Using Airborne Lidar to Discern Age Classes of Cottonwood Trees in a Riparian Area

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ABSTRACT: *Airborne lidar (light detecting and ranging) is a useful tool for probing the structure of forest canopies. Such information is not readily available from other remote sensing methods and is essential for modern forest inventories. In this study, small-footprint lidar data were used to estimate biophysical properties of young, mature, and old cottonwood trees in the San Pedro River basin near Benson, Arizona. The lidar data were acquired in June 2004, using Optech's 1233 ALTM during flyovers conducted at an altitude of 600 m. Canopy height, crown diameter, stem dbh, canopy cover, and mean intensity of return laser pulses from the canopy surface were estimated for the cottonwood trees from the data. Linear regression models were used to develop equations relating lidar-derived tree characteristics with corresponding field acquired data for each age class of cottonwoods. The lidar estimates show a good degree of correlation with ground-based measurements. This study also shows that other parameters of young, mature, and old cottonwood trees such as height and canopy cover, when derived from lidar, are significantly different ($P < 0.05$). Additionally, mean crown diameters of mature and young trees are not statistically different at the study site ($P = 0.31$). The results illustrate the potential of airborne lidar data to differentiate different age classes of cottonwood trees for riparian areas quickly and quantitatively. West. J. Appl. For. 21(3):149–158.*

Key Words: Lidar, canopy, cottonwood, riparian, San Pedro River basin.

Vegetation patterns and associated canopy structure influence landscape functions such as water use, biomass production, and energy cycles. The properties of vegetation and canopy must be quantified to understand their roles in landscapes and before management plans can be developed for the purpose of conserving natural resources.

Vegetation patterns can be mapped from ground-based inventory techniques, or by using aerial photography or satellite imagery. If sampling is sufficiently intense, ground-based techniques alone can produce accurate results. However, determining the physical properties of canopy architecture and structure (i.e., height, density, and timber volume) with conventional ground-based technology is dif-

ficult, labor-intensive, costly, and usually very limited for assessing large-scale or landscape characteristics. Resource managers have become increasingly interested in developing and using alternative sources of information that are more cost-effective or offer opportunities to manage resources more efficiently.

Recent progress in three-dimensional forest characterization at the stand level mainly includes digital stereophotogrammetry, synthetic aperture radar, and lidar (light detecting and ranging). Lidar is a technique in which light at high frequencies, typically in the infrared wavelengths, is used to measure the range between a sensor and a target, based on the round-trip travel time between source and target. Airborne laser scanning is a measurement system in which pulses of light (most commonly produced by a laser) are emitted from an instrument mounted in an aircraft, directed to the ground in a scanning pattern. This method of recording the travel time of the returning pulse is referred to as pulse ranging (Wehr and Lohr 1999). The type of information collected from this returning pulse distinguishes two broad categories of lidar sensors: discrete-return (small footprint) lidar devices and full-waveform (large footprint) recording devices.

The foundations of lidar forest measurements lie with the photogrammetric techniques developed to assess tree height, canopy density, forest volume, and biomass. Airborne laser measurements were used in place of photogrammetric measurements to estimate forest heights and canopy density (Nelson et al. 1984) and forest volume or biomass (Maclean and Krabill 1986, Nelson et al. 1988a, 1988b). For instance, Nelson et al. (1988b) predicted the volume and biomass of southern pine (*Pinus taeda, Pinus elliotti, Pinus echinata, and Pinus palustris*) forests using several estimates of canopy height and cover from small-footprint lidar, explaining between 53% and 65% of the variance in field measurements of these variables.

Research efforts investigated the estimation of forest stand characteristics with scanning lasers that provided lidar data with either relatively large laser footprints (Blair et al. 1999, Lefsky et al. 1999) or small footprints, but with only one laser return (Naesset 1997a, 1997b, Magnussen et al. 1999). Small-footprint lidars are available commercially and research results on their potential for forestry applications are very promising. Despite the intense research efforts, practical applications of small-footprint lidar have not progressed as far, mainly because of the current cost of lidar data.

The height of a forest stand is a crucial forest inventory attribute for calculating timber volume, site potential, and silvicultural treatment scheduling. Tree heights have been derived from scanning lidar data sets and have been compared with ground-based canopy height measurements (Naesset 1997a, 1997b, Magnussen et al. 1999). Results were well correlated with ground-based data, but a high spatial density of lidar shots is required to achieve an acceptable level of accuracy.

An estimate of canopy cover has been made using discrete-return lidar devices. This estimate is produced by counting the number of measurements considered to have been returned from the canopy surface and dividing the result by the total number of measurements for the study site (Ritchie et al. 1993, Weltz et al. 1994), where the measurements are the number of discrete returns.

The primary purpose of this research was to use a small-footprint lidar to estimate biophysical variables in cottonwood trees in the San Pedro Riparian National Conservation Area (SPRNCA) in southeastern Arizona. The SPRNCA is a globally important migratory bird route. Its cottonwood riparian forest supports a great diversity of species and is widely recognized as a regionally and globally important ecosystem (World Rivers Review 1997, Internet document available online at www.irn.org/pubs/wrr/9701/briefs.html. May 15, 2004). Additionally, lidar studies published to this point have shown success in several forest types with large-footprint lidar, but applications of small-footprint lidar to forestry have not progressed as far (Means 2000), being limited mainly to measuring even-aged conifer stands. Thus, the performance of lidar in cottonwood riparian forests remains untested and any related analytical and processing issues still need to be identified. The main objective of this study was to differentiate different age classes of

cottonwood trees by using small-footprint lidar for riparian areas. Riparian cottonwood trees use water in proportion to their age (Schaeffer et al. 2000) and are especially large users of water in floodplains along rivers in semiarid environments. More accurate quantification of riparian water use is required to manage basin water resources to maintain the economic, social, and ecological viability of these areas and ensure water for a growing human population in the basin. Cottonwoods of different age cannot be distinguished by multispectral methods. However, the older cottonwoods exhibit a canopy that is more crowned in shape than the younger trees; thus, differences in tree shape as a function of tree age led us to investigate the use of lidar to identify and classify cottonwoods of different age classes. Another important reason for determining the age and canopy characteristics of cottonwood is to discern the recruitment and establishment of cottonwood seedlings in riparian corridors. Because of regulation of streamflow by dams and reservoirs in many western rivers, the occurrence of significant floods, which are essential for the recruitment of young cottonwoods, has been reduced greatly. The capability of rapidly quantifying the age distribution of cottonwoods from lidar in a riparian corridor would provide a useful indicator of cottonwood regeneration capacity of a given corridor. The specific goals of this study were:

1. Derive various geometric measures for different age classes of cottonwoods from lidar data and determine the relationships between cottonwood biophysical properties with ground-based measurements.

2. Use lidar-derived metrics to differentiate different age classes of cottonwood trees.

Materials and Methods

Study Area

The study was conducted along a reach of the San Pedro River (Escalante study site; 31°51′ N 110°13′ W; 1,110-m elevation) within the SPRNCA in southeastern Arizona (Figure 1). The study site is about 1.2 km long north to south and 1.4 km wide east to west and is relatively flat. The overstory is dominated by riparian forest vegetation, consisting of cottonwood (*Populus fremontii*) and mesquite (*Prosopis velutina*) as dominant and subdominant overstory species, respectively. The study area is populated by young-to-old dense cottonwood stands. Patches of cottonwood riparian forest are located along the stream channel. The understory consists mainly of a perennial bunchgrass (*Sporobolus wrightii*), creosote (*Larrea tridentata*), and saltcedar (*Tamarix chinensis*).

Ground Inventory Data

Ground validation data were collected from July 2004 to April 2005. Three different ages of cottonwood trees were included in the field sampling: young cottonwoods (less than 15 years), mature cottonwoods (16–50 years), and old cottonwoods (greater than 50 years; Figure 2). Stem dbh (diameter measured at 1.37 m above the ground) were measured with a diameter tape and recorded to the nearest millimeter to discriminate between young, mature, and old
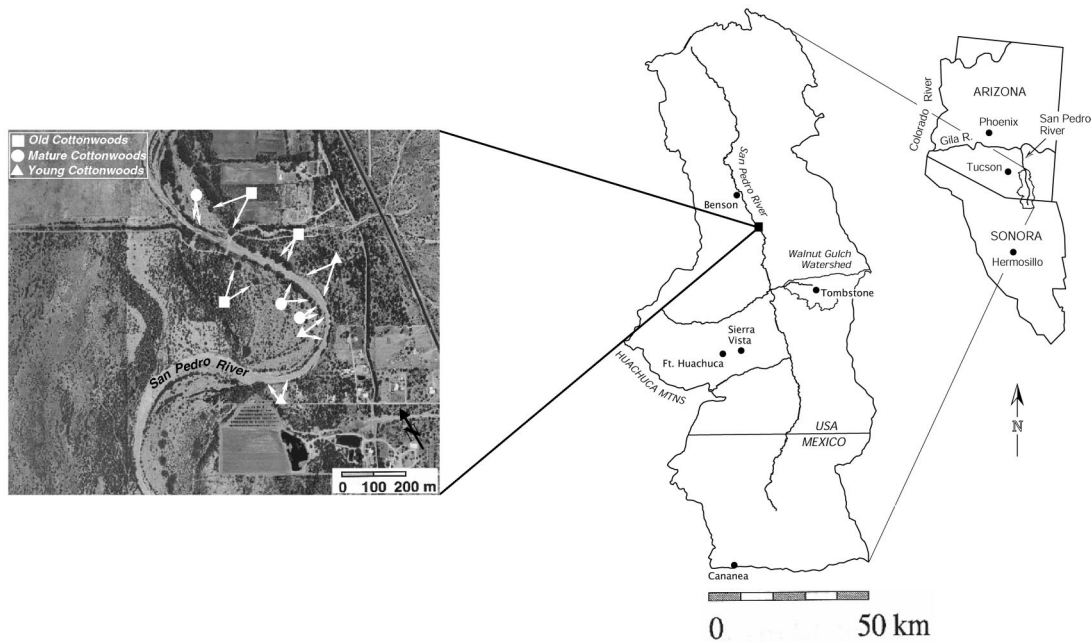
Figure 1. Location map and color infrared aerial photograph of the Escalante study site in the San Pedro River basin, Arizona.

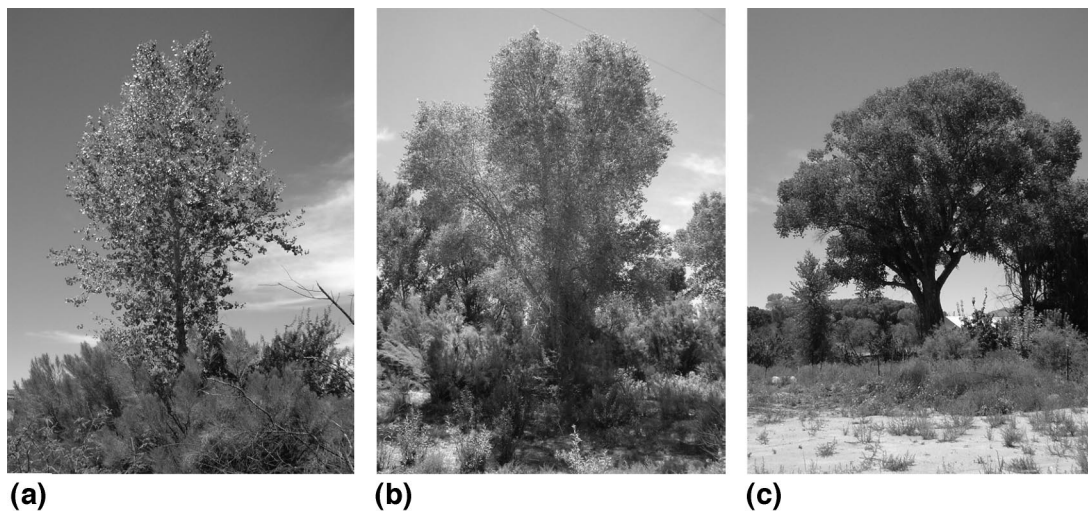**(a)**   **(b)**   **(c)**

Figure 2. Photos depicting (a) young, (b) mature, and (c) old cottonwood trees.

cottonwood patches, based on river-specific equations that relate dbh to tree age (Stromberg 1998). The dbh values varied from less than 25 cm for young cottonwoods, 25–90 cm for mature cottonwood stands, and greater than 90 cm for old cottonwoods.

A total of 84 cottonwood trees were used to determine forest mensuration. Of the 84 cottonwoods, 25 old, 30 mature, and 29 young isolated trees were selected that were at least 6 m apart. A differential global positioning system (DGPS) was used to determine the location of each individual tree within submeter planimetric accuracy (5700 GPS, Trimble Navigation, Ltd., Sunnyvale, CA). We measured four points around each tree at the edge of the tree canopy. In addition, all tree locations were determined using 60-second static measurements with a 12-channel GPS re-

ceiver. The GPS antenna height varied between 1.8 and 3.6 m, with an average height of 2.5 m. All measurements were collected during the leaf-off season. The lack of canopy foliage and the raised antenna in the old cottonwood stands reduced the error effects of forest canopies on GPS measurements. These trees were identified in the lidar data set by matching field DGPS locations with the georeferenced lidar data.

Within the study area, dbh, tree height, and crown widths along the major and minor axes were measured for each cottonwood tree. It was assumed that cottonwood tree crowns could be represented by an ellipsoidal geometric shape. The height and crown widths along the major and minor axes were estimated using a handheld laser distance measuring instrument (Impulse 200LR, Laser Technology,

Inc., Englewood, CO). Two measures for height were taken from different vantage points separated by 90°. The mean of these two height measures for each tree was regressed on the corresponding height estimated from lidar data. The crown diameter, the average of crown widths along two perpendicular directions, was measured for each crown. Descriptive statistics of the field inventory data for young, mature, and old cottonwoods were computed and are given in Table 1. The mean dbh was 22 cm for young cottonwoods. The mean dbh for mature and old cottonwoods was 51 and 106 cm, respectively. As would be expected, the young cottonwoods had the lowest height with values ranging from approximately 7 to 16 m. The lowest mean crown diameter also corresponded to the young trees with a value of 5 m. Old cottonwoods were the tallest trees with values ranging from 20 to 27 m in height with a mean crown diameter at 21 m. For mature cottonwoods, height ranged from 15 to 22 m, with a mean crown diameter of 10 m.

Lidar Data Set and Analysis

The Optech ALTM 1233 (Optech, Inc., Toronto, Canada) was used to survey the study site on June 22, 2004. Characteristics of the ALTM 1233 include a pulse rate of 33 kHz, a scanning frequency of 28 Hz, a scan angle of ±20°, a collection mode of first and last returns, and intensity of returns from a 1,064-nm laser. The ALTM 1233 was mounted on a University of Florida plane flying at 600 m above the ground at a velocity of 60 m/s. The aircraft and ALTM 1233 configuration resulted in a cross-track point spacing of 0.73 m, a forward point spacing of 2.1 m, and a footprint size of approximately 15 cm. The density of lidar point measurements is approximately 2–4 points/m²; as a result, the entire study area was covered by eight parallel flight lines. For the entire research area, 50% overlapping flight lines were used to ensure complete coverage, which generated approximately 5 million laser returns. The lidar data were processed and classified using the Optech REALM 3.0.3d software (Optech, Inc.). Three data layers were produced from the classification: (1) ground last, (2) vegetation last, and (3) vegetation first. The ground last data layer was a robust representation of the terrain. For this

study, vegetation last and vegetation first data layers were merged into a single vegetation class.

To derive any type of tree height measurement, a ground reference level must be established. The point data in the ground class were interpolated using the kriging interpolation technique to produce a digital elevation model (DEM) with a 0.5-m spatial resolution. Kriging is a method of interpolation that predicts unknown values from data observed at known locations. This method uses a variogram to express the spatial variation, and it minimizes the error of predicted values, which are estimated by spatial distribution of the predicted values (Oliver and Webster 1990). The DEM was created by ordinary kriging (no drift) using the linear semivariogram model (slope = 1, anisotropy ratio = 1, and anisotropy angle = 0) and the 25 closest points at each grid node. Kriging is a powerful and flexible gridding method. This method sufficed in producing accurate elevation models in comparison with other techniques such as inverse distance weighted (Cressie 1991). Kriging interpolation also works best for known values that are not evenly scattered (Oliver and Webster 1990). Additionally, the kriging technique has the ability to provide an assessment of the interpolation error (Cressie 1991). The point data in vegetation-classified hits were interpolated to a regular grid that corresponded to the DEM, thereby creating a canopy altitude model. The canopy altitude model was produced by ordinary kriging (no drift) using the linear semivariogram model with a nugget effect (error variance = 0.05 and microvariance = 1) and the 16 closest points at each grid node. Additionally, the search radius for the canopy altitude model is less than the DEM search radius. The canopy altitude model has a grid size of 0.5 m. Figure 3 shows the terrain and overlaid canopy altitude model for the study site. The local maximum technique (Wulder et al. 2000) was used to discriminate cottonwoods in the canopy altitude model. The process for using the local maximum technique took place in different steps. First, four differentially corrected GPS points were acquired in the field at the corners of a square centered on each cottonwood, from which we identified each cottonwood on the canopy altitude model. Second, the algorithm reads the elevation value at each pixel in the tree's canopy altitude model and if the current pixel corresponds to the local maximum, it is flagged as a tree top. The base of the tree was taken to be the point on the DEM beneath the top of the tree. Tree height was calculated by subtracting the elevations of the bottom from the top of the tree. Finally, successful identification of the tree crown using the local maximum technique depends on the careful selection of the filter window size. Tree crown form has been associated with different geometric shapes. Although the form of a tree crown does not follow exactly a Euclidean geometric shape, when seen from above, the tree crown can be projected most closely within a circle. Therefore, it is evident that using local maximum technique to identify individual crowns with a circular window of variable diameter is more appropriate than using a square window (Popescu et al. 2003). The derivation of the appropriate window size is based on the assumption that there is a
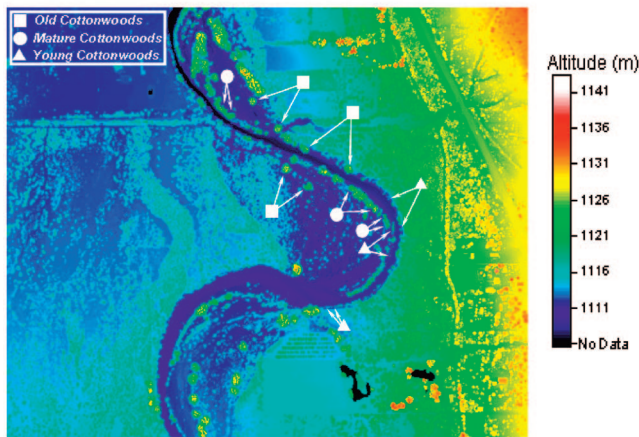
Table 1. Descriptive statistics of the field inventory data for young, mature, and old cottonwoods.

Statistic	dbh (cm)	Height (m)	Crown diameter (m)
Young (n = 29)			
Mean	22	12	5
Minimum	10	7	4
Maximum	29	16	9
SD	6	3	1
Mature (n = 30)			
Mean	51	19	10
Minimum	27	15	6
Maximum	73	22	15
SD	15	3	3
Old (n = 25)			
Mean	106	24	21
Minimum	93	20	11
Maximum	131	27	32
SD	12	2	7

SD, standard deviation.
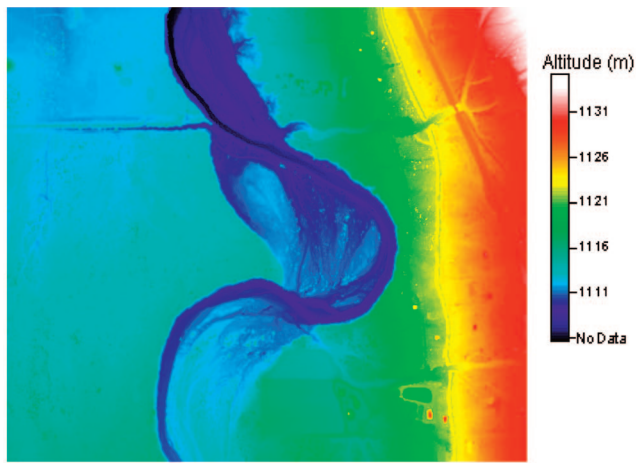
Figure 3. Spatial pattern of DEMs (a) bare ground model and (b) canopy altitude model for the study site.

relationship between the height of the trees and their crown width. Thus, tree height and crown width data from the field inventory were used to derive a relationship between tree height and crown width. Based on the canopy altitude model heights and the relationships between the height and crown width, the window size varied between 8×8 pixels and 63×63 pixels, which corresponds to crown widths between 4.0 and 31.5 m. This algorithm was implemented in IDL version 6.0 (Research Systems, Inc., Boulder, CO).

The process for computing the lidar estimate of dbh for different age classes of cottonwoods took place in three steps: (1) the relation of field measurements of tree height and dbh was incorporated into a second-order polynomial regression procedure; (2) field height was replaced by lidar height in the regression analysis, with Equations 1, 4, and 7 in Table 2; and (3) lidar tree dbh was predicted from lidar tree height metric by using second-order regression equation. The lidar estimate of canopy cover was determined for each age class of cottonwood tree by counting the number of first returns from the canopy surface and dividing by the total number of the first and last returns. Canopy cover is estimated in percent and is related to the size of the objects (tree crowns).

Lidar crown diameter is the average of two values measured along two perpendicular directions of the same canopy altitude models. The two perpendicular directions of each tree crown are centered on the tree top. The fourth-degree polynomial allows the corresponding function to have a convex shape along the vertical profile of each direction of tree crown. The fitted function follows the vertical profile of a tree crown, and points of inflection or critical points occur on the edges of a crown profile, where the concavity of the fitted function changes. When these conditions are met, the fitted function indicates a tree crown profile; the distance between critical points was used to calculate the length of each of the two directions. The critical points of the fitted function were found based on the first and second derivatives. A similar technique was used by Popescu et al. (2003) with lidar data to estimate crown diameter for stands of pine and deciduous trees.

Intensity of Reflected Laser Pulse

Little work has been published on the information content of lidar intensity returns for vegetation/forest analysis. For instance, Schreier et al. (1984) developed a method to discriminate broadleaf and conifer forests based on canopy heights, the power of the laser intensity return, and the variability of the power; Lim et al. (2003) derived mean laser height from filtered lidar returns, based on a threshold applied to the intensity return values for tolerant hardwood forests in Canada. The return intensity is related to surface

Table 2. Regression equations and statistics for cottonwood forest structural characteristics.

Forest structural characteristic	Equation	$*R^2$ values	RMSE
Young			
Height (m)	(1) Field height = 1.16 + 0.90 × Lidar height	0.90	0.74
Crown diameter (m)	(2) Field crown diameter = −1.13 + 1.17 × Lidar crown diameter	0.84	1.58
dbh (cm)	(3) Field dbh = 0.02 + 1.03 × Lidar dbh	0.67	3.27
Mature			
Height (m)	(4) Field height = 1.03 + 0.97 × Lidar height	0.87	0.97
Crown diameter (m)	(5) Field crown diameter = 3.32 + 0.76 × Lidar crown diameter	0.81	1.77
dbh (cm)	(6) Field dbh = −2.46 + 1.03 × Lidar dbh	0.64	8.85
Old			
Height (m)	(7) Field height = 4.26 + 0.89 × Lidar height	0.81	1.97
Crown diameter (m)	(8) Field crown diameter = 0.20 + 1.02 × Lidar crown diameter	0.88	1.23
dbh (cm)	(9) Field dbh = 38.27 + 0.64 × Lidar dbh	0.59	9.42

* All values significant ($P < 0.01$).

reflectance. At lidar wavelength, young cottonwoods exhibit different reflectance than older ones because of their different leaf area index (LAI; Schaeffer et al. 2000). Thus, the return intensity could potentially assist in the discrimination of different age classes of cottonwoods. Using basic exploratory data analysis techniques, the mean of the intensity distribution of each canopy surface was calculated for all cottonwoods.

Results and Discussion

Lidar versus Ground-Based Estimates of Canopy Properties

Linear regression models were used to develop equations relating lidar-derived parameters, such as tree height and crown diameter, with corresponding field inventory data for each age class of cottonwood trees. The linear regression models that were found to be the most predictive were then cross-validated (Cressie 1991) to define a generalization error (root mean square error [RMSE]). Lidar forest biophysical properties such as mean height have been compared, with varying accuracy and strength of correlation, to ground measurements in temperate (Maclean and Krabill 1986), tropical (Nelson et al. 1997), and boreal (Naesset 1997a, Magnussen et al. 1999) forests. However, the performance of lidar in cottonwood riparian forests remained untested and any related analytical and processing issues still have to be identified. Also, in previous studies, regression models for developing equations relating lidar-derived variables with corresponding field inventory data were used to differentiate between different forest types; but in this study, these models are used to differentiate between different ages of one forest type (cottonwood). A summary of all regression models that we developed is presented in Table 2. Figure 4, a–c, contains the scatterplots comparing lidar-derived and field-measured height for each type of cottonwood tree. In this case, the coefficients of determination for lidar versus field heights were 0.90, 0.87, and 0.81 for young, mature, and old, respectively. The lowest r^2 value was obtained for old cottonwoods. The lidar system presents difficulties in detecting the uppermost portion of old cottonwood tree canopies because of the conical nature of the tree crown. 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 addition, determining the exact elevation of the ground surface poses difficulties for both old and mature cottonwoods because the understory is dense enough to substantially occlude the ground surface. As a result, old cottonwood tree heights were underestimated. During fieldwork, many situations arose where the top of an old tree crown was not discernible and Impulse 200LR was simply pointed at what was perceived to be the tree top. The r^2 increased from 0.81 to 0.90 when young cottonwoods were considered. The actual ground terrain detected by lidar for young trees is more accurate and precise than those estimates for old and mature trees because the area beneath the young trees is predominantly bare soil. However, even given these complications,

it is encouraging that the height RMSE was less than the typical vertical accuracy of small-footprint lidar (~10 cm). The scatterplots comparing lidar-derived and field-measured crown diameter for each age class of cottonwood trees are presented in Figure 4, d–f. The coefficients of determination for lidar versus field crown diameters were 0.84, 0.81, and 0.88 for young, mature, and old, respectively. The lowest r^2 value was obtained for mature cottonwoods because some of the crowns of mature cottonwoods overlap, whereas the algorithm for calculating crown diameter on the lidar canopy altitude model applies best to measuring nonoverlapping crowns. The field measurements considered crowns to their full extent and therefore measured overlapping crown diameters. The r^2 improved from 0.81 to 0.88 when old cottonwoods were examined. The crowns of these old cottonwoods are isolated from each other, and, therefore, lidar distinguished them easily and more accurately. Also, there is a large difference between the elevations of each tree crown and its surrounding understory vegetation, allowing easier discrimination between their pixels on the lidar canopy altitude model. Part of the unexplained variance for crown diameter can also be attributed to errors of coregistration between lidar and the ground location of trees, influenced by both lidar positioning accuracy and DGPS errors for locating trees.

The scatterplots comparing lidar-derived and field-measured dbh for each age class of cottonwoods are shown in Figure 4, g-i. Results from regressing dbh on all age classes of cottonwoods did not produce r^2 values greater than 0.70. The relatively poor regression relationship is likely because dbh derived indirectly from the relation of field tree height to field-measured dbh; therefore, lidar dbh accuracy is directly related to the accuracy of the height estimate from lidar. The highest r^2 was found for young trees, because the relative accuracy of young tree height estimates from lidar data is the highest of the three tree age groups. Meanwhile, the RMSE for all age classes of tree dbh (Table 2) is the highest.

The results of comparison of tree height between lidar and the field measurement for old, mature, and young cottonwood trees are presented in Figure 5, a-c. The range of differences of tree height between lidar and the field measurements for all types of cottonwoods is 10~200 cm, reflecting a relatively good correlation overall. Lidar heights tend to be somewhat lower than field measurements (Figure 5a). However, in some of the young trees (Figure 5c), tree height calculated by lidar is higher than field measurements. This may have occurred because of lidar returns reflected from the canopy top of taller trees in close proximity to the field-measured trees.

Differences among Age Classes of Cottonwood Trees

In contrast to Lefsky et al. (1999), which explained differences in canopy structure between four age classes of Douglas-fir and western hemlock forests using full-waveform lidar, we differentiated different age classes of cottonwoods using various lidar metrics such as height
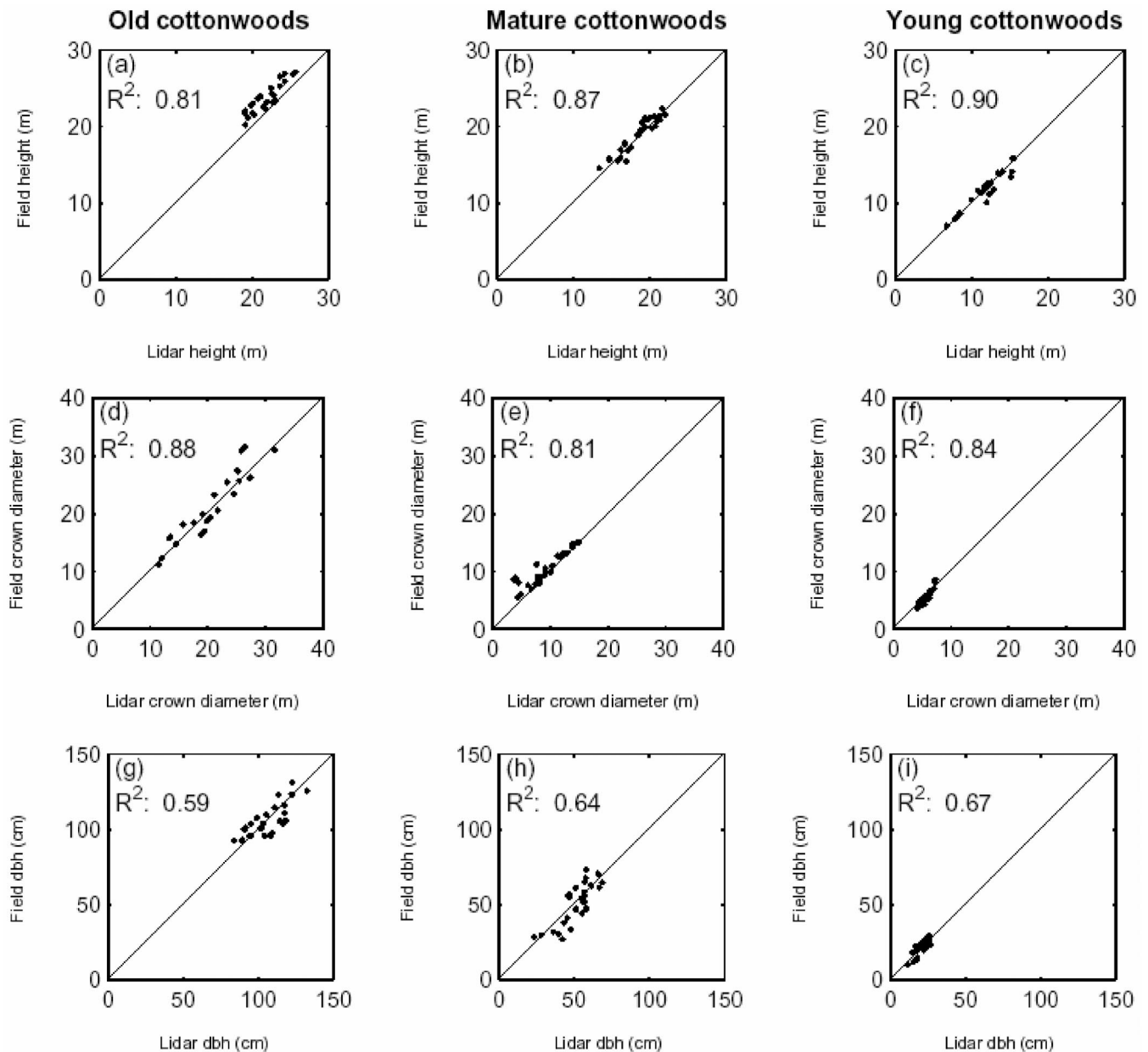
Figure 4. Scatterplots comparing lidar-derived and field-measured (a-c) height, (d-f) crown diameter, and (g-i) dbh for different age classes of cottonwood trees in the study region.

based on statistical analysis. Comparing lidar-derived mean heights for age classes indicates, as expected, that tree height is correlated to age (Figure 6a) and is statistically significant by age class. The old cottonwoods had the highest mean height estimate. An independent samples t-test showed the difference between young and mature means of height was significant ($P < 0.001$). Also, mean heights of young and old trees differed significantly ($P < 0.001$). The old and mature trees were taller and lidar showed this difference quite well. Similarly, Figure 6, b and c, compare the mean of crown diameter and canopy cover. As expected, the young cottonwoods had the lowest mean crown diameter. The highest mean crown diameter was estimated for old cottonwoods. The mean crown diameter of old trees was higher than young trees ($P = 0.0001$) because old cotton-

woods had cone- or cylinder-shaped crowns, whereas young cottonwoods had narrow and upright crowns. Some of the crowns of mature trees overlapped. Because the algorithm for calculating crown diameter on the lidar canopy altitude model was best suited to measure the nonoverlapping portion of crowns, the lidar-estimated crown diameter is lower than field-determined size. Thus, mean crown diameters of mature and young trees were not statistically different at the study site ($P = 0.31$).

The mean canopy cover was significantly different for young and old cottonwoods with young canopy cover less than old canopy cover ($P = 0.0003$). The young cottonwoods have columnar-shaped crowns and thus their crown size is much smaller than for old trees, which have conical and flat-topped crowns. Mean canopy covers of mature and
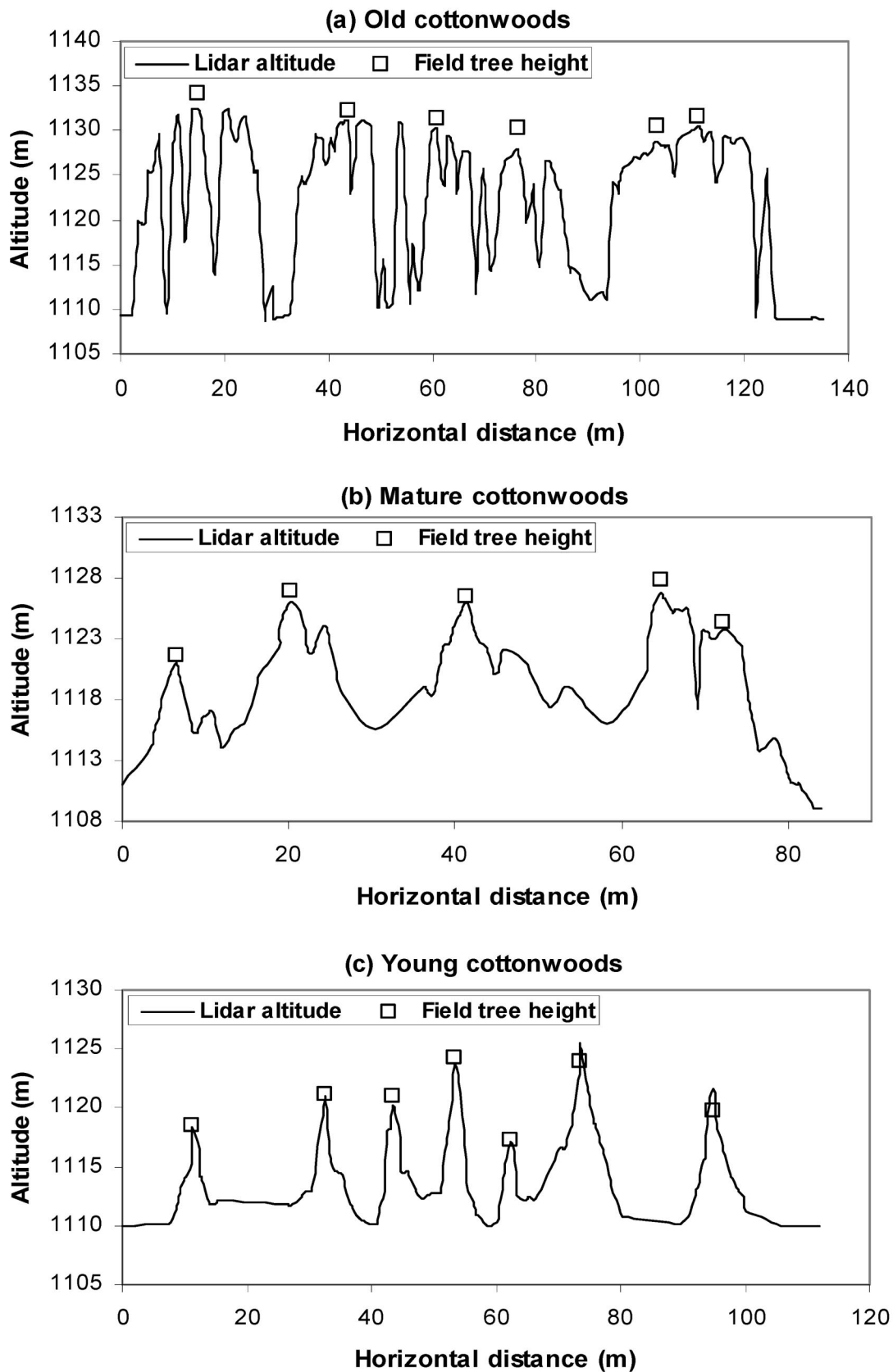
Figure 5. Comparison of height (cross-section) for (a) old, (b) mature, and (c) young cottonwood trees.

young also differed significantly ($P < 0.05$) at the study site. The lidar estimate of canopy cover is related directly to the number of laser returns from a crown, and because of the gaps in young canopies, a number of the laser pulses were able to penetrate the canopy, generating lower values for canopy cover.
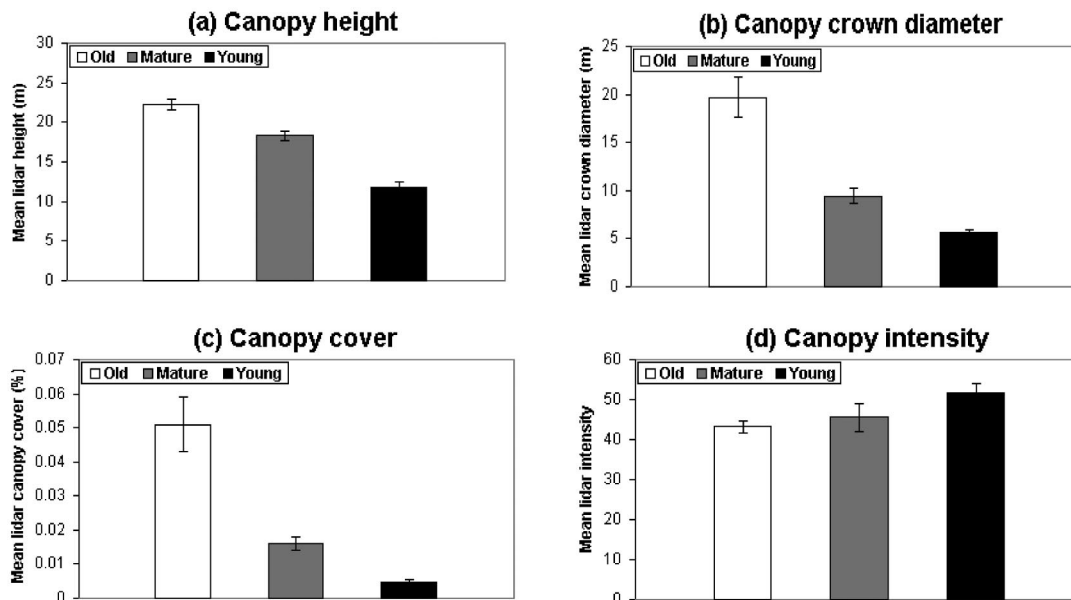
Figure 6. The *t*-test analyses comparing the means of (a) height, (b) crown diameter, (c) canopy cover, and (d) canopy intensity derived from lidar data for different age classes of cottonwood trees.

Mean lidar intensities were least for old and greatest for young canopies (Figure 6d). The return intensity is related to surface reflectance. At 1,064-nm wavelength, young cottonwoods exhibit higher reflectance than older ones because of their higher LAI (Schaeffer et al. 2000) and different leaf architecture, such as less drooping and less microgaps between leaves. Mean intensity of mature trees did not differ significantly ($P = 0.16$) from young ones. The reflectance of mature and young canopies is similar because of their leaves and branches having almost the same color and brightness, as seen in Figure 2. It is evident from this discussion that more study is required, focusing on the information content of intensity return data and the factors that influence how much energy is reflected from a surface back to a lidar sensor. Furthermore, lidar-derived canopy metrics from this study and the return intensity data will be incorporated into supervised image classification algorithms, using a maximum likelihood technique, to differentiate age classes of cottonwood trees.

Conclusions

The results of this study show that lidar data can be used to accurately estimate the properties of cottonwood canopies at the individual tree level. Lidar offers the possibility of rapidly deriving biophysical variables in riparian areas using automated techniques. Thus, seeing the cottonwoods in the riparian forest and, more importantly, measuring them with lidar brings an important contribution to concepts such as precision forest inventory and automated data processing for riparian forestry applications.

Overall, this research proved that small-footprint airborne lidar data are able to predict stand structure attributes such as height, crown diameter, and canopy cover of riparian cottonwood forests. Measurements of cottonwood canopy properties made with lidar data in the riparian area were not significantly different from measurements taken on the ground. The main objective of this research was to use lidar-derived estimates to differentiate young, mature, and old cottonwood patches. The results illustrate the potential of lidar data to differentiate different age classes of cottonwood trees for riparian areas quickly and quantitatively. Furthermore, there is value in the intensity return data for assisting in differentiating cottonwood trees, but this parameter needs further investigation to develop a good understanding of the factors affecting how intensity returns are produced and recorded by the lidar sensor.

Future research will apply the well-known Penman-Monteith model (Monteith and Unsworth 1990) to model age classes of cottonwood transpiration using lidar-derived canopy metrics, such as height and LAI, so improved riparian water use estimates can be made. The LAI will be derived by synthetically constructing a large-footprint lidar waveform from the airborne small-footprint lidar data. In addition, the capability to rapidly quantify the age distribution of cottonwoods in a riparian area will provide an indicator of cottonwood regeneration capacity of a given area.

Literature Cited

BLAIR, J.B., D.L. RABINE, AND M.A. HOFTON. 1999. The laser vegetation imaging sensor (LVIS): A medium-altitude, digitization-only, airborne laser altimeter for mapping vegetation and topography. ISPRS J. Photogramm. Remote Sens. 54:115–122.

CRESSIE, N.A. 1991. Statistics for spatial data. Wiley, New York. 900 p.

LEFSKY, M.A., W.B. COHEN, S.A. ACKER, T.A. SPIES, G.G. PARKER, AND D. HARDING. 1999. Lidar remote sensing of biophysical properties and canopy structure of forest of Douglas-fir and western hemlock. Remote Sens. Environ. 70:339–361.

LIM, K., P. TREITZ, K. BALDWIN, I. MORRISON, AND J. GREEN. 2003. Lidar remote sensing of biophysical properties of tolerant northern hardwood forests. Can. J. Remote Sens. 29:658–678.

MACLEAN, G.A., AND W.B. KRABILL. 1986. Gross-merchantable timber volume estimation using an airborne LIDAR system. Can. J. Remote Sens. 12:7–18.

MAGNUSSEN, S., P. EGGERMONT, AND V.N. LARICCIA. 1999. Recovering tree heights from airborne laser scanner data. For. Sci. 45:407–422.

MEANS, J.E. 2000. Comparison of large-footprint and small-footprint lidar systems: design, capabilities, and uses. P. 85–192 *in* Proc. of the 2nd international conf. on geospatial information in agriculture and forestry, Vol. 1, Jan. 10–12, 2000, Lake Buena Vista, FL (ERIM International). Altarum Agricultural Conferences; Ann Arbor, MI.

MONTEITH, J.L., AND M.H. UNSWORTH. 1990. Principles of environmental physics. Edward Arnold, London. 291 p.

NAESSET, E. 1997a. Determination of mean tree height of forest stands using airborne laser scanner data. ISPRS J. Photogramm. Remote Sens. 52:49–56.

NAESSET, E. 1997b. Estimating timber volume of forest stands using airborne laser scanner data. Remote Sens. Environ. 61:246–253.

NELSON, R.F., W.B. KRABILL, AND G.A. MACLEAN. 1984. Determining forest canopy characteristics using airborne laser data. Remote Sens. Environ. 15:201–212.

NELSON, R.F., R. SWIFT, AND W.B. KRABILL. 1988a. Using airborne lasers to estimate forest canopy and stand characteristics. J. For. 86:31–38.

NELSON, R.F., W.B. KRABILL, AND J. TONELLI. 1988b. Estimating forest biomass and volume using airborne laser data. Remote Sens. Environ. 24:247–267.

NELSON, R.F., R. ODERWALD, AND T.G. GREGOIRE. 1997. Separating the ground and airborne laser sampling phases to estimate tropical forest basal area, volume, and biomass. Remote Sens. Environ. 60:311–326.

OLIVER, M.A., AND R. WEBSTER. 1990. Kriging: A method of interpolation for geographical information system. Int. J. Geogr. Inf. Syst. 4(3):313–332.

POPESCU, S.C., R.H. WYNNE, AND R.F. NELSON. 2003. Measuring individual tree crown diameter with lidar and assessing its influence on estimating forest volume and biomass. Can. J. Remote Sens. 29:564–577.

RITCHIE, J.C., D.L. EVANS, D. JACOBS, J.H. EVERITT, AND M.A. WELTZ. 1993. Measuring canopy structure with an airborne laser altimeter. Trans. ASAE 36:1235–1238.

SCHAEFFER, S.M., D.G. WILLIAMS, AND D.C. GOODRICH. 2000. Transpiration of cottonwood/willow forest estimated from sap flux. Agric. For. Meteorol. 105:257–270.

SCHREIER, H., J. LOUGHEED, J.R. GIBSON, AND J. RUSSELL. 1984. Calibrating an airborne laser profiling system. Photogramm. Eng. Remote Sens. 50(11):1591–1598.

STROMBERG, J.C. 1998. Dynamics of Fremont cottonwood (*Populus fremontii*) and saltcedar (*Tamarix chinensis*) populations along the San Pedro River, Arizona. J. Arid Environ. 40:133–155.

WEHR, A., AND U. LOHR. 1999. Airborne laser scanning-an introduction and overview. ISPRS J. Photogramm. Remote Sens. 54:68–82.

WELTZ, M.A., J.C. RITCHIE, AND H.D. FOX. 1994. Comparison of laser and field measurements of vegetation height and canopy cover. Water Resourc. Res. 30:1311–1319.

WULDER, M., K.O. NIEMANN, AND D.G. GOODENOUGH. 2000. Local maximum filtering for the extraction of tree locations and basal area from high spatial resolution imagery. Remote Sens. Environ. 73:103–114.