated power of a waveform. In some cases, a scaling factor is needed to correct for the relative reflectance of ground and canopy surfaces at the wavelength of the laser (Lefsky 1997). As with the measurement of canopy height, the definition of the ground surface is a critical aspect of cover determination. If the number of the measurements assigned to the ground return is overestimated cover will be underestimated, and vice versa. Although the height and cover of the canopy surface are useful canopy structure descriptions, there are more detailed measurements that can better describe canopy function and structure. The height distribution of outer canopy surfaces, which quantifies such important features as light gaps (Watt 1947, Canham et al. 1990, Spies et al. 1990), has been manually mapped in several studies (Leonard and Federer 1973, Ford 1976, Miller and Lin 1985). These maps were laboriously made, using devices such as plumb bobs and telescoping rods; with lidar, the process is greatly accelerated (Nelson et al. 1984, Lefsky et al. 1999b). The vertical distribution of all material within the canopy may be inferred, using the foliage-height profile technique (MacArthur and Horn 1969, Aber 1979) adapted for use with large-footprint waveform-recording lidar as the canopy height profile (Lefsky 1997, Harding et al. 2001). Calculation of these height profiles relies on assumptions about the rate of occlusion of canopy surfaces that are not applicable to all forests; however, they have been shown to yield a good approximation in closed-canopy, temperate deciduous forests (Aber 1979, Fukushima et al. 1998, Harding et al. 2001). Lidar data have been used to predict the fractional transmittance of light as a function of height, based on a series of assumptions relating the penetration of the laser light into the canopy to the penetration of natural light into the canopy. Although both the wavelength and orientation of typical laser illumination differ from that of natural illumination, a study (Parker et al. 2001) indicates that lidar can accurately estimate the rate of photosynthetically active radiation absorption and define the location and depth of the zone where the maximum rate of absorption occurs (Parker 1997). Lidar has also been used to predict the aerodynamic properties of plant canopies and landscapes. In modeling airflow over a forest canopy, the aerodynamic roughness length is the height at which the wind speed becomes zero. Menenti and Ritchie (1994) used a profiling laser altimeter to predict aerodynamic roughness length of complex landscapes containing a mixture of grassland, shrub, and woodland areas, and found good agreement with field estimates. The techniques described so far use lidar data to make measurements of canopy structure that had been made with technologically simpler and more time-consuming methods. The ability of lidar to rapidly measure the three-dimensional structure of canopies should stimulate the development of new systems of canopy description. One such system, the canopy volume method (CVM), is the first to take advantage of the ability of a waveform-recording sensor (SLICER) to directly measure the three-dimensional distribution of canopy structure. This approach led to a better understanding of the structure of the old-growth forest canopy, new visualizations of the multiple canopy aspect of old-growth development, and improved estimates of forest stand structure.

Predictions of Forest Stand Structure

Lidar data have been used to predict biophysical characteristics of forest communities (Dubayah and Drake 2000). Although the following studies may not by themselves constitute forest research, they lay the groundwork for future studies that use these relationships to map biophysical variables over large extents, making possible a new class of large-scale forest research. Prediction of forest stand structure using small-footprint lidar had its start in the work of Maclean and Krabill (1986), who adapted the canopy profile cross-sectional area photogrammetric technique to the interpretation of lidar data. Nelson et al. (1988) successfully predicted the volume and biomass of southern pine (Pinus taeda, P. elliotti, P. echinata, and P. palustris) forests using several estimates of canopy height and cover from small-footprint lidar, explaining between 53% and 65% of variance in field measurements of these variables. Later work by Nelson et al. (1997) in tropical wet forests at the La Selva Biological Station obtained similar results for prediction of basal area, volume, and biomass. They also developed a canopy structure model that led to greater understanding of the optimal spatial configuration of field sampling for comparison with profiling lidar data. Naesset (1997b) explained 45%–89% of variance in stand volume of Norway spruce (Picea abies) and Scots pine (Pinus sylvestris), using measurements of maximum and mean canopy height and cover. Nilsson (1996) adapted a bathymetric lidar system for use in forest inventory, and successfully predicted timber volume for stands of even-aged Scots pine (P. sylvestris). He used the height and the total power of each waveform as independent variables, and explained 78% of variance. Lefsky and colleagues (1999a) used data from SLICER to predict aboveground biomass and basal area in eastern deciduous forests using indices derived from the canopy height profile. Of particular note, they found that relationships between height indices and forest structure attributes (basal area and aboveground biomass) could be generated using field estimates of the canopy height profiles, and applied directly to the lidar-estimated profiles, resulting in unbiased estimates of forest structure. Means and colleagues (1999) applied similar methods to evaluate 26 plots in forests of Douglas-fir and western hemlock at the H. J.Andrews Experimental Forest. They found that very accurate estimates of basal area, aboveground biomass, and foliage biomass could be made using lidar height and cover estimates. Farid et al (2006a, 2006b, and 2008) used multi-return small-footprint lidar to identify riparian tree species, age, and canopy characteristics. Stepwise multiple regressions (canopy height, height of median energy, ground return ratio, and canopy return ratio) were performed to predict ground-based measures of stand structure from riparian canopy structure indices including LAI. The method used four metrics (canopy height, height of median energy, ground return ratio, and canopy return ratio) that were derived by synthetically construction of a large footprint lidar waveform from the airborne small-footprint lidar data (see Figure 3). Farid et al (2008) concentrated on individual cottonwood trees to develop the relationships to estimate LAI for riparian water use estimates and may not be applicable to dense, overlapping canopies. Additionally, lidar cannot provide information on stomatal control which also regulates riparian cottonwood water use so independent estimates or typical ranges of canopy level stomatal resistance will be required. However, strategically acquired lidar data and derived spatially explicit LAI measurements, offer significant potential to improve riparian water use estimates. Future research will investigate how well lidar can derive LAI in more complex and interacting canopies.

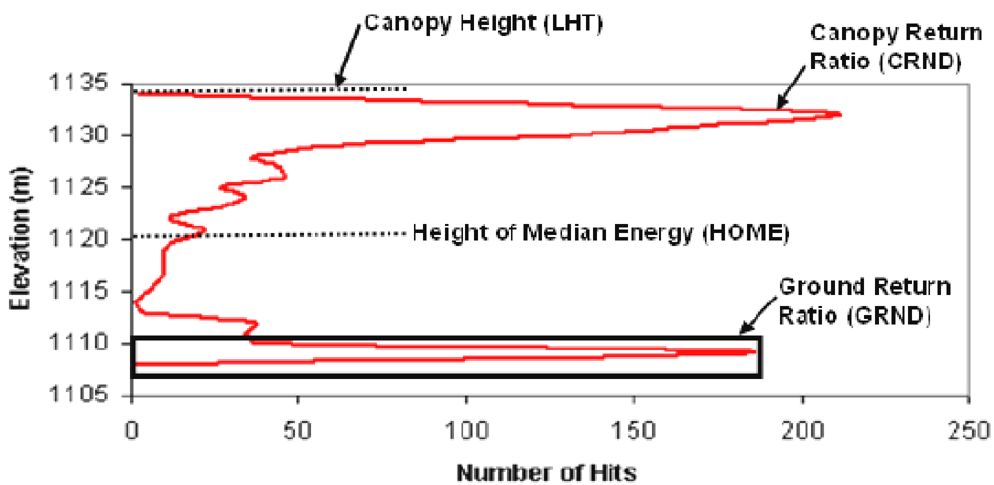

Figure 3. Metrics derived from synthetic large footprint lidar waveforms. These metrics were then used to estimate LAI for different age classes of cottonwoods. Figure adapted from Farid et al. (2008), with permission from Elsevier Science.

CONCLUSIONS

Lidar remote sensing recently has become available as a research tool, and it has yet to become widely available. Nevertheless, it has already been shown to be an extremely accurate tool for measuring topography, vegetation height, and cover, as well as more complex attributes of canopy structure and function. Additionally, the basic canopy structure measurements made with lidar sensors have been shown to provide highly accurate estimates of important forest stand structure indices, such as leaf area index and aboveground biomass. Because the basic measurements made by lidar sensors are directly related to vegetation structure and function, we expect that these findings will continue to be corroborated in a variety of biomes, with similar results. The availability of lidar data will increase with the broader use of airborne sensors for topographic and forest canopy mapping. As data availability grows, a variety of applications will become feasible. It is likely that lidar will be useful in detecting habitat features associated with particular species, including those that are rare or endangered. For instance, the large open-grown trees and associated old-growth habitat that serve as nesting habitat for marbled murrelets (Hamer and Nelson 1995) should be readily identifiable from lidar data. Another likely application of lidar data is the identification of forest areas with accumulations of fuels that make them particularly susceptible to large, especially damaging fires (Agee 1993). Lidar's ability to discriminate the spatial pattern as well as the total volume of materials within a forest canopy would be especially useful for identifying, at the least, classes of forest structure that are associated with varying fire behavior. For instance, lidar should enable the detection of "ladder" fuels, which provide a pathway for ground-level fires to reach the upper canopy and cause more damaging crown fires. Additionally, the ability to identify the size and depth of canopy gaps should allow estimation of the quantity of large woody fuels associated with the creation of those gaps. Lidar remote sensing shows great potential for integration with forest research. It directly measures the physical attributes of vegetation canopy structure, which are highly correlated with the basic plant community measurements of interest to ecologists. The detailed measurement and modeling of canopies has largely been the province of specialists. By reducing the time and effort associated with measuring canopy structure, lidar can foster the wider incorporation of a canopy science perspective into forest research and put vegetation canopy structure squarely at the center of efforts to measure and model global carbon dynamics.

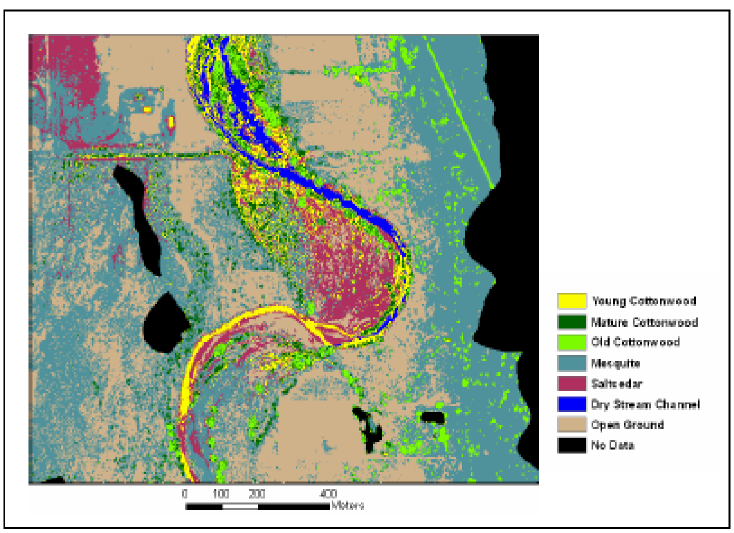

Figure 4. Classified lidar image, showing three cottonwood age classes, mesquite, saltcedar, dry stream channel, and open ground. Adapted from Farid et al (2006a), with permission from Canadian Journal Remote Sensing.

REFERENCES

Aber JD. 1979. Foliage-height profiles and succession in northern hardwood forests. *Ecology* 60: 18–23.

Agee JK. 1993. Fire Ecology of Pacific Northwest Forests. Washington (DC): Island Press.

Aldred A, Bonnor G. 1985. Application of airborne lasers to forest surveys. Chalk River (Ontario, Canada): Petawawa National Forestry Institute, *Canadian Forestry Service*. Information Report PI-X-51.

Bachman CG. 1979. Laser Radar Systems and Techniques. Norwood (MA): Artech House.

Blair JB, Coyle DB, Bufton JL, Harding DJ. 1994. Optimization of an airborne laser altimeter for remote sensing of vegetation and tree canopies. Pages 939–941 in Proceedings of the International Geosciences Remote Sensing Symposium. Pasadena (CA): *California Institute of Technology*.

Blair JB, Hofton MA. 1999. Modeling laser altimeter return waveforms over complex vegetation using high-resolution elevation data. *Geophysical Research Letters* 26: 2509–2512.

Brown MJ, Parker GG. 1994. Canopy light transmittance in a chronosequence of mixed-species deciduous forests. *Canadian Journal of Forestry Research* 24: 1694–1703.

Bufton JL, Garvin JB, Cavanaugh JF, Ramos-Izquierdo L, Clem TD, Krabill WB. 1991. Airborne lidar for profiling of surface topography. *Optical Engineering* 30: 72–78.

Canham CD, Denslow JS, Platt WJ, Runkle JR, Spies TA, White PS. 1990. Light regimes beneath closed canopies and tree-fall gaps in temperate and tropical forests. Canadian *Journal of Forestry Research* 20: 620–631.

Drake, J.B., Dubayah, R.O., Clark, D.B., Knox, R.G., Blair, J.B., Hofton, M.A., Chazdon, R.L., Weishampel, J.F., Prince, S.D., 2002. Estimation of tropical forest structural characteristics using large-footprint lidar. *Remote Sensing of Environment* 79, 305-319.

Dubayah R, Blair JB, Bufton JL, Clark DB, JaJa J, Knox R, Luthcke SB, Prince S, Weishampel J. 1997. The vegetation canopy lidar mission. Pages 100-112 in Proceedings of Land Satellite Information in the Next Decade, II: Sources and Applications. Bethesda (MD): American Society of Photogrammetry and Remote Sensing.

Dubayah R, Knox R, Hofton M, Blair JB, Drake J. 2000. Land surface characterization
using lidar remote sensing. Pages 25–38 in Hill MJ, Aspinall RJ, eds. Spatial Information for Land Use Management. Singapore: *International Publishers Direct.*

Dubayah RO, Drake JB. 2000. Lidar remote sensing for forestry. *Journal of Forestry* 98: 44–46.

Farid, A., Rautenkranz, D., Goodrich, D.C., Marsh, S.E., Sorooshian, S., 2006a. Riparian vegetation classification from airborne laser scanning data with an emphasis on cottonwood trees. *Canadian Journal of Remote Sensing* 32, 15-18.

Farid, A., Goodrich, D.C., Sorooshian, S., 2006b. Using airborne lidar to discern age classes of cottonwood trees in a riparian area. Western Journal of Applied Forestry 21, 149-158.

Farid, A., Goodrich, D.C., Bryant, R., Sorooshian, S., 2008. Using airborne lidar to predict leaf area index in cottonwood trees and refine riparian water-use estimates. *Journal of Arid Environments*, Vol. 72, No. 1, pp. 1-15.

Flood M, Gutelis B. 1997. Commercial implications of topographic terrain mapping using scanning airborne laser radar. *Photogrammetric Engineering and Remote Sensing* 63: 327–366.

Ford ED. 1976. The canopy of a Scots pine forest: Description of a surface of complex roughness. *Agricultural and Forest Meteorology* 17: 9–32.

Fukushima Y, Hiura T, Tanabe S. 1998. Accuracy of the MacArthur-Horn method of estimating a foliage profile. *Journal of Agricultural Forest Meteorology* 92: 203–210.

Hamer TE, Nelson SK. 1995. Characteristics of marbled murrelet nest trees and nesting stands.Pages 69–82 in Ralph CJ,Hunt GL, Raphael MG, Platt JF, eds. Ecology and Conservation of the Marbeled Murrelet.Albany (CA): US Department of Agriculture, Forest Service,Pacific Southwest Research Station. *General Technical Report* PSW-152.

Hansen A, Rotella JJ. 2000. Bird responses to forest fragmentation. Pages 201–219 in Knight RL, Smith FW, Romme WH, Buskirk SW, eds. Forest Fragmentation in the Southern Rockies. Boulder:University Press of Colorado.

Harding DJ, Blair JB, Garvin JB, Lawrence WT. 1994. Laser altimetry waveform measurement of vegetation canopy structure. Pages 1251–1253 in Proceedings of the International Remote Sensing Symposium 1994. Pasadena (CA): California Institute of Technology.

Harding DJ, Lefsky MA, Parker GG, Blair JB. 2001. Lidar altimeter measurements of canopy structure: Methods and validation for closed canopy, broadleaf forests. *Remote Sensing of Environment* 76: 283–297.

Hollinger DY. 1989. Canopy organization and photosynthetic capacity in a broad-leaved evergreen montane forest. *Functional Ecology* 3: 53–62.

Lefsky MA, Cohen WB, Geoffrey GP, Harding DJ 2002. Lidar Remote Sensing for Ecosystem Studies. *BioScience,* Vol. 52, No. 1, pp. 19-30.

Lefsky MA, Cohen WB, Acker SA, Spies TA, Parker GG, Harding D. 1999b. Lidar remote sensing of biophysical properties and canopy structure of forest of Douglas-fir and western hemlock. *Remote Sensing of Environment* 70: 339–361.

Lefsky MA,Harding D,Cohen WB, Parker GG. 1999a. Surface lidar remote sensing of the basal area and biomass in deciduous forests of eastern Maryland, USA. *Remote Sensing of Environment* 67: 83–98.

Lefsky MA. 1997. Application of Lidar Remote Sensing to the Estimation of Forest Canopy and Stand Structure. PhD dissertation. University of Virginia, Charlottesville,VA.

Leonard RE, Federer CA. 1973. Estimated and measured roughness parameters for a pine forest. *Journal of Applied Meteorology* 12: 302–307.

MacArthur RH, Horn HS. 1969. Foliage profile by vertical measurements. *Ecology* 50: 802–804.

Maclean GA, Krabill WB. 1986. Gross-merchantable timber volume estimation using an airborne LIDAR system. *Canadian Journal of Remote Sensing* 12: 7–18.

Magnussen S, Boudewyn P. 1998. Derivations of stand heights from airborne laser scanner data with canopy-based quantile estimators. *Canadian Journal of Forestry Research* 28: 1016–1031.

Magnussen S, Eggermont P, LaRiccia VN. 1999. Recovering tree heights from airborne laser scanner data. *Forest Science* 45: 407–422.

Means JE, Acker SA, Harding DJ, Blair JB, Lefsky MA, Cohen WB, Harmon M, McKee WA. 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.

Menenti M, Ritchie JC. 1994. Estimation of effective aerodynamic roughness of Walnut Gulch Watershed with laser altimeter measurements. *Water Resources Research* 30: 1329–1337.

Miller DR, Lin JD. 1985. Canopy architecture of a red maple edge stand measured by the point drop method. Pages 59–70 in Hutchinson BA, Hicks BB, eds. The Forest–Atmosphere Interaction. Dordrecht (Netherlands): Reidel Publishing.

Naesset E. 1997a. Determination of mean tree height of forest stands using airborne laser scanner data. *ISPRS Journal of Photogrammetry and Remote Sensing* 52: 49–56.

Naesset E. 1997b. Estimating timber volume of forest stands using airborne laser scanner data. *Remote Sensing of Environment* 61: 246–253.

Nelson R, Oderwald R, Gregoire TG. 1997. Separating the ground and airborne laser sampling phases to estimate tropical forest basal area, volume, and biomass. *Remote Sensing of Environment* 60: 311–326.

Nelson RF, Krabill WB, Tonelli J. 1988. Estimating forest biomass and volume using airborne laser data. *Remote Sensing of Environment* 24: 247–267.

Nelson RF, Krabill WB, Maclean GA. 1984. Determining for est canopy characteristics using airborne laser data. *Remote Sensing of Environment* 15: 201–212.

Nilsson M. 1996. Estimation of tree heights and stand volume using an airborne lidar system. *Remote Sensing of Environment* 56: 1–7.

Parker GG, Lefsky MA, Harding DJ. 2001. PAR transmittance in forest canopies determined from airborne lidar altimetry and from in-canopy quantum measurements. *Remote Sensing of Environment* 76: 298–309.

Parker GG. 1997. Canopy structure and light environment of an old-growth Douglas fir/western hemlock forest. *Northwest Science* 71: 261–270.

Ritchie JC, Everitt JH, Escobar DE, Jackson TJ, Davis MR. 1992. Airborne laser measurements of rangeland canopy cover and distribution. *Journal of Range Management* 45: 189–193.

Ritchie JC, Humes KS, Weltz MA. 1995. Laser altimeter measurements at Walnut Gulch watershed,Arizona. *Journal of Soil and Water Conservation* 50: 440–442.

Ritchie JC, Menenti M, Weltz MA. 1996. Measurements of land surface features using an airborne laser altimeter: The HAPEX-Sahel experiment. *International Journal of Remote Sensing* 17: 3705–3724.

Spies TA, Franklin JF, Klopsch M. 1990. Canopy gaps in Douglas-fir forests of the Cascade Mountains. *Canadian Journal of Forestry Research* 5: 649–658.

Watt AS. 1947. Pattern and process in the plant community. Journal of Ecology 35: 1–22.

Wehr A, Lohr U. 1999. Airborne laser scanning—an introduction and overview. ISPRS *Journal of Photogrammetry and Remote Sensing* 54: 68–82.

Weltz MA, Ritchie JC, Fox HD. 1994. Comparison of laser and field-measurements of vegetation height and canopy cover.*Water Resources Research* 30: 1311–1319.