

# Lidar Remote Sensing for Ecosystem Studies

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**R**emote sensing has facilitated extraordinary advances in the modeling, mapping, and understanding of ecosystems. Typical applications of remote sensing involve either images from passive optical systems, such as aerial photography and Landsat Thematic Mapper (Goward and Williams 1997), or to a lesser degree, active radar sensors such as RADARSAT (Waring et al. 1995). These types of sensors have proven to be satisfactory for many ecological applications, such as mapping land cover into broad classes and, in some biomes, estimating aboveground biomass and leaf area index (LAI). Moreover, they enable researchers to analyze the spatial pattern of these images.

However, conventional sensors have significant limitations for ecological applications. The sensitivity and accuracy of these devices have repeatedly been shown to fall with increasing aboveground biomass and leaf area index (Waring et al. 1995, Carlson and Ripley 1997, Turner et al. 1999). They are also limited in their ability to represent spatial patterns: They produce only two-dimensional (*x* and *y*) images, which cannot fully represent the three-dimensional structure of, for instance, an old-growth forest canopy. Yet 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 (MacArthur and MacArthur 1961), especially in systems where biomass accumulation is significant (Hansen and Rotella 2000). Individual bird species, in particular, are often associated with specific three-dimensional features in forests (Carey et al. 1991). In addition, other functional aspects of forests, such as productivity, may be related to forest canopy structure.

Laser altimetry, or lidar (light detection 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 (*z*) dimension. Lidar sensors directly measure the three-dimensional distribution of plant canopies as well as subcanopy topography, thus providing high-resolution topographic maps and highly accurate estimates of vegetation 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.

LIDAR, AN EMERGING REMOTE SENSING TECHNOLOGY THAT DIRECTLY MEASURES THE THREE-DIMENSIONAL DISTRIBUTION OF PLANT CANOPIES, CAN ACCURATELY ESTIMATE VEGETATION STRUCTURAL ATTRIBUTES AND SHOULD BE OF PARTICULAR INTEREST TO FOREST, LANDSCAPE, AND GLOBAL ECOLOGISTS

## *Lidar sensors*

The basic measurement made by a lidar device is the distance between the sensor and a target surface, obtained by determining the elapsed time between the emission of a short-duration 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 sur-

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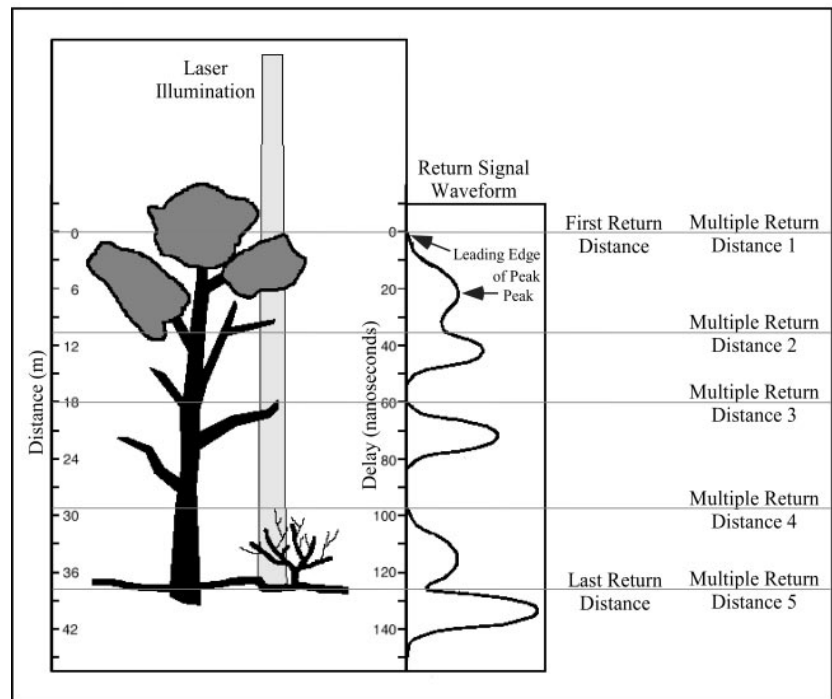
face is repeatedly measured along a transect, the result is an outline of both the ground surface and any vegetation obscuring it. Even in areas with high vegetation cover, where most measurements will be returned from plant canopies, some measurements will be returned from the underlying ground surface, 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 (if any), and the information recorded for each reflected pulse. Lasers for terrestrial applications generally have wavelengths in the range of 900–1064 nanometers, where vegetation reflectance is high. In the visible wavelengths, vegetation absorbance is high and only a small amount of energy would be returned to the sensor. One drawback of working in this range of wavelengths is absorption by clouds, which impedes the use of these 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. Early lidar sensors were profiling systems, recording observations along a single narrow transect. Later systems operate in a scanning mode, in which the orientation of the laser illumination and receiver field of view is directed from side to side by a rotating mirror, or mirrors, so that as the plane (or other platform) moves forward, the sampled points fall across a wide band or swath, which can be gridded into an image.

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 morphologically complex surface, such as 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* 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 some-

times the power of each peak, are typical values recorded by this type of system (Wehr and Lohr 1999). *Waveform-recording* 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). By analogy to chromatography, the discrete-return systems identify, while receiving the return signal, the retention times and heights of major peaks; the waveform-recording 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 discrete-return and waveform sampling 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 ref-



**Figure 1.** Illustration of the conceptual differences between waveform-recording and discrete-return lidar devices. At the left is the intersection of the laser illumination area, or footprint, with a portion of a simplified tree crown. In the center of the figure is a hypothetical return signal (the lidar waveform) 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 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, a recent advance, records the height of a small number (generally five or fewer) of objects in the path of illumination.

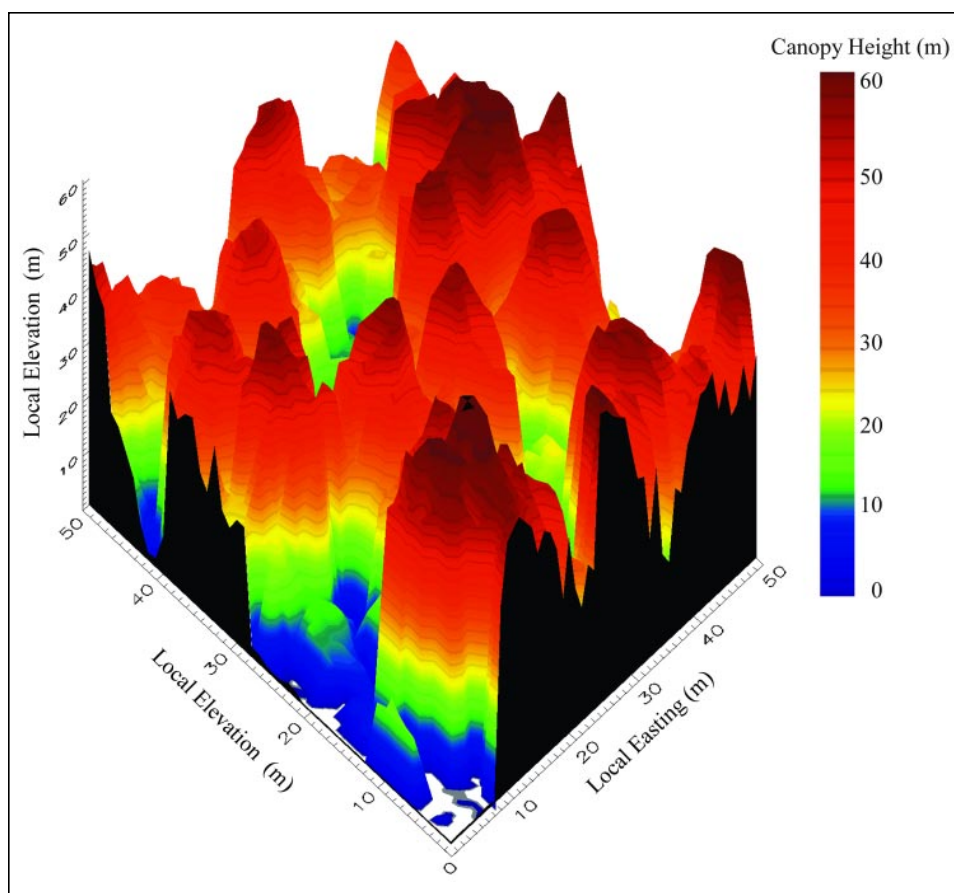
erencing of each source of data yields the absolute position of the reflecting surface, or surfaces, for each laser pulse.

There are advantages to both discrete-return and waveform-recording lidar sensors. For example, discrete-return 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 33,000 points per second), which together can yield dense distributions of sampled points. Thus, discrete-return systems are preferred for detailed mapping of ground (Flood and Gutelis 1997) and canopy surface topography, as in Figure 2. 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, discrete-return 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 terrain models (DTMs). A potential drawback is that proprietary data-processing algorithms and established sensor configurations designed for commercial use may not coincide with scientific objectives. A detailed technical review of the various sensors can be found in Wehr and Lohr (1999). Baltsavias (1999) reviews a directory of sensors and lidar remote sensing firms.

The advantages of waveform-recording 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 (the extent of their coverage varies, however). Examples of waveform-recording 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), SLA (Shuttle Laser Altimeter; Garvin et al. 1998), LVIS (Laser Vegetation Imaging Sensor; Blair et al. 1999), and VCL (Vegetation

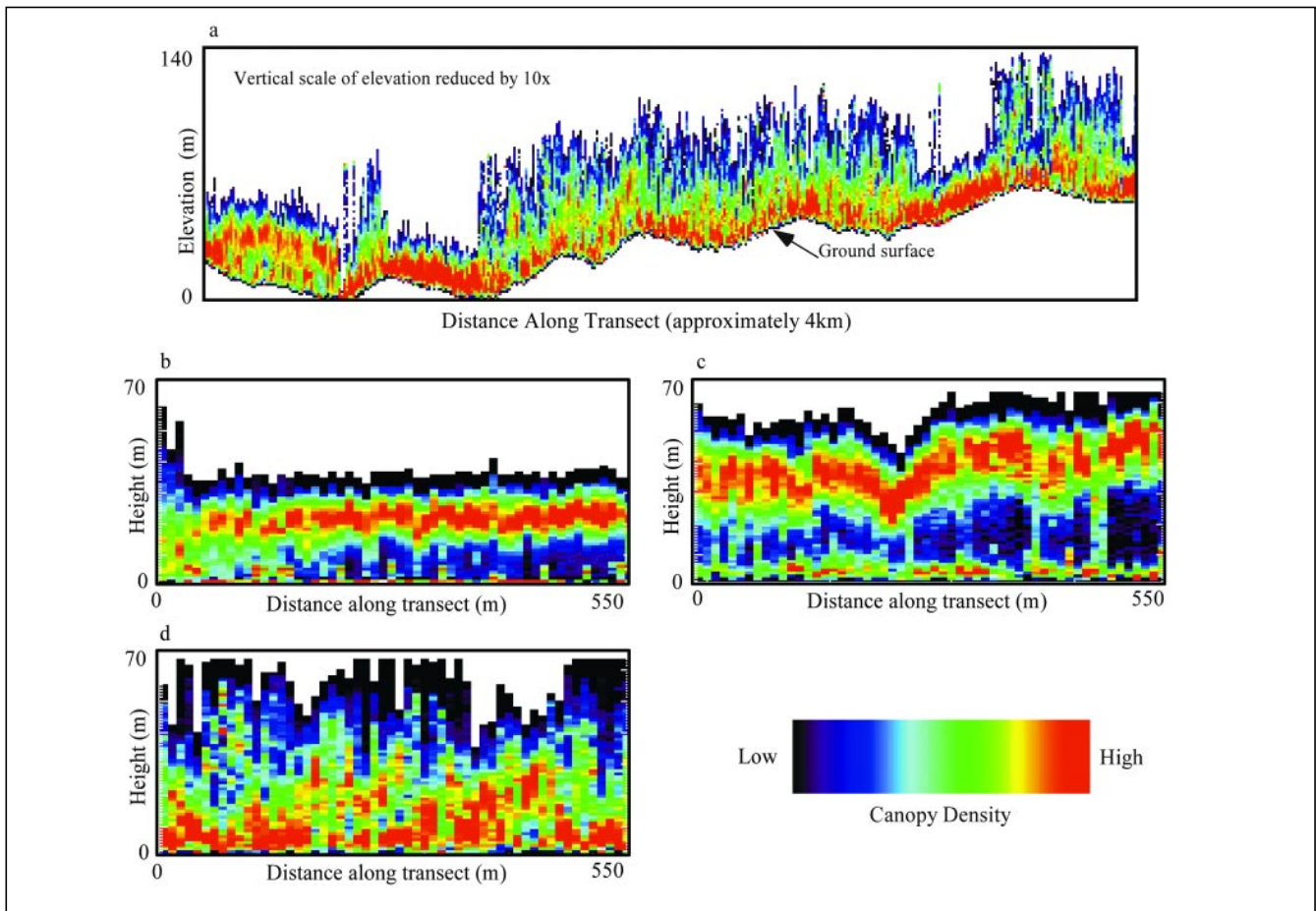
Canopy Lidar; Dubayah et al. 1997) satellite. One advantage of these waveform-recording lidar systems is that they record the entire time-varying power of the return signal from all illuminated surfaces and are therefore capable of collecting more information on canopy structure than all but the most spatially dense collections of small-footprint lidar (Figure 3). In addition, waveform-recording 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. Finally, only waveform-recording lidar will, in the near future, be collected globally from space.

Spaceborne waveform-recording lidar techniques have been successfully demonstrated by the Shuttle Laser Altimeter missions (Garvin et al. 1998), which were intended to collect topographic data and to test hardware and algorithm approaches from orbit. These data were collected along a single track, using footprints of approximately 100 meters in diameter, which limits their utility for the measurement of vegetation canopy structure, especially in high-slope areas (Harding et al. 2001). The Ice, Cloud, and Land Elevation Satellite (ICESat) mission, scheduled for launch in December 2001, will carry the Geoscience Laser Altimeter System, which will



**Figure 2.** Canopy surface topography of a subsection of the Wind River Canopy Crane Research Facility in Washington State. The data have been gridded; individual lidar samples would be represented by individual points in three-dimensional space.





**Figure 3.** Measurements of canopy structure made using NASA's SLICER (Scanning Lidar Imager of Canopies by Echo Recovery) device. Panel a shows ground topography and the vertical distribution of canopy material along a 4-km transect in the H. J. Andrews Experimental Forest, Oregon. Each column is the width of one laser pulse waveform. Panels b, c, and d show close-ups of the canopies of three 550-m transects in young, mature, and old-growth Douglas fir–western hemlock forest stands, with their ground elevations adjusted to a uniform level.

make measurements along a single track with 70-m diameter footprints, which approaches the size needed to characterize vegetation in low- and moderate-slope areas.

The Vegetation Canopy Lidar mission, scheduled to be launched around 2003, is the first satellite specifically designed with the problem of vegetation inventory in mind. VCL is a waveform-recording system, expected to inventory, using 25-m diameter footprints, canopy height and structure over approximately 5% of the Earth's land surface between  $\pm 68^\circ$  latitude during its 18-month mission (Dubayah et al. 1997). Associated with the VCL mission is the Lidar Vegetation Imaging System (LVIS), an airborne, wide-swath mapping system developed at NASA's Goddard Space Flight Center that is being used to validate VCL's capabilities. Although LVIS can collect waveforms with 25-m diameter footprints contiguously across swaths over 2 kilometers in width, VCL is a sampling device. It will make waveform measurements along a group of three transects, spaced every 2 km perpendicular to the randomly placed ground track of the satellite, resulting in a "web" of samples covering the Earth's surface. These samples

will not provide images of canopy structure, but they could be combined with images from other sensors (such as Enhanced Thematic Mapper+ data from Landsat 7) using a number of strategies, with VCL data augmenting or even replacing the roles usually played by field-collected data (Lefsky et al. 1999c, Dubayah et al. 2000).

Although we present them as distinct types, discrete-return and waveform-recording lidar are closely related. The correspondence between data from each is illustrated in Figure 4, using data collected with a first-return lidar at the Wind River Canopy Crane Research Facility. Section a (left) illustrates the three-dimensional distribution of first-return data from within a 25-m footprint centered on a tree approximately 50 m tall. Section b (right) illustrates the distribution of these points as a function of height. Blair and Hofton (1999) demonstrated that this vertical distribution of the single-return data is closely related to the waveforms 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 25 cm) so

that elevation data can be collected from within very small gaps in the canopy structure. To completely simulate a lidar waveform, the vertical distribution of the discrete return 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**

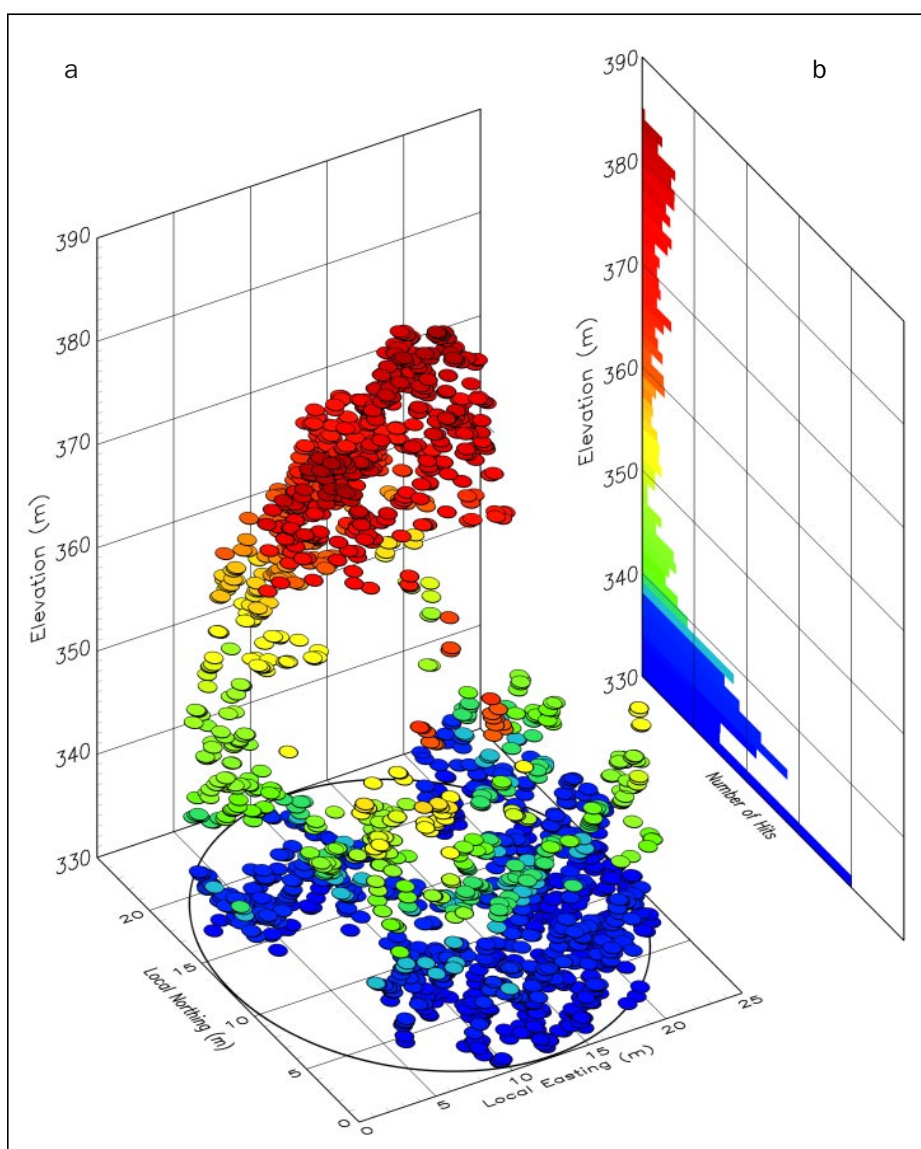
Only a few areas of application for lidar remote sensing have been rigorously evaluated. Numerous other applications are generally considered feasible, but they have not yet been explored; developments in lidar remote sensing are occurring so rapidly that it is difficult to predict which applications will be dominant in 5 years. Currently, applications of lidar remote sensing in ecology fall into three general categories: remote sensing of ground topography, measurement of the three-dimensional structure and function of vegetation canopies, and prediction of forest stand structure attributes (such as aboveground biomass).

#### **Topographic applications.**

Mapping of topographic features is the largest and fastest growing area of application for lidar remote sensing, because of its use in commercial land surveys (Flood and Gutelis 1997). Ecologists are also interested in topography (and bathymetry), which often has a strong influence on the structure, composition, and function of ecological systems. Traditional survey and photogrammetric techniques for determining ground elevations are limited in several ways. The primary disadvantages of traditional surveying are its substantial time and labor requirements and associated costs. Photogrammetric methods for determining elevations from aerial photographs or images collected by other sensors are an established alternative to field surveys (Baltsavius 1999). However, they are inaccurate in forested areas, where the ground is not visible, and in areas of low relief and texture, such as wetland areas and coastal dune systems. In these cases, airborne laser altimetry can be an accurate and cost-effective alternative.

Topographic applications most often use discrete-return data. When ranging information from the lidar is combined with position and pointing

information, the result is a series of xyz data points, or "triplets," describing the location of the observed surfaces in three-dimensional space. With adequate quality control, the accuracy of these points can achieve 50-cm root mean square error (RMSE) in the horizontal planes and 20-cm RMSE in the vertical. However, the elevations recorded in these triplets will be associated with myriad features, including the ground, human-made objects, clouds, vegetation, or anything else in the path of the laser pulse. To extract a topographic surface from these points, a series of filters must be applied to eliminate points not on the ground surface. Numerous methods exist for this process, but generally they combine highly automated processes with some manual correction (Kilian et al. 1996, Kraus and Pfeifer 1998). Most commercial data suppliers



**Figure 4.** Illustration of the potential for creating synthetic lidar waveforms from discrete-return lidar data. Section a shows the three-dimensional distribution of discrete-return lidar data from within a 25-m footprint. Section b shows the vertical distribution of these returns.

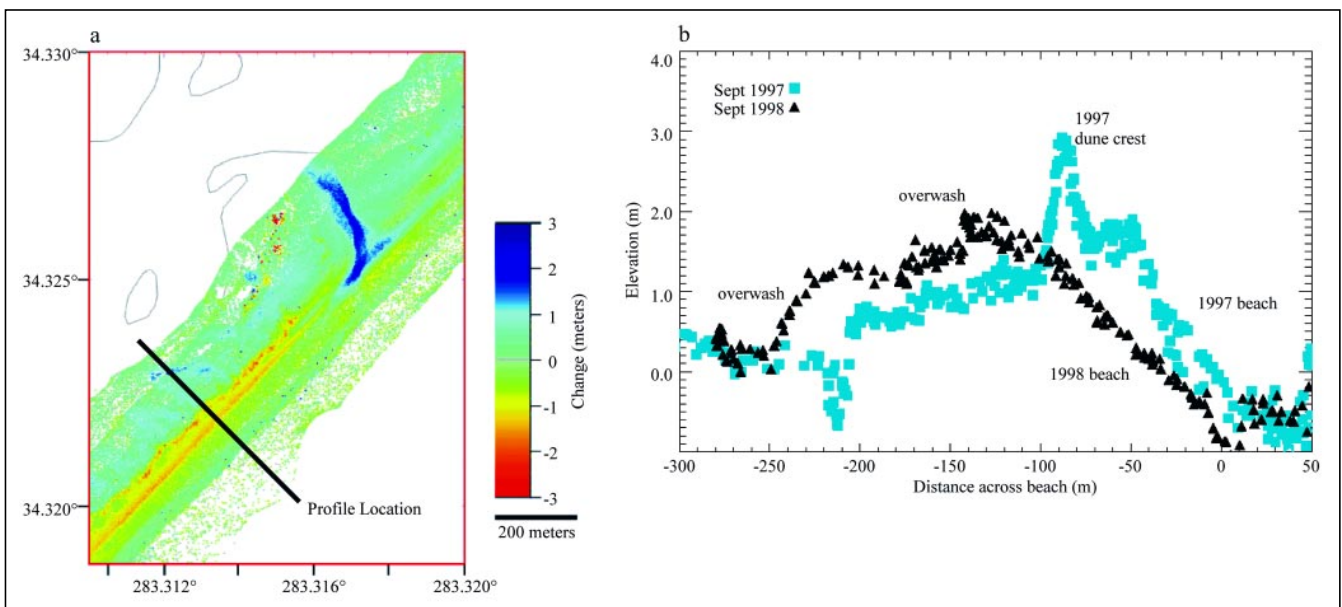
use proprietary routines they are often reluctant to describe in detail, a potential problem for scientists.

Examples of topographic applications of lidar include mapping of polar ice sheets for mass balance investigations (Krabill et al. 1999), mapping of wetlands and shallow water (Irish and Lillycrop 1999), and high-resolution mapping of topography under forest for geomorphic investigations and hydrologic modeling (Harding and Berghoff 2000). The mapping of dynamic features such as beaches and dunes (Krabill et al. 2000) is one application for which lidar is proving to be particularly well suited. The ability of airborne lidar to create surveys of the coastal environment is being demonstrated by the ALACE (Airborne Lidar Assessment of Coastal Erosion) project, a joint program of the National Oceanic and Atmospheric Administration's Coastal Services Center, the US Geological Survey's Center for Coastal Geology, and the National Aeronautics and Space Administration (Krabill et al. 2000). Using the Airborne Topographic Mapper (ATM) developed at NASA's Wallops Flight Facility Observational Sciences Branch, detailed topographical maps are being created for areas along the Atlantic, Pacific, Great Lakes, and Gulf of Mexico coastlines. Through periodic resurveying of the same areas, precise measurements and images of coastal change are produced (Figure 5). The resulting data products are designed for accurate and cost-effective mapping of coastal erosion and could easily be applied to gain further understanding of the links between, for instance, geomorphologic and vegetation dynamics in coastal dune ecosystems.

**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.

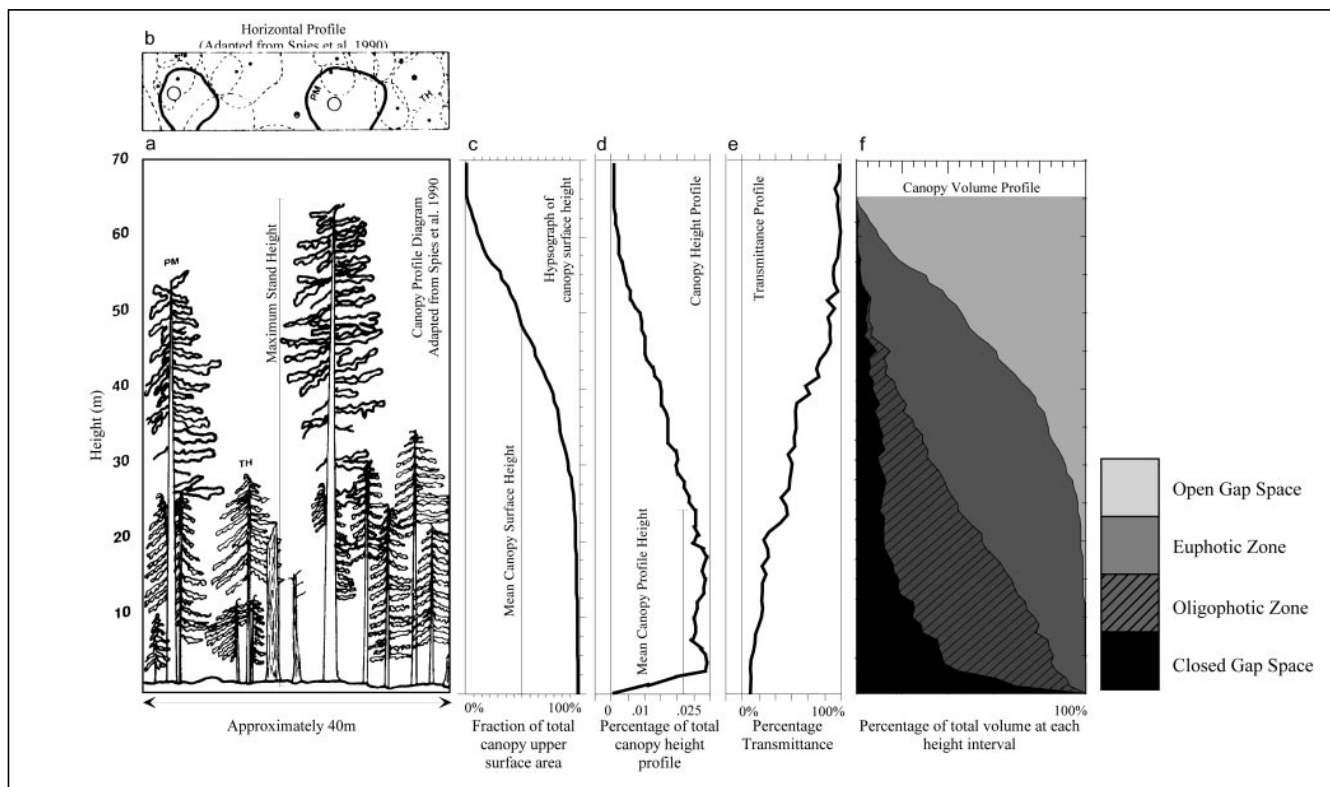
However, for most ecological applications, it is the returns from the vegetation canopy that will be of primary interest. Canopy structure—"the organization in space and time, including the position, extent, quantity, type, and connectivity, of the above-ground components of vegetation" (Parker 1995, p. 74)—contains a substantial amount of information about the state of development of plant communities (Lefsky et al. 1999a, 1999b) and therefore about canopy function (Monsi and Saeki 1953, Horn 1971, 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 (Figures 6a, 6b). Altimetric 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), and boreal (Naesset 1997a, Magnussen and Boudewyn 1998, Magnussen et al. 1999) forests. In addition, Ritchie and colleagues (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 (~1 m), 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 discrete-return and 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 discrete-return lidar, very



**Figure 5.** Lidar measurements of the effect of Hurricane Bonnie on the topography of Topsail Island, North Carolina. Panel a maps the overall change for this section of the island. Panel b shows pre- and posthurricane topography for a single profile. Figure courtesy of the ALACE (Airborne LIDAR Assessment of Coastal Erosion) project.





**Figure 6. Conceptual comparison of three canopy description methods. Panels a and b are a canopy profile diagram prepared by Spies et al. (1990). Panel c is a canopy surface hypsograph, showing the vertical distribution of the upper canopy surface. Panel d is a canopy height profile, showing the relative vertical distribution of foliage and woody surfaces. Panel e shows the vertical profile of transmittance. Panel f is a canopy volume profile, showing the vertical distribution of four classes of canopy structure. Figure adapted from Lefsky et al. (1999b), with permission from Elsevier Science.**

high footprint densities are required to ensure that the highest portion of individual tree crowns is sampled. With 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 discrete-return and 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 discrete 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, Means et al. 1999). As with the measurement of canopy height, the definition of the ground surface is a critical aspect of cover determination. If the number (or power) of the measurements assigned to the ground return is overestimated—that is, if the elevation of the ground surface 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 (Figure 6c), 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 (not just the outer canopy surfaces) may be inferred, using the foliage-height profile technique (MacArthur and Horn 1969, Aber 1979) recently adapted for use with waveform-recording lidar as the canopy-height profile (Figure 6d; 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 (Figure 6e), 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 recent study (Parker et al. 2001) indicates that lidar can accurately estimate the rate of photosynthetically active radiation (PAR) absorption and define the location and depth of the zone where the maximum rate of PAR absorption occurs (Parker 1997).

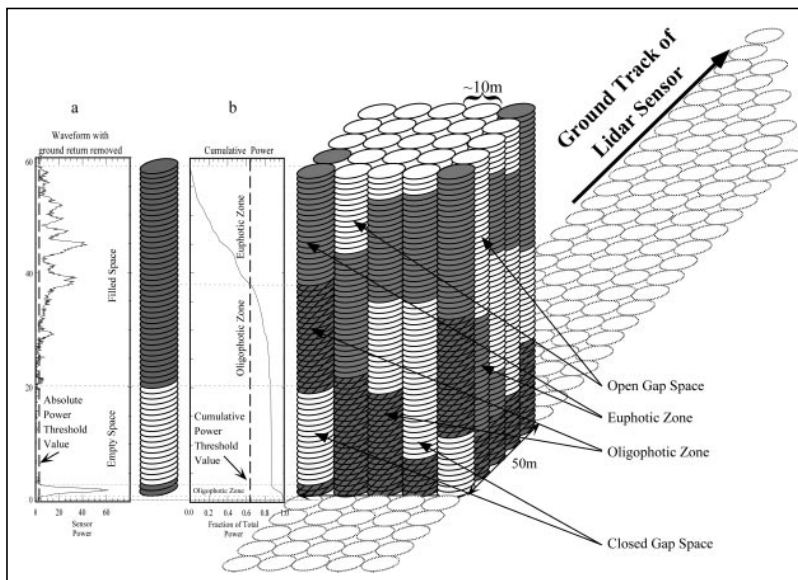
Lidar has also been used to predict the aerodynamic properties of plant canopies and landscapes. In modeling airflow over a forest canopy, the aerodynamic roughness length is the height at which the wind speed becomes zero. Menenti and Ritchie (1994) used a profiling laser altimeter to predict aerodynamic 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. Lidar's ability 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. Using lidar data, Lefsky and colleagues (1999b) were able to treat the forest canopy as a matrix of voxels (three-dimensional pixels; Figure 7), each of which could be defined as containing canopy or not, and either in the brightly or dimly sunlit portion of the canopy. This information was then used to describe the quantitative and qualitative differences in canopy structure between four age classes (Figure 8). 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.

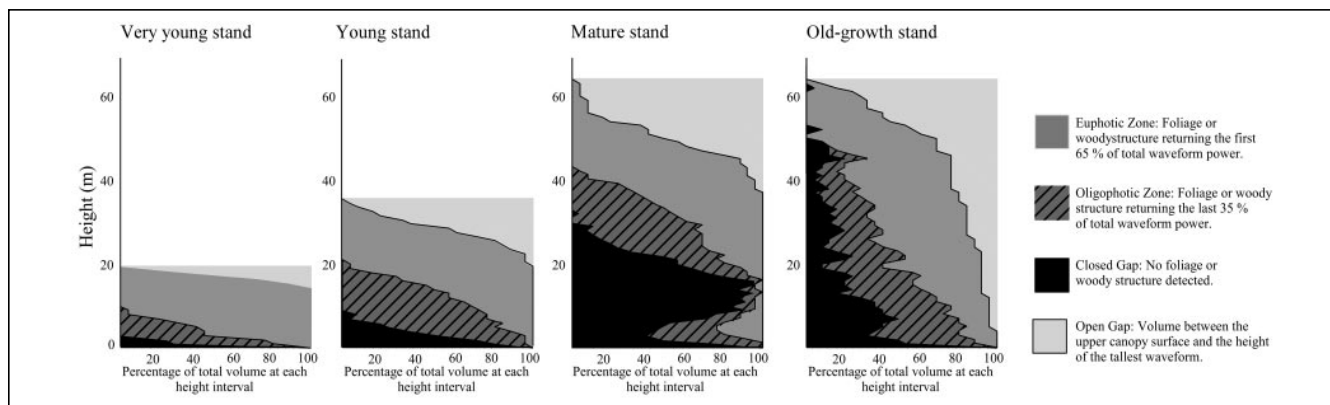
**Prediction of forest stand structure.** Lidar data also have been used to predict biophysical characteristics of plant communities, most notably forests (Dubayah and Drake 2000). Although the following studies may not by themselves constitute ecological research, they lay the groundwork for future studies that use these relationships to map biophysical variables over large extents (using data from sensors such as LVIS and VCL), making possible a new class of large-scale ecological research.

Prediction of forest stand structure using discrete return lidar had its start in the work of Maclean and Krabill (1986), who adapted a photogrammetric technique—the canopy profile cross-sectional area—to the interpretation of lidar data. The canopy profile cross-sectional area is the total area between the ground and the upper canopy surface along a transect. When species composition was taken into account, the authors were able to explain 92% of the variation in gross-merchantable timber volume (the volume of the main stem of trees, excluding the stump and top but including defective and decayed wood) in stands dominated by oaks (*Quercus* spp.), loblolly pine (*Pinus taeda*), or mixtures of the two types. Similar methods have proved effective in a variety of forest communities. 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 discrete-return 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 in stands of Norway spruce (*Picea abies*)



**Figure 7. Conceptual basis for the canopy volume method.** The cells of the matrix are 10 m in diameter and 1 m tall; they correspond to a 1-m vertical bin within a single waveform. Each waveform is processed to remove background noise (a), and a threshold value is used to classify each element of the waveform into either “filled” or “empty” volume. The cumulative top-down distribution of the waveform (b) is used to classify filled elements of the matrix into a euphotic zone, which returns the majority of energy back to the sensor, and an oligophotic zone, consisting of the balance of the profile. These two classifications are then combined to form three canopy structure classes: empty volume within the canopy (i.e., closed gap space), the euphotic zone, and the oligophotic zone. “Open gap” volume is then defined as the empty space between the top of each of the waveforms and the maximum height in the array. Figure adapted from Lefsky et al. (1999b), with permission from Elsevier Science.





**Figure 8.** Canopy volume profile diagrams for representative young, mature, and old-growth Douglas-fir and western hemlock forest plots. These diagrams indicate, for each 1-meter vertical interval, the percentage of each plot's 25 waveforms that belong to each of the four canopy structure classes. Young stands are characterized by short stature, a uniform upper canopy surface, and an absence of empty space within the canopy. Mature stands are taller, characterized by a uniform upper canopy surface but with a large volume of empty space within the canopy. Old-growth stands are distinguished from mature stands by their uneven canopy surface and the broad vertical distribution of each of the four canopy structure classes. Whereas stands from earlier stages in stand development have canopy structure classes in distinct vertical layers, in the old-growth stands each canopy structure class occurs throughout the height range of the stands. This trait has been cited as a key physical feature distinguishing old-growth forests from the simpler canopies of young and mature stands (Spies and Franklin 1991). Figure adapted from Lefsky et al. (1999b), with permission from Elsevier Science.

and Scots pine (*Pinus sylvestris*), using measurements of maximum and mean canopy height and cover.

Five published studies document the utility of waveform-recording lidar in predicting forest stand structure. 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.

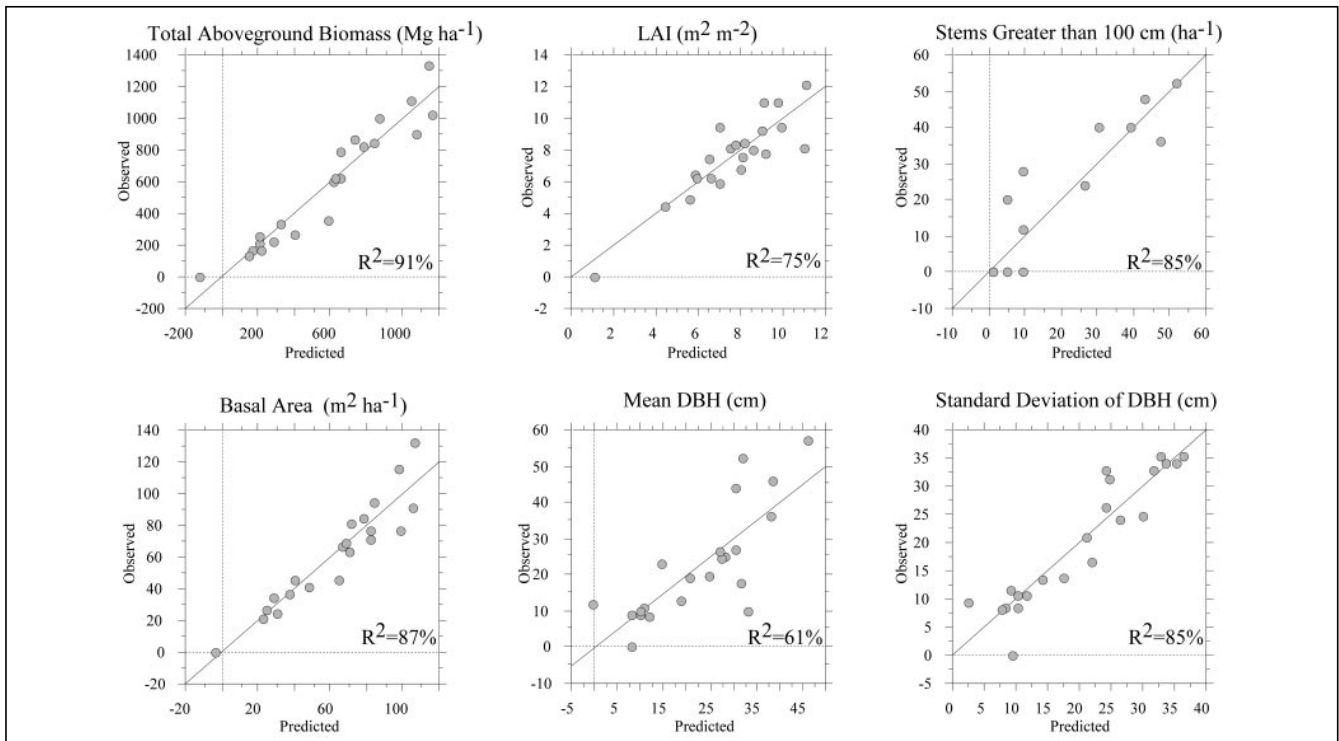
A fourth study (Lefsky et al. 1999b) used statistics derived from the CVM to predict numerous forest structure attributes, including several not previously predicted from lidar remote sensing. Stepwise multiple regressions were performed to predict ground-based measures of stand structure from both conventional canopy structure indices (mean and maximum canopy surface height, canopy cover, etc.) and CVM indices such as filled canopy volume, open and closed gap vol-

ume, and a canopy diversity index—the average number of CVM classes per unit height. Scatterplots of predicted versus observed stand structure attributes are presented in Figure 9. Examination of the scatterplots indicates that the predicted values of aboveground biomass and LAI show no asymptotic tendency, even at extremely large values (1200 Mg per ha<sup>-1</sup> of aboveground biomass). In addition, the three-dimensional aspects of the canopy lidar were able to accurately estimate indices related to more complex aspects of the diameter distribution, such as the standard deviation of diameter at breast height (DBH) and the number of stems greater than 100 cm DBH.

The fifth published study (Drake et al. forthcoming) extends the application of waveform-recording lidar to a tropical wet forest in Costa Rica, where, using the LVIS sensor, data were collected near the La Selva Biological Station. Using a set of indices describing the vertical distribution of the raw waveforms and the fraction of total power associated with the ground returns, they were able to predict field-measured quadratic mean stem diameter, basal area, and aboveground biomass, explaining up to 93%, 72%, and 93% of variance, respectively. The resulting map (Figure 10), which depicts the landscape scale patterns in aboveground biomass with unprecedented detail and accuracy, should be useful in itself and should also inform other studies in the area.

## Conclusions

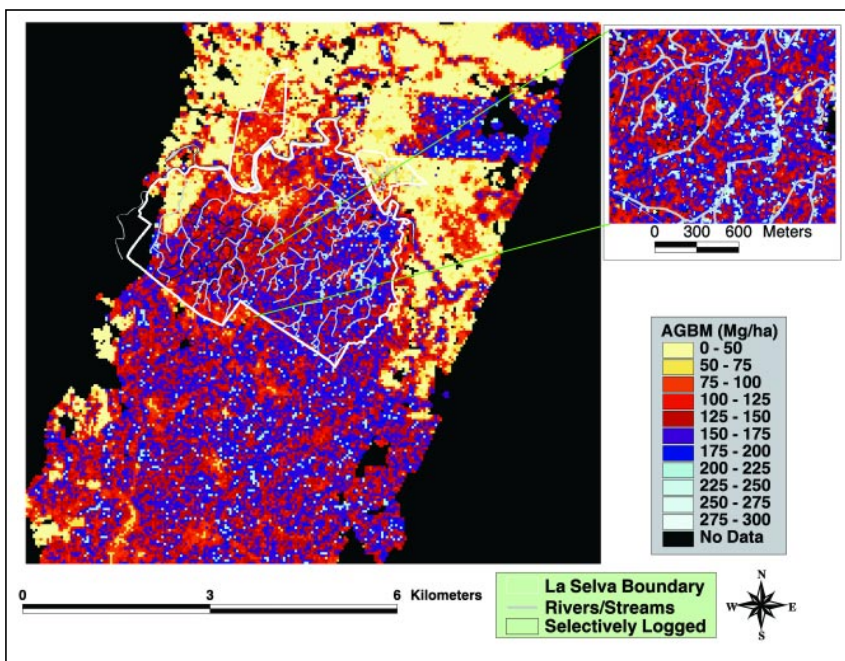
Lidar remote sensing only recently has become available as a research tool, and it has yet to become widely available. Nevertheless, it has already been shown to be an extremely accurate tool for measuring topography, vegetation height, and



**Figure 9.** Scatterplots of predicted and observed stand attributes from 22 plots at the H. J. Andrews Experimental Forest. Figure adapted from Lefsky et al. (1999b), with permission from Elsevier Science.

cover, as well as more complex attributes of canopy structure and function. In addition, the basic canopy structure measurements made with lidar sensors have been shown to provide highly accurate and nonasymptotic estimates of im-

portant 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.



**Figure 10.** Map of aboveground biomass (AGBM) predicted from LVIS data over La Selva Biological Station, adapted from Drake et al. (forthcoming), with permission from Elsevier Science and Jason Drake.

The availability of lidar data will increase with the launch of several spaceborne lidar missions and the broader use of airborne sensors for topographic 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. Indices of structural complexity also may be able to identify areas of probable high biodiversity, which could then be used to assist projects such as the national Gap Analysis Program (GAP; Scott and Jennings 1998).

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. In addition, 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.

More generally, lidar remote sensing shows great potential for integration with ecological research precisely because it directly measures the physical attributes of vegetation canopy structure that are highly correlated with the basic plant community measurements of interest to ecologists. Until recently, detailed measurement and modeling of canopies have 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 ecological research and put vegetation canopy structure squarely at the center of efforts to measure and model global carbon dynamics.

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