Small-footprint Lidar Estimations of Sagebrush Canopy Characteristics

Jessica J. Mitchell, Nancy F. Glenn, Temuulen T. Sankey, DeWayne R. Derryberry, Matthew O. Anderson and Ryan C. Hruska

Abstract

The height and shape of shrub canopies are critical measurements for characterizing shrub steppe rangelands. Remote sensing technologies might provide an efficient method to acquire these measurements across large areas. This study compared point-cloud and rasterized lidar data to field-measured sagebrush height and shape to quantify the correlation between field-based and lidar-derived estimates. The results demonstrated that discrete return, small-footprint lidar with high point density (9.46 points/m^2) can provide strong predictions of true sagebrush height (R^2 of 0.84 to 0.86), but with a consistent underestimation of approximately 30 percent. Our results provided the first successful lidar-based descriptors of sagebrush shape with R^2 values of 0.65, 0.74, and 0.78 for respective predictions of shortest canopy diameter, longest canopy diameter, and canopy area. Future studies can extend lidar-derived shrub height and shape measurements to canopy volume, cover, and biomass estimates.

Introduction

The height and shape of shrub canopies are critical measurements for characterizing shrub steppe landscapes in terms of structure, age, cover, critical wildlife habitat, fuel type, erosion, infiltration, evapotranspiration, disturbance history, and biomass. Aerial biomass estimates for big sagebrush (*Artemisia tridentata*) have been used to assess fuel loads (Frandsen, 1983), calculate available forage (Wambolt, 1994), delineate wildlife habitat (e.g., Eng and Schladweiler, 1972; Beck, 1977; Davies *et al.*, 2007), and study climate response (Harte and Shaw, 1995; Harte *et al.*, 2006). The traditional, direct method of measuring vegetative biomass by clipping and weighing (Bonham, 1987) is destructive and extremely cost-inefficient (Uresk, 1977; Clark *et al.*, 2008). Allometric equations have therefore been developed for rapid biomass assessments using volume-based metrics derived from height and crown characteristics (e.g., diameter, elliptical area, density, cover) (Harniss and Murray, 1976; Rittenhouse and Sneva, 1977; Uresk, 1977; Dean *et al.*, 1981; Murray and Jacobson, 1982; Frandsen, 1983; Tausch, 1989; Wambolt *et al.*, 1994; Clark 2008; Cleary *et al.*, 2008).

Remote sensing technologies offer potential solutions for extending sagebrush measurements collected on the ground to a range of spatial scales in a cost-efficient manner. Multispectral and hyperspectral studies designed to estimate shrub cover and leaf area index in semiarid shrub steppe are limited by multiple scattering, bright soil reflectance, open canopies and spectrally indiscriminate targets (e.g., Smith *et al.*, 1990; Jakubauskas *et al.*, 2001; Okin *et al.*, 2001; Mirik *et al.*, 2007). Small-footprint, discrete return lidar (airborne laser scanning) is not limited by many of these spectral challenges and has the potential for estimating shrub canopy characteristics at a range of scales appropriate for landscape assessments (Ritchie *et al.*, 1992 and 2001; Mundt *et al.*, 2006; Riano *et al.*, 2007; Streutker *et al.*, 2006; Su and Bork 2006, 2007). However, separating lidar returns in low-height rangeland vegetation is difficult because the vegetation canopy returns are often close to ground returns in both space and time. Furthermore, there are fewer vegetation returns in sparsely vegetated semiarid ecosystems than in more foliated ecosystems.

A limited number of studies have evaluated the use of lidar in shrub environments (Hopkinson *et al.* 2005; Streutker and Glenn, 2006; Riano *et al.*, 2007; and Su and Bork, 2007) and these studies have consistently found that small-footprint lidar systems underestimate shrub canopy height. Shrub height underestimation is attributed to the low probability of the laser hitting the top of the canopy, or laser pulses penetrating the canopy, which generates return signals from material within the canopy (Weltz 1994; Næsset and Økland 2002; Gaveau and Hill 2003, Clark *et al.* 2004). Hopkinson *et al.* (2005), using a sensor with an average point sampling density of over 3 m^{-2}, determined that their low shrub class (<2 m) had the highest proportion of height underestimation: 62 percent (52 cm) using the raw lidar point cloud data and 48 percent (39 cm) using a raster. Streutker and Glenn (2006) found that lidar data with an average point density of 1.2 m^{-2} systematically underestimated mountain sagebrush (*Artemisia tridentata* subsp. *vaseyana*) heights (<2 m) by approximately 50 percent and that underestimation was dependent upon canopy cover, with lower cover having greater error estimates. Riano *et al.*

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(2007) underestimated shrub height (<1.68 m) in a dense mixed shrub environment using a lidar sensor with an average point density of 3.5 m^{-2}. Although the magnitude of underestimation was not documented in their study, near-infrared imagery co-registered to the lidar point-cloud data reduced underestimation. Su and Bork (2007) used small-footprint lidar with an average point density of 0.54 m^{-2} to characterize a variety of community types and found a tendency toward shrub height underestimation (<1.30 m) in open environments. This study reported the magnitude of height underestimation in terms of signed-mean error, which varied from −4 to −16 cm, depending on the species.

To our knowledge, only a few lidar studies have estimated the accuracy of shrub canopy shape characteristics, and mixed results were obtained using an aerial cover approach defined by the ratio of vegetation returns to the total number of returns (Ritchie *et al.*, 1992; Weltz *et al.*, 1994; White *et al.*, 2000). Hopkinson *et al.* (2005) evaluated the accuracy of small-footprint lidar estimates of shrub volume by defining canopy volume as the vertical frequency distribution of the number of vegetation returns, stratified by height quantiles. This study compares lidar point-cloud data to sagebrush canopy characteristics measured in the field with the goal of quantifying prediction errors associated with height and 2D aerial shape measurements (canopy diameter and area) for individual shrubs.

Methods

Study Area

The study area is located in a cold desert sagebrush steppe environment on the Department of Energy, Idaho National Laboratory (INL) in southeastern Idaho. The INL site is located along the eastern Snake River plain in an intermountain landscape bounded by mountain ranges, buttes, and open plains. Dominant parent materials are loess and olivine basalt (DOE-ID, 1989). Air tends to be relatively dry (the average annual precipitation is 284.73 mm) and the area experiences extreme diurnal and seasonal fluctuations in ground temperature with an average daily temperature that ranges from −12.22°C in January to 15.70°C in July (DOE-ID, 1989). The area of analysis (Figure 1) consists of all land within an 805 m radius of an unmanned aerial vehicle test runway (43° 35′N; −112° 54′W). This portion of the INL has been closed to livestock grazing over the last 61 years. Fire burned patches in the southeastern portion of the study site in 2000. The study area and its vicinity are extremely flat, with elevations in the study area ranging from approximately 1,479 m to 1,496 m. The most abrupt elevation changes in the study site are associated with archaic drainage channels, including the Big Lost River, which does not presently conduct surface water through the study area. Microtopographical fluctuations created by historical agricultural practices are present in the northeastern portion of the project area. The study site is dominated by Wyoming big sagebrush (*Artemisia tridentata* subsp. *wyomingensis*), while basin big sagebrush (*Artemisia tridentata* subsp. *tridentata*) occurs in association with depressional areas and drainage channels. Other species common to the study area include yellow rabbitbrush (*Chrysothamnus viscidiflorus),* pricklypear cactus (*Opuntia* spp.), and crested wheatgrass (*Agropyron cristatum*).

Lidar Data Acquisition and Processing

High density (average density of 9.46 points/m^{-2}), small-footprint discrete return lidar data were collected for the study area on 13 December 2006. The seasonal timing of the acquisition was not anticipated to influence the outcome of this study since it was conducted in a shrub steppe landscape where sagebrush species still have overwintering leaves present after the ephemeral leaf drop at the end of the growing season (Bilbrough and Richards, 1993). The lidar data were acquired using an ALS50-II scanner (Airborne Laser Scanner, Leica Geosystems, Norcross, Georgia) operated by Merrick and Company (Aurora, Colorado). The sensor operates at a fixed wavelength (1.064 μm) and was flown at 2,286 m above sea level, which generated an illuminated footprint diameter of 18 cm at nadir for a +/−15° field of view and an average ground sample distance of 0.46 m in the along and cross track directions.

A vertical accuracy assessment was performed by the vendor using 125 control points collected throughout the paved runway, which is the most prominent flat feature in the project area. The resultant RMSE was 0.4 cm. The sensor manufacturer reports a lateral positional accuracy of 7 to 64 cm after postprocessing (depending on the field of view and scan angle). Project area vertical and horizontal accuracies were re-calculated to verify the integrity of the data. The absolute vertical accuracy of the lidar data was assessed by comparing elevations obtained using a survey grade Global Positioning System (GPS) to the nearest lidar posting. The receiver used to collect the elevation measurements is a Topcon HiPer Lite +, a Real Time Kinematic (RTK) unit capable of 1 cm horizontal and 1.5 cm vertical accuracies (Topcon, Livermore, California). A collection of 40 survey points along the runway indicated a tendency for the GPS reading to be slightly lower than the nearest lidar posting, with a maximum vertical difference of 5.1 cm and an RMSE of 2.2 cm. We assessed relative vertical accuracy by calculating the standard deviation of randomly selected clusters of lidar returns within the runway. The resultant relative vertical error was estimated at ± 1.8 cm. Maximum horizontal error was derived from surveyed building corners and conservatively estimated at 50 cm.

The image processing software Environment for Visualizing Images, version 4.5 (ITT Visual Information Solutions, Boulder Colorado) and the BCAL LIDAR Tools developed for rangeland vegetation (**http://bcal.geology.isu.edu/envitools.shtml**; Streutker and Glenn 2006) were used to height filter all of the lidar laser pulse returns and transform the resultant filtered returns into raster products. The vegetation height filtering procedure classified returns as either bare ground or vegetation; optimal filtering results were obtained using a natural neighbor interpolation method. Raster surfaces were generated in 0.5 m and 1 m grid sizes and included products such as maximum vegetation height, bare earth elevation, total point density, vegetation roughness, and local roughness.

Ground Reference Sampling

A total of 107 individual sagebrush shrubs were sampled throughout the project area from May to October 2009. It should be noted that the 2.5 year time lapse between lidar acquisition and field data collection could affect differences between lidar predictions and ground measurements. Annual sagebrush height growth, which is highly correlated with crown growth, is 8.5 cm and 12.7 cm for Wyoming big sagebrush and basin big sagebrush, respectively (McArthur and Welch, 1982). Since big sagebrush growth tends to stabilize about 30 years after disturbance (Watts and Wambolt, 1996; Lesica *et al.*, 2007; Sankey *et al.*, 2008), we tried to eliminate sampling in any portion of the project area that burned in 2000 by avoiding patches of standing, burned dead wood. Random points were generated, and the nearest spatially isolated sagebrush was sampled to minimize noise associated with mismatching data collected on the ground to

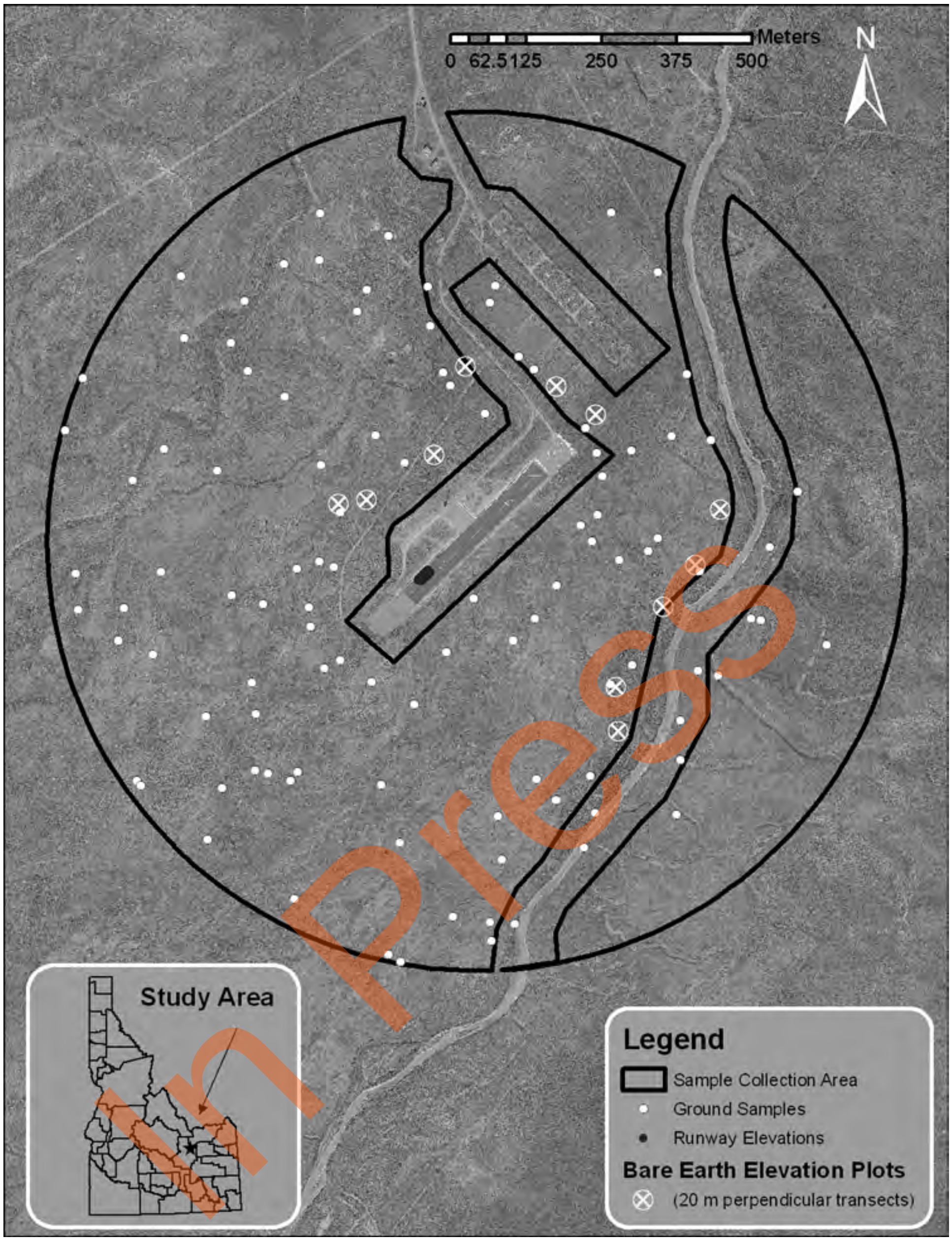

Figure 1. Location of lidar acquisition area and ground reference samples.

data collected by the lidar sensor. The center location of each shrub was recorded using a Wide Area Augmentation System (WAAS) enabled Trimble GeoXT (Sunnyvale, California) model GPS receiver and Trimble Pathfinder® differential correction software. Post-processed point data from this GPS unit is capable of sub-meter positional accuracy (Serr *et al.*, 2006). A maximum vegetation height value was obtained for each shrub by measuring from the ground level to the highest point of stem growth. An average maximum shrub height value was also obtained for 50 of the 107 samples to determine if a greater number of field-based height measurements were needed for each shrub. Average maximum shrub height was calculated by segmenting the canopy into six sections (60° segments centered on the center of the sagebrush). The highest point of stem growth within each segment was measured, and the six height measurements were then averaged. As a result, 50 of the total shrubs sampled in the field were measured using (a) the single tallest height measurement, and (b) an average of the six tallest sagebrush heights. Sagebrush shape was characterized in the field for 86 of the shrub samples by measuring the shortest and longest canopy diameters. The longest diameter (D_L) was defined by the greatest shrub width, with a line intercepting the center of the shrub. The shortest diameter (D_S) was defined by the shortest shrub width, with a line bisecting the longest diameter, not necessarily perpendicular. In the final analysis, five shrubs were removed from the pool of height samples (total n = 102) and eight shrubs were removed from the pool of shape samples (total n = 78) due to locational uncertainty or sampling along the boundary of two lidar tiles.

In addition, eleven circular plots were established in representative cover types throughout the project area to assess elevation accuracies in the point cloud data and raster bare earth model. Three of the plots were located in low shrub cover (1 to 10 percent), three in moderate shrub canopy cover (15 to 20 percent), two in high shrub canopy cover (>20 percent), and three in bunchgrass-dominant sites. Each plot included two line transects oriented perpendicular to each other and crossing at the center of the circular plot. The circular plots were 20 m in diameter, so each line transect was also 20 m in length. Bare earth elevations were collected along each transect at 1 m intervals, which generated 42 bare earth elevation measurements per plot. Measurements were collected using the survey grade Topcon HiPer Lite+ GPS receiver. Whenever vegetation was present at an elevation data collection point, the height of the vegetation was also recorded.

Assessment of Lidar Vegetation Height Predictions

Two different approaches were used to assess lidar-based sagebrush height estimations. First, lidar-derived maximum sagebrush height predictions were assessed by comparing field-based maximum height measurements of individual shrubs to corresponding lidar estimates from the point cloud data. Height comparisons using the lidar point-cloud data were made by manually subtracting the local minimum return from the highest lidar return within the target canopy. The local minimum return was typically considered the lowest return with a 3.0 m radius of the shrub center. Second, rasterized lidar estimates of maximum shrub heights at grid resolutions of 0.5 m and 1.0 m were compared to the field-based height measurements. Height comparisons using lidar raster products were made by identifying shrub samples on the 0.5 m and 1.0 m maximum vegetation height grids, extracting cell values, and then selecting the maximum cell value. In some cases field notes and photos were used to maximize certainty in relating shrubs measured in the field to corresponding lidar pixels. The data were assessed for normality and multiple least squares regression was used to quantify how well the lidar predicted true sagebrush height across scales. If there were no bias, the model would be, "Field Height = 0 + 1(lidar Height)." Observed vertical error in maximum sagebrush height estimations were also assessed using signed-mean error, mean absolute error, and RMSE by subtracting field height measurements from lidar estimates (Hodgson and Breshnahan, 2004). We compared the two different height measurement techniques used in this study (single maximum height and average of six maximum height values, $n = 50$) by regressing lidar-derived estimates of maximum vegetation height (0.5 m grid resolution only) against values obtained from each technique.

Assessment of Lidar Crown Area Predictions

The shortest and longest diameters of sagebrush shrubs measured in the field were related to lidar point cloud data using a combination of extraction and visualization techniques implemented in Esri ArcGIS® and ArcScene® 9.2 (Esri, Redlands, California). Circular 3 m buffers generated from the center of individual shrubs were used to extract height filtered lidar point data. A buffer radius of 3 m was chosen because the longest shrub canopy diameter measured in the field did not exceed 3 m. The extracted lidar point data were displayed three dimensionally and converted to triangulated irregular networks (TINs). To delineate individual shrub canopy boundaries, we visually examined the distribution of TIN elevation classes for each sample to distinguish background from shrub (Figure 2). If the shrub sample was part of a larger cluster of shrubs, photographs were used to isolate the shrub of interest. Crown diameter measurements (D_L, D_s) were used to calculate elliptical crown area, which has been successfully used in previous sagebrush studies as a variable in developing predictive relationships for biomass (Rittenhouse and Sneva, 1977; Murray and Jacobson, 1982; Frandsen, 1983; Wambolt *et al.*, 1994; Cleary *et al.*, 2008). Elliptical crown area (CV) was calculated as follows:

$$CV = (n D_L D_s)/4. \quad (1)$$

Lidar predictions of sagebrush crown area were assessed using linear regression analysis of lidar-derived and field-based measurements of shortest and longest diameters, and areas of individual shrubs.

Assessment of Lidar Bare Earth Elevation Predictions

Bare earth elevations surveyed within the 11 circular transect plots (20 m diameter) were related to lidar bare earth elevation predictions in the point-cloud data by creating bare earth transects from the lidar ground return data using BCAL LIDAR Tools (**http://bcal.geology.isu.edu/envitools.shtml**). For appropriate use of the bare earth elevation data, we examined each 20 m transect for evidence of spatial autocorrelation by generating partial autocorrelation function plots for the GPS elevation data, the lidar bare ground return data, and residuals from subsequent regressions of lidar and GPS elevations. The partial autocorrelation plots were constructed using the statistical software package SYSTAT, version 12 (Systat Software, Inc., Chicago Illinois). It was determined that autocorrelation appeared uniform throughout the study area and was moderate on average ($\rho = 0.2$ to 0.7). Consequently, by selecting the four outermost transect points of each plot (minimum separation distance of approximately 14 m), the points could be treated as independent observations in a single multiple least squares linear regression ($n = 44$), with autocorrelation between sample points estimated at $\rho = 0$ to 0.01. In all, three regressions were generated: one using the lidar point cloud data, and two using bare earth raster models (0.5 m and 1.0 m grid resolutions) created with BCAL lidar Tools. Vertical error estimations were computed for each regression by calculating signed-mean error, mean absolute error, and RMSE.

Results

When lidar predictions of maximum sagebrush height were regressed against corresponding field measurements of sagebrush height, the coefficients of determination (R^2) were 0.84 for the point cloud data and 0.86 for the maximum vegetation height grid products (both 0.5 m and 1.0 m resolution; Table 1). Residual plots (i.e., residuals probability plots and histograms of the residuals) and fitted line plots of the same data indicate that the regressions were correcting biases equally well for different sagebrush sizes. In general, predictions using the 0.5 m and 1.0 m grid based models (Field Height = 36.64 + 0.93(Lidar Height); Figure 3) are accurate to within ±27.94 cm (two standard deviations of S_E). As such, when the lidar reading is 40 cm, for example, the regression adjusts for bias in the lidar reading by estimating the true height to average 73.84 cm and vary between 45.90 cm and 101.78 cm. Observed vertical error in the predictions (Table 1) resulted in a slightly better RMSE for the point cloud data (34.27 cm) than for the grid products (34.90 cm). The lidar point cloud data produced slightly less maximum absolute error (30.86 cm) than the maximum vegetation height grid products (32.04 cm). Similarly, the signed-mean error indicated a strong tendency toward lidar underestimation: −30.69 cm using the

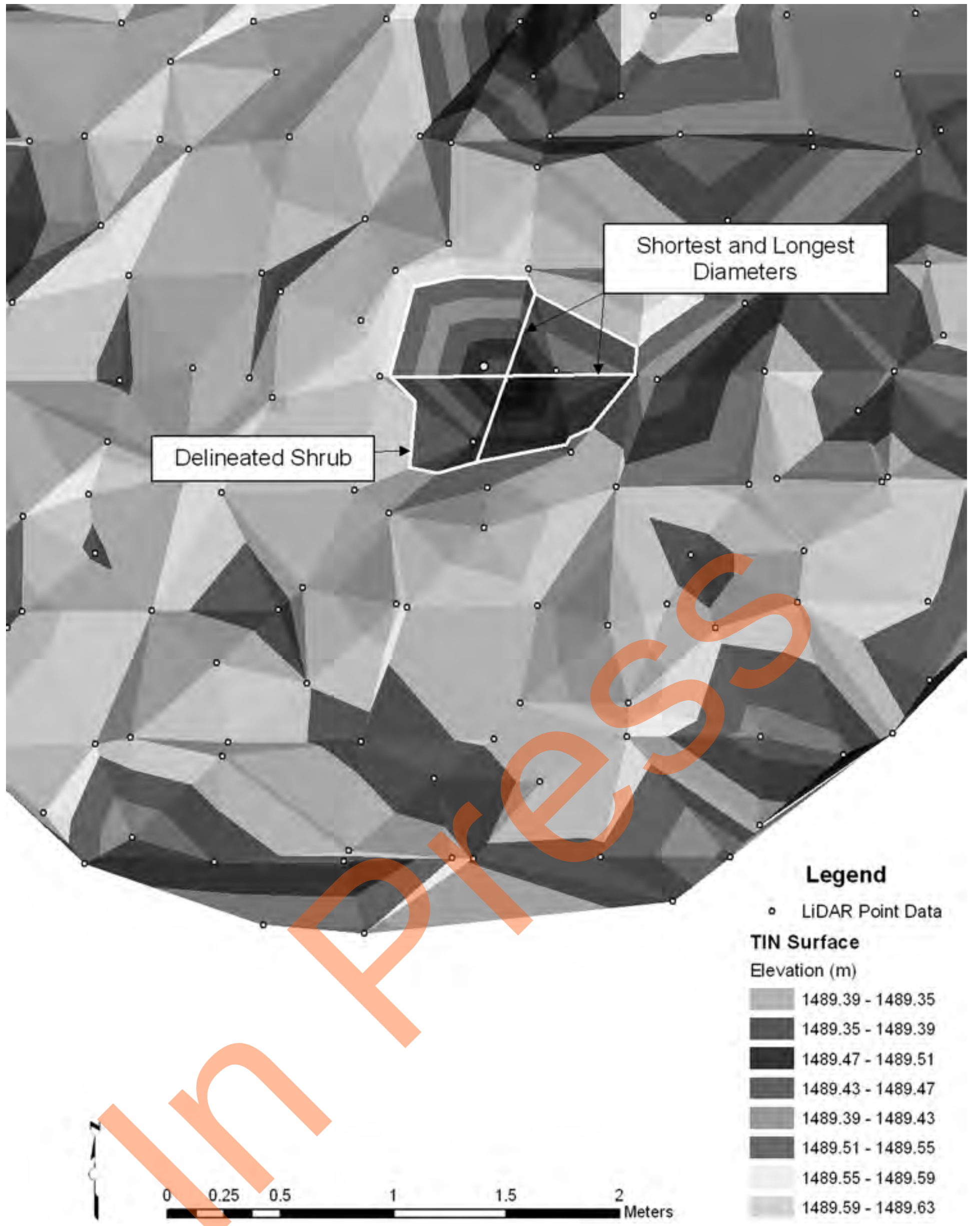

Figure 2. Illustration of a visualization method for calculating sagebrush shape metrics from lidar point data.

Table 1. Regression Analysis and Vertical Error Assessment of Lidar Maximum Sagebrush Height Predictions (cm) versus Field Measurements of Sagebrush Height (cm)

Scale	Regression Equation	p	R^2	S_E[a]	SME[b]	MAE[c]	RMSE[d]
Lidar point cloud data	**$y = 0.905x + 37.228$**	**<.01**	**0.84**	**14.97**	**−30.69**	**30.86**	**34.27**
Maximum vegetation height raster (0.5 m resolution)	**$y = 0.930x + 36.638$**	**<.01**	**0.86**	**13.97**	**−31.94**	**32.04**	**34.90**
Maximum vegetation height raster (1.0 m grid resolution)	**$y = 0.930x + 36.638$**	**<.01**	**0.86**	**13.97**	**−31.94**	**32.04**	**34.90**

[a] S_E is the standard deviation of regression
[b] SME is signed mean error.
[c] MAE is mean absolute error.
[d] RMSE is root mean squared error.

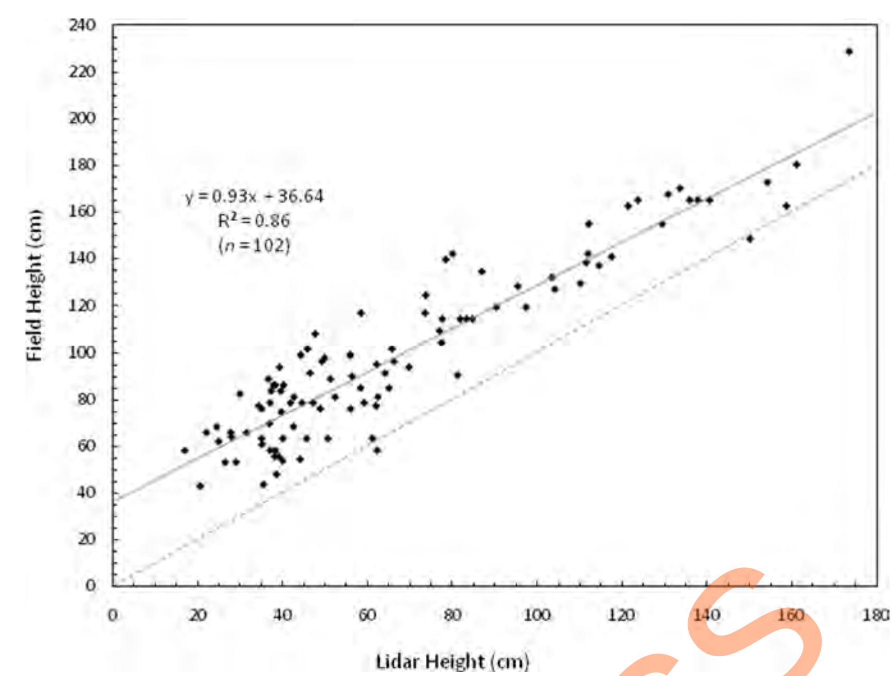

Figure 3. A comparison of lidar-predicted sagebrush heights (0.5 m grid resolution) versus field measurements of sagebrush height. The solid line is a best-fit linear regression to the data and the dashed line represents a 1:1 correspondence.

lidar point cloud data and −31.94 cm using the maximum vegetation height grid products. A comparison of prediction strength using single maximum field height measurements versus an average of six field height measurements resulted in a correlation coefficient of 0.923 for the single maximum height method and a correlation coefficient of 0.925 for the averaging method.

When lidar predictions of bare earth elevation were related to GPS elevations, results did not vary significantly among the point cloud and raster datasets (0.5 m and 1.0 m grid resolutions). The coefficients of determination (R^2) were 0.99 for the point cloud data and the bare earth models (Figure 4). The slope of all three regression equations was 1.01, while the intercept varied slightly: −15.36 for the point cloud data, −14.106 for the 0.5 m grid product, and −13.81 for the 1.0 m grid product. Mean absolute error was 5.0 to 5.1 cm, signed-mean error was − 4.0 to −4.3 cm and RMSE was 6.0 to 6.1 cm.

Correlation coefficients for lidar predictions of the shortest canopy diameter, the longest canopy diameter, and canopy area were 0.65, 0.74, and 0.78, respectively (Table 2). Relative standard errors of prediction were 20.0 percent for the average shortest diameter field measurement, 18.1 percent for the longest diameter, and 32.8 percent for the average crown area. The regression equations all indicate underestimation (negative bias) (Table 2). However, five disproportionately tall sagebrush shrubs skewed signed-mean error results, as estimation error for these tall shrubs was on the order of 100 cm.

Discussion

Our results demonstrated that discrete return, small-footprint lidar with high sampling density (9.46 points/m^{-2} average) can provide sagebrush height predictions that are strongly related to true sagebrush height, as measured in the field (R^2 = 0.84 to 0.86), but with a systematic tendency toward underestimation on the order of 30 percent. Lidar height underestimation was observed despite the fact the experiment was designed under optimal conditions. For example, the sagebrush sampling strategy in this study was biased to minimize noise associated with locational uncertainty in matching lidar sensor data to the correct ground targets. Also, the effects of terrain slope, off-nadir scan angles and general surface roughness on errors of elevation were minimized. Additional height estimation error could have been introduced from sources such as the absolute and relative vertical accuracy of the sensor (±1.8 cm and ±5.1 cm, respectively), the accuracy of lidar bare earth elevation predictions (maximum RMSE of 6.1 cm), and the 2.5 year time lapse between lidar acquisition and field measurements. Any sagebrush growth over this time period is well within the RMSEs for height and shape in our study (21.77 to 46.34 cm). We also investigated speculation that lidar returns beneath vegetation canopies are biased toward overestimating elevation, and therefore contributing to vegetation height underestimations. Profiles comparing lidar elevation returns from bare ground and vegetation lidar nearest a given GPS survey point along 20 m transects do not provide evidence of inflated elevations under sagebrush (e.g., Figure 5).

The sagebrush height regression results obtained in this study (R^2 = 0.84 to 0.86) are comparable to similar lidar studies recently conducted in separate sagebrush steppe locations throughout Idaho (Streutker and Glenn, 2006; Glenn *et al.*, 2011; Sankey and Bond, 2011). The Streutker and Glenn (2006) sagebrush height study obtained an R^2 value of 0.72 and systematic height underestimation on the order of 50 percent at a 5 m pixel resolution. Two major factors could have contributed to a slightly smaller R^2 value

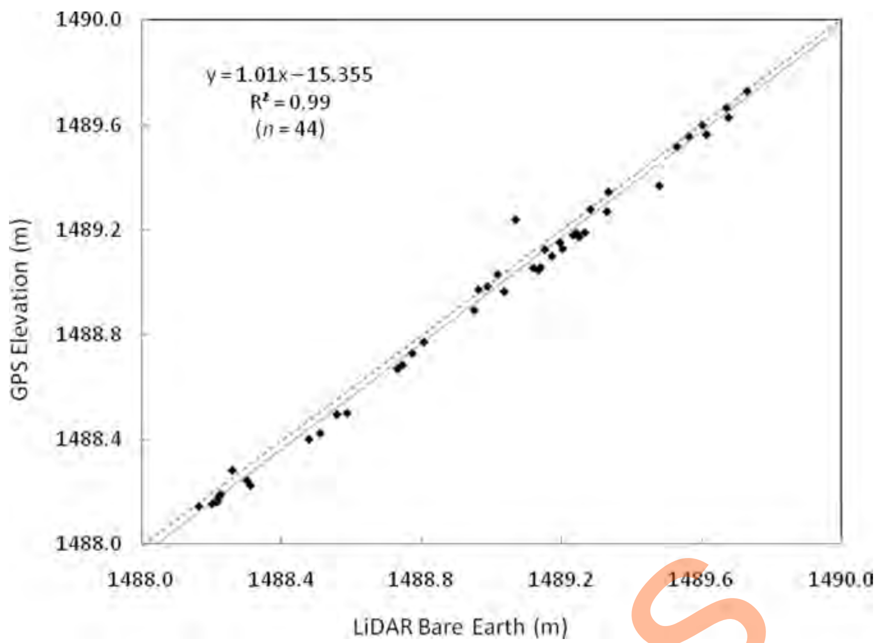

Figure 4. A comparison of lidar-predicted bare earth elevations to corresponding GPS elevations. The solid line is a best-fit linear regression to the data and the dashed line represents a 1:1 correspondence.

TABLE 2. REGRESSION ANALYSIS AND ERROR ASSESSMENT OF LIDAR-BASED SHAPE PREDICTIONS VERSUS FIELD MEASUREMENTS OF SAGEBRUSH SHAPE

Shape Metric	Regression Equation	p	R^2	S_E[a]	SME[b]	MAE[c]	RMSE[d]
Shortest shrub canopy diameter (cm)	$y = 0.863x + 15.500$	<.01	0.65	20.02	−2.43	61.34	21.77
Longest shrub canopy diameter (cm)	$y = 0.929x + 6.454$	<.01	0.74	25.79	3.87	91.06	27.96
Shrub canopy area (cm^2)	$y = 0.977x + 4.684$	<.01	0.78	40.20	5.50	124.07	46.34

[a] S_E is standard error of the estimate
[b] SME is signed mean error
[c] Max AE is maximum absolute error
[d] RMSE is root mean squared error

in the Streutker and Glenn (2006) study. First, the study was conducted using lidar data with a lower average point density (1.2 m^{-2}) than the lidar data used in our study (9.46 points m^{-2}). Second, the study included a large number of shrub samples shorter than 20 cm, while the minimum shrub height in our study area was 43.82 cm. Streutker and Glenn (2006), obtained a maximum R^2 value of 0.64 for sagebrush shrubs (39 cm to 130 cm tall) in two study sites selected to evaluate the influence of slope on shrub height and shape estimation error. Average slopes varied from 8° to 16° and the average lidar point density was 4.28 to 4.77 points m^{-2}. Sankey and Bond (2011) reported an R^2 value of 0.77 when correlating field-based and lidar-derived shrub heights to determine if lidar data can be used to separately classify varying shrub community types. The comparisons were made at the 3 m pixel resolution using lidar data with an average point density of 5.6 points m^{-2}.

Given the observed tendency toward lidar height underestimation, we expected that lidar height prediction strength might increase if estimations were regressed against field measurements obtained by averaging the six tallest measurements for each shrub rather than by simply recording the single tallest shrub height measurement. Although the repeatability of single measurements was not considered, the increase in lidar prediction strength is negligible, particularly in the context of additional time spent in the field collecting six height measurements. We suspect that the point density is high enough in our lidar data that additional shrub height measurements did not improve height predictions.

We examined the relationship between field measurements of vegetation height and lidar-derived rasters of local roughness (per-pixel, slope calculations are removed from the standard deviation of all laser pulse returns) and vegetation roughness (the standard deviation of vegetation returns within each pixel) following methods described in Davenport *et al.* (2000), Cobby *et al.* (2001) and Streutker and Glenn (2006). We did not find evidence to support a vegetation roughness-based adjustment factor that could account for high canopy penetration in sagebrush steppe vegetation.

Interpolation errors associated with bare earth or digital elevation models (DEMs) are typically at the centimeter scale (e.g., Hodgson and Bresnehan (2004); Hopkinson *et al.*,

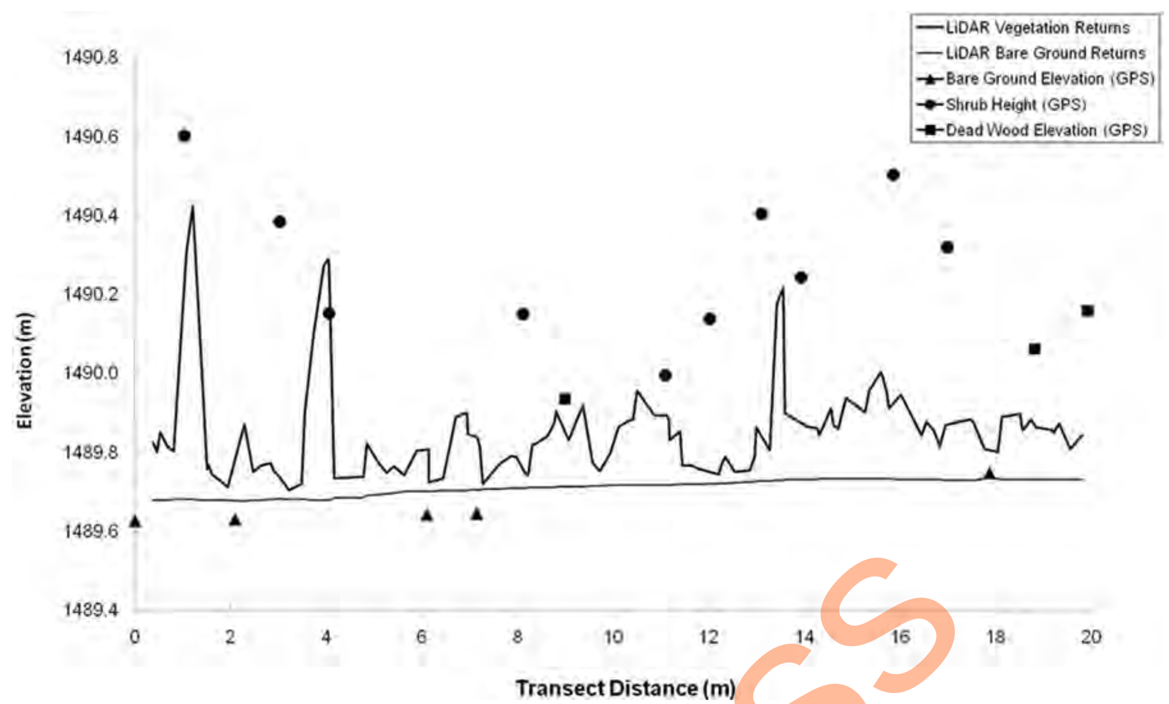

Figure 5. Elevation (m) profile depicting lidar bare ground and vegetation returns nearest to GPS elevations surveyed at 1 m intervals along a 20 m transect. This example is from a transect in Plot 12 (shrub cover >20 percent).

(2005). In our study, we found evidence of overestimation in lidar bare earth elevation at the same scale, as indicated by signed-mean error values of −4.1 to 4.3 cm. The fact that lidar prediction performance did not vary significantly when scaling from bare ground returns to bare earth rasters (0.5 m and 1.0 m grid resolutions) confirms that the BCAL LIDAR Tools are accurately interpolating terrain in our sagebrush landscape. While bare earth prediction error (~6 cm) is a relatively small component of the overall prediction error, the tendency toward bare ground overestimation does exacerbate the issue of shrub height underestimation. In other words, vegetation height predictions would improve with true bare ground elevations.

Lidar predictions of sagebrush crown area were significantly and strongly correlated with field-based measurements resulting in coefficients of determination of 0.65 to 0.78. It is likely that the primary source of shape estimation error is related to the task of properly delineating individual shrubs in the lidar data. For example, the number of lidar returns per individual shrub canopy area varies between 0.02 and 0.56, which we partially attribute to how the shrub boundary is delineated. Existing alternative interpolation methods (e.g., inverse distance weighting, kriging) are not expected to adequately address this delineation issue. Although shrub area was also underestimated, our shrub crown measurements, along with the sagebrush crown measurements presented in Glenn *et al* (2011), provide the first lidar-based low-height vegetation shape descriptors.

Conclusions

Although lidar predictions of shrub canopy height and area were strongly correlated with field-based measurements, prediction error could account for as much as 35.6 percent of the average height and 37.4 percent of the average canopy area of shrubs sampled. Given this level of uncertainty and that prediction error is expected to decrease when scaling from the individual shrub scale to coarser scales, we believe that a small-footprint (18 cm diameter at nadir) lidar sensor with a high average point return density (9.46 points m^{-2}) is a non-destructive sampling tool. Depending on the application, lidar could provide sufficiently accurate bulk sagebrush volume estimates across shrub canopies in semiarid landscapes. A lidar-derived biomass application may prove viable considering that the level of error may be an acceptable trade off to alternative methods that are too time consuming, destructive and costly to extend across landscapes. Other potential applications include the improvement of sagebrush presence/ absence classifications as well as identification of patterns and landscape metrics perhaps unique to sagebrush.

We found that working with individual lidar returns was time consuming, and did not improve upon results obtained using raster products such as bare earth elevation or maximum vegetation height. We also found our method of shrub delineation to be subjective, for in many cases it relied heavily on photos and other field reference data to distinguish individual shrubs. An accurate automated shape extraction procedure would be difficult to implement, but could be augmented using concepts such as crown volume classes (Bentley *et al.*, 1970) or shape modeling (Murray and Jacobson, 1982).

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