Errors in LiDAR-derived shrub height and crown area on sloped terrain

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\textbf{ABSTRACT}

This study developed and tested four methods for shrub height measurements with airborne LiDAR data in a semiarid shrub-steppe in southwestern Idaho, USA. Unique to this study was the focus of sagebrush height measurements on sloped terrain. The study also developed one of the first methods towards estimating crown area of sagebrush from LiDAR. Both sagebrush height and crown area were underestimated by LiDAR. Sagebrush height was estimated to within ±0.26–0.32 mm (two standard deviations of standard error). Crown area was underestimated by a mean of 49%. Further, hillslope had a relatively low impact on sagebrush height and crown area estimation. From a management perspective, estimation of individual shrubs over large geographic areas can be accomplished using a 0.5 m rasterized vegetation height derivative from LiDAR. While the underestimation of crown area is substantial, we suggest that this underestimation would improve with higher LiDAR point density (>4 points/m\textsuperscript{2}). Further studies can estimate shrub biomass using LiDAR height and crown area derivatives.

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\textbf{1. Introduction}

Sagebrush (\textit{Artemisia} spp.) communities constitute the largest temperate semi-desert in North America (\textit{West, 1983, 2000}) and approximately 60 million hectares of rangelands in the western US (\textit{Watts and Wambolt, 1996}). Sagebrush species are the dominant or co-dominant species of over 40 habitat types (\textit{Blaiddell et al., 1982; Monsen et al., 2004}), where they provide food or cover for over 350 wildlife species including canopy height and shape, are important input parameters required for wildlife habitat modeling (e.g. \textit{Crawford et al., 2004; Krogh et al., 2002}) and fuel load estimates (e.g. \textit{Keane et al., 2002}) in semiarid environments. Canopy height provides stature information that is relevant to above ground woody biomass estimates (\textit{Uresk et al., 1977}). Coupled with height, canopy shape provides information about the spatial pattern of vegetation roughness, which directly affects aeolian sediment transport (\textit{Breshers et al., 2009}). Similarly, mapping at the resolution of an individual shrub provides detail at a level suitable for understanding plant–soil biogeochemical interactions related to desertification and climate systems in semiarid environments (\textit{Schlesinger and Plammanis, 1998}).

Vegetation communities in semiarid environments are typically low in stature and spectrally indeterminate (\textit{Mitchell and Glenn, 2009}) and, therefore, challenging to quantify with remotely sensed data. Spectral measurements can provide spatially contiguous information on 2-dimension canopy projection (crown area) and cover (e.g. \textit{Chopping et al., 2008; Glenn et al., 2005; Goslee et al., 2003; Kerr and Ostrovsky, 2003}) but require additional ground measurements to establish relationships between these parameters and height.

Light detection and ranging (LiDAR) remote sensing, also known as laser altimetry, provides direct estimates of vegetation height that complement spectral data used for canopy cover estimation (\textit{Mundt et al., 2006; Sankey et al., 2010}). However, the low-height (typically < 2 m tall) and sparse cover of semiarid shrub-steppe communities present challenges for LiDAR data retrieval (\textit{Streutker and Glenn, 2006}). These challenges include confusion of vegetation and ground returns (\textit{Riano et al., 2007}), high canopy penetration due to sparse cover (\textit{Streutker and Glenn, 2006}), and vegetation and ground classification errors on steep slopes (\textit{Chow and Hodgson, 2009; Hodgson and Bresnahan, 2004; Spaete et al., 2010; Su and Bork, 2006}). In their brush/low tree class, Hodgson...
and Bresnahan (2004) estimated a two-fold increase in the root mean square error (RMSE) of LiDAR point estimates between slopes of 4° and 25°. Spaete et al. (2010) and Su and Bork (2006) observed a similar increase in RMSE between slopes < 10° and slopes > 15° for digital elevation model (DEM) accuracy.

Recent LiDAR-based rangeland studies of shrub-steppe under-estimated sagebrush height by 1.2–2 m at the 5-m raster scale (Streutker and Glenn, 2006) and 0.25–0.4 m at the 3-m raster scale (Sankey and Bond, 2011). Mitchell et al. (in review), the only previous study that has focused on individual sagebrush plants, measured height in flat terrain with a standard error (SE) (two standard deviations) of ± 0.28 m.

LiDAR-based studies are most commonly conducted in forest ecosystems. LiDAR applications in forestry studies, however, have also had difficulty in characterizing shrubs and lower vegetation in the understory. Andersen et al. (2003) found a weak relationship between field measured and LiDAR-derived understory shrub cover. They attributed shrub sampling error to occlusion of shrub vegetation by the overstory. Hopkinson et al. (2005), in a wetland environment, underestimated shrub heights (≤ 2 m) on average by 0.52 m using the raw LiDAR point cloud and 0.39 m using a raster.

In this study, we focus on LiDAR canopy measurements at the individual shrub scale in a semi-arid shrub-steppe ecosystem. Sagebrush canopy measurements included height and crown area, which is equivalent to the 2-dimensional canopy projection. Shrub crown area measurements across large areas using LiDAR data could provide useful information on disturbance history and shrub age, which are important input variables in wildlife habitat models and community-level assessments (Chopping et al., 2008; Varga and Asner, 2008). Our objectives in this study were to evaluate: 1) methodology for estimating individual shrub height and crown area; and 2) the influence of hillslope on shrub height and crown area estimates.

2. Materials and methods

2.1. Study area

The study area is located within the Reynolds Creek Experimental Watershed (RCEW) in southwestern Idaho, USA. RCEW is approximately 239 km² and is located in the Owyhee Mountains. Experimental activities within RCEW are overseen by the United States Department of Agriculture (USDA) Agricultural Research Service (ARS). Elevations in the watershed range from 1049 to 2245 m. Sagebrush and grassland communities are the dominant vegetation cover. Common shrub species include low sagebrush (Artemisia arbuscula Nutt.), big sagebrush (Artemisia tridentata Nutt. subsp. vaseyana [Rydb.] Beetle and subsp. wyomingensis) and bitterbrush (Purshia tridentata [Pursh] DC), which typically grow up to 50 cm, 50–100 cm, and 60–185 cm in height, respectively. Aspen (Populus tremuloides), subalpine fir (Abies lasiocarpa), and Douglas-fir (Pseudotsuga menziesii) communities are found in higher elevations where snow accumulation is higher (Clark et al., 2001).

Within the RCEW, two areas were selected for sampling. Selection of sampling sites was based on slope, density of sagebrush, and the presence of 1 m spacing between plants. The first site, Dobson Creek, had an average slope of 8°. The second site, Black Mountain, had an average slope of 16°.

2.2. Field sampling

Field sampling was conducted during October 2009. The location and physical characteristics of 100 big sagebrush were recorded. We stratified our selection based on three hillslope classes, which resulted in one class with 36 sagebrush occupying slopes < 10°, a second class with 32 sagebrush occupying slopes between 10° and 15°, and a third class with 32 sagebrush occupying slopes > 15°. All sampled sagebrush plants were spatially isolated with at least a 1-m space around the plant. The center of each plant was recorded with a Topcon Hyper Lite +, a Real Time Kinematic (RTK) survey grade GPS (Topcon, Livermore, CA). GPS positions were further processed using Online Positioning User Service (OPUS), a National Geodetic Survey (NGS) service to remove positional errors (http://www.ngs.noaa.gov/OPUS/) (Mader et al., 2003). This resulted in post-processing errors of 0.011 m RMSE.

Height and canopy diameter measurements were collected for each sagebrush. The longest diameter and a second diameter measured perpendicular to the longest were recorded. The crown was divided into six equal zones from a planimetric view and the maximum height was recorded for each zone.

2.3. LiDAR data

LiDAR data were acquired for RCEW during November 2007 using a Leica ALS50 Phase II laser at a flight height of approximately 900 m above ground level (AGL). The Leica ALS50 Phase II laser recognizes four returns per pulse. For the two sampling sites, Dobson Creek and Black Mountain, mean point densities were 4.28 and 4.77 points/m², respectively. Pulse beam diameter at nadir was approximately 0.20 m at ground level.

To assess the vertical accuracy of the LiDAR, ground elevation points (n = 52) were collected using the RTK GPS over a flat gravel parking lot. The closest LiDAR point to each GPS location was determined and the elevations were compared. RMSE was used to determine a vertical accuracy of 0.10 m. Based on the relationship between horizontal error and flight altitude (1/3000th), the horizontal accuracy is estimated at approximately 0.30 m. We also calculated the horizontal accuracy by comparing the locations of seven building corners (n = 28) collected with RTK GPS to building corners extracted from the LiDAR, resulting in an RMSE of 0.28 m.

2.4. LiDAR processing

The LiDAR data for the two study areas were processed using Idaho State University’s publically available LiDAR processing tools (http://bcal.geology.isu.edu/Envitools.shtml) as described in Streutker and Glenn (2006). The LiDAR point clouds were height filtered to separate ground returns from vegetation returns using a 7 m natural neighbor interpolation method. The height filtered point cloud data were then used to develop a bare earth elevation raster and a maximum vegetation height raster, both at 0.5 m pixel resolution. The vegetation height was calculated for each raster cell using the difference between the highest vegetation return and lowest (ground) elevation return.

Sagebrush crown diameter measurements were converted into ellipses (Cleary et al., 2008) using Military Analyst in ESRI ArcMap 9.3 (ESRI, 2006). Ellipses were manually orientated to match the field measured sagebrush using the maximum vegetation height raster as a guide. The sagebrush ellipses were then used to create LiDAR subsets by extracting the corresponding LiDAR point cloud data using the identity tool in ESRI ArcMap 9.3 (ESRI, 2006). The ellipse point cloud subsets were then used in subsequent analyses to predict sagebrush height and approximate 2-D sagebrush crown area (Cleary et al., 2008).

2.5. Sagebrush height estimates

To extract accurate vegetation height information from LiDAR data, it is necessary to identify appropriate ground returns in the vicinity of the target. We explored three different methods to...
identify ground elevations that were subsequently used in sagebrush height estimation (Table 1). Method 1 used the field observed ground elevation recorded by the RTK GPS at the sagebrush center. The GPS elevations were then subtracted from all LiDAR points in the ellipse point cloud subset and the maximum difference was used to represent the sagebrush height. Method 2 used the ground elevation of the underlying LiDAR bare earth elevation raster at a resolution of 0.5 m pixels. The intersect point tool in Hawth’s Tools (Beyer, 2004) was used to extract the bare earth raster value for each LiDAR point in the ellipse point cloud subset, because each ellipse covered several bare earth raster cells. The maximum difference was used to represent the sagebrush height. Method 3 used the elevation of the closest LiDAR ground return to the sagebrush center to establish the ground elevation. The near tool in ESRI ArcMap 9.3 (ESRI, 2006) was then used to locate the nearest LiDAR ground return to each ellipse center. The sagebrush height was estimated as the maximum difference between the identified ground return and each LiDAR point in the ellipse point cloud subset. An alternative and fourth method for deriving the sagebrush height was to use the maximum vegetation height raster from the LiDAR tools noted above (Table 1). Maximum vegetation height raster values were extracted for each raster cell that had a center point within each ellipse subset. Of the cells with center points within an ellipse subset, the maximum value was used to represent sagebrush height (method 4).

For methods 1–3, heights for 98 ellipses were calculated (the sample size reduced by two because two of the ellipses contained no LiDAR returns). For method 4, heights for 99 ellipses were calculated (one ellipse contained no raster center cell).

### 2.5.1. Statistical analysis of sagebrush height estimates

In order to compare sagebrush measurements collected in the field to the LiDAR-derived sagebrush height, GPS sagebrush locations were compiled in a geographic information system (GIS). The sagebrush ellipse subsets and resulting heights were stratified by the three hillslope classes we defined earlier (<10°, 10°–15°, >15°). The response variable was the average height of each sagebrush (using the six field height measurements). Linear regressions were used to examine each combination of hillslope (3) and method (4), resulting in 12 regressions (Table 2).

Analysis of covariance (ANCOVA) was used for each method to determine whether the hillslope class had an effect on the shrub height estimation (Drake et al., 2003) (Table 3). We used a sample size of n = 97 due to insufficient data points in methods 1–4 for several of the sagebrush samples. In this analysis formal hypothesis tests were used to determine if the linear regression slopes and intercepts were the same for all hillslope classes (coincidence of lines), whether the intercept changed with each hillslope class (equality of intercepts), or whether the slope of the regression lines were different for each hillslope class (parallelism).

Akaike’s information criterion (AIC) was used to test which of the four shrub height estimation methods provided the best estimate of field measured height. AIC was also used to determine if an interaction term of hillslope and estimated height improved the regression models. AIC provides an estimate of goodness of fit by comparison of modeled and observed values. The model with the lowest AIC value is considered the best. AIC was used as an alternative to hypothesis testing because the models were not all nested and several comparisons were made at the same time (Burnham and Anderson, 2002). In all of the models, the true height of the sagebrush measured in the field was the response variable (n = 97). The models included all meaningful combinations of the parameters of LiDAR estimated sagebrush height, hillslope class, an interaction term between the estimated height and hillslope class, and inclusion and exclusion of method 3. Statistical analyses were performed using the R software package (R Development Core Team, 2008) and Minitab Statistical Software (Minitab, 2007).

### 2.6. LiDAR estimates of sagebrush crown area

Vegetation height was initially used to screen points belonging to individual sagebrush plants for further analysis of crown area. The vegetation height for each LiDAR point was calculated using method 2 described above (0.5 m pixels). A conservative height of 15 cm was used as a threshold between LiDAR ground and vegetation returns. The use of this threshold was based on both the ±10 cm vertical accuracy discussed above and the typical sagebrush heights observed in the field data. The sagebrush GPS location was then overlaid on the LiDAR vegetation returns. The vegetation returns that were distinguishable as belonging to the sagebrush of interest (based on locational accuracy) were retained. If the resulting sagebrush had three or more LiDAR returns (29 of the original 100 sampled plants), the data were used for further analysis of sagebrush crown area. The longest diameter and diameter perpendicular to the longest diameter were recorded from the point cloud. Military Analyst in ESRI ArcMap 9.3 (ESRI, 2006) was then used to approximate the 2-D sagebrush crown area (an elliptical area).

### 2.6.1. Statistical analysis of sagebrush crown area

Areas derived from the ellipses (n = 29) were compared to the field measured ellipse area of each sagebrush. Linear regression was used to investigate the relationship between the LiDAR- and field-derived areas. An ANCOVA model was used to test for statistically significant differences between LiDAR- and field-derived areas for two hillslope classes: slopes less than 10° and slopes between 10° and 15°. Two hillslope classes were used to preserve a large enough sample size for statistical testing.

### 3. Results

#### 3.1. Sagebrush height estimates

LiDAR-derived sagebrush heights on slopes <10° ranged from 0.0 to 0.92 m with a mean of 0.44 m. Heights on slopes between 10° and 15° were not significantly different from those on slopes <10°. Regression of LiDAR- and field-derived heights on slopes >15° were not significantly different from those on slopes 10°–15°. Regression of LiDAR- and field-derived heights on slopes <10° was significantly different from those on slopes >10°–15°. The field-derived height was used to screen points belonging to individual sagebrush plants for further analysis of crown area.
and 15° ranged from 0.14 to 1.04 m with a mean of 0.59 m, and heights on slopes >15° ranged from 0.0 to 1.15 m with a mean of 0.60 m (Fig. 1). In 11 of the 12 linear regressions (performed on each of the four LiDAR shrub height estimation methods and each of the three hillslope classes), a statistically significant relationship was found between the LiDAR and field measurements (Table 2). The models with the highest R² and lowest SE are Method 1 for slopes <10°; Method 4 for slopes 10–15°; and Method 2 for >15° slopes (Fig. 1). No singular approach for determining sagebrush height proved to yield the best results for all hillslope classes. There was no evidence of a difference between methods 1, 2, and 4 (Table 2). However, method 3 produced the only non-significant regression. The AIC analysis (combined with the results of Tables 2 and 3) indicates that method 3 performed the worst out of the four methods, and that an interaction term of hillslope and estimated height does not improve the regressions from methods 1, 2, and 4. Using the regressions of methods 1, 2, and 4, sagebrush height was estimated accurately with LiDAR to within ±0.26–0.32 m (two standard deviations of SE = 0.13–0.16 m) (Table 2). The regression equations indicate that sagebrush height is underestimated by LiDAR in most cases (Fig. 1).

3.2. Sagebrush crown area

The comparison between the LiDAR-derived 2-D sagebrush crown area and the field-based sagebrush crown area indicate an average underestimation using LiDAR by 49% (LiDAR-derived average area and standard deviation of 0.97 m² and 0.62 m², respectively, in comparison to a field average area and standard deviation of 1.81 m² and 0.55 m², respectively) (Table 4). A linear regression between the two data sets indicate an R² = 0.33 and SE of 0.46 m². Further ANCOVA analysis indicates no significant difference between hillslope classes <10° and >10° (Table 4).

4. Discussion and conclusions

Overall, sagebrush height was estimated accurately to within ±0.26–0.32 m (SE = 0.13–0.16 m). We conclude that sloped terrain has little influence on height and crown area estimations. The field-based and LiDAR-derived sagebrush heights for methods 1, 2, and 4 are significantly and strongly correlated, regardless of hillslope.

The average shrub height in the focus areas was 0.80 m and thus our height error is equivalent to roughly one third of the total sagebrush height. Our sagebrush height errors are similar in absolute values to the results of Mitchell et al. (in review), where sagebrush samples were collected in a relatively flat study area. The errors are also similar to those reported by Sankey and Bond (2011), who measured 0.25–0.40 m underestimates in mean heights of varying sagebrush vegetation communities including herbaceous-, shrub-, and trees-dominated communities. A related study (unpublished data) indicates a similar underestimate in LiDAR-derived shrub heights even after sampling 500 shrub-dominated plots of 3 m × 3 m. Taken together, our results indicate that LiDAR data can be successfully used in medium height vegetation of big sagebrush and bitterbrush-dominated communities when corrected for underestimated heights. However, LiDAR applications might be limited in low sagebrush-dominated communities, especially in younger plants of low stature.

The limited effect of hillslope on height estimations from methods 1, 2, and 4 may be due to the high canopy penetration in sagebrush and thus, a high enough number of ground points to accurately model the bare ground, resulting in low-height errors. The limited hillslope effect may also be due to the relatively small size of an individual sagebrush crown. In a related study, Spaete et al. (2010) report increased RMSE values of LiDAR-derived ground elevation with increased slope. However, they analyzed data at the 1 m grid scale and not at the scale of isolated sagebrush plants. Hodgson et al. (2005) hypothesized that the elevation errors due to slopes 0–8° were not any greater than those introduced from other sources (e.g. point density, return labeling). In their scrub/shrub class, the vegetation type comparable to this study, the mean signed errors (MSE) did not increase with increasing slope.

The sagebrush height errors may be attributed to errors in the bare ground raster used for height estimates (including vertical accuracy of the LiDAR sensor), horizontal accuracy of the LiDAR sensor, and the LiDAR canopy penetration (including the LiDAR missing the top of the sagebrush crown). The error associated with the bare ground raster used for height estimates was calculated using a comparison to field measured bare ground GPS points. The resulting RMSE was 0.11 m (approximately equal to the vertical accuracy of 0.10 m of the LiDAR sensor) and MSE was 0.0099 m. Methods 2 and 4 performed similar to method 1 (which did not use a bare ground raster), further suggesting that the bare ground raster was not likely a problem. Mitchell et al. (in review) had point density twice the point density in this study and an RMSE (MSE) of 0.06 m (−0.04 m) to 0.061 m (−0.043 m) for the bare ground raster. Further, Spaete et al. (2010) report an RMSE (MSE) of 0.074 m (−0.045 m) and 0.140 m (−0.081 m) in slopes <10° and >10°, respectively, for mean ground elevation in low-density big sagebrush. Our collective results indicate that bare ground estimation likely has a minor effect on the height estimation error in sagebrush canopy where penetration is relatively high and point density is at least 4 points/m².

A decrease in horizontal accuracy will result in increased horizontal displacement, and thus elevation error of the LiDAR returns in sloped terrain. Our method of sampling individual shrubs,
and to use ellipse subsets, minimized the elevation error associated with the horizontal accuracy. However, future studies of overlapping sagebrush on slopes will need to account for horizontal displacement of LiDAR returns.

In summary, while bare ground estimation errors and vertical accuracy of the LiDAR system account for a portion of the sagebrush height error, at least two-thirds of the error (approximately 20 cm) is attributed to canopy penetration and/or the LiDAR missing the top of the sagebrush crown. The likelihood of missing the top of the sagebrush crown decreases as point density increases.

Interestingly, there was no significant difference in height estimations between methods 1, 2, and 4. The ANCOVA results indicate that any of the methods can be used with nearly the same results for sagebrush height in similar environments. We also conclude that the use of point cloud or raster data work equally well for determining sagebrush heights. These results are contrary to the Hopkinson et al. (2005) wetland study, which showed improved vegetation height estimation using a raster instead of the point cloud data. In our study, the point clouds are necessarily filtered for ground and vegetation returns in order to develop subsequent bare earth and maximum vegetation height rasters. However, the ellipse point clouds do not need to be filtered for methods 1–2 (and 3). For processing large geographic areas, method 4 may be most practical for individual shrub identification. Furthermore, based on the regression fit in relation to a 1:1 line (Gauch et al., 2003), method 4 may only require a simple offset correction for LiDAR-derived shrub height estimations (Fig. 1). Method 1 may be least practical as it requires the acquisition of GPS ground measurements in the field for each shrub. We demonstrate that method 3 is inferior to methods 1, 2, and 4 because it is sensitive to hillslope class and provides poor predictions relative to the other three methods.

Along with Mitchell et al. (in review), our crown area estimates provide the first available descriptors for LiDAR-based low-height-vegetation crown area. Underestimation of canopy-projected area by a mean of 49% is substantial; however, these, and height estimation errors, may be corrected by supplementary ground measurements. Development of a methodology to characterize smaller-stature vegetation is an important first step toward future estimates of biomass and mixed canopy characterization with LiDAR. We were only able to use one third \((n = 29)\) of our sagebrush samples for shrub crown area measurements due to the lack of LiDAR points to delineate the shrub. Thus, point density and canopy penetration are major factors in accurate measurements of crown area. Furthermore, artifacts of data collection likely influenced our ability to correctly model crown area given the point density and sagebrush scale in this study. For example, due to the systematic sampling of the LiDAR pulses, trough-like patterns were evident when viewing the raw point cloud data. Mitchell et al. (in review) used a triangulated irregular network (TIN) method for delineating shrub elliptical crown area. Their results are more compelling, with \(R^2\) values ranging from 0.65 to 0.78, likely due to increased point density. However, they similarly hypothesize that the primary source of crown area estimation error is difficulty in delineating individual shrubs in the LiDAR data.

LiDAR data could be effectively used for biomass estimations of sagebrush with more focus on developing the ellipse-based area estimates, coupled with our height estimation methods. The underestimation of sagebrush biomass would be a function of both

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**Fig. 1.** Regression plots using the height estimation method which yielded the highest \(R^2\) and lowest SE values: a) method 1 for slopes \(<10^\circ\); b) method 4 for slopes 10–15\(^\circ\); c) method 2 for slopes > than 15\(^\circ\).
the height and crown area errors. Increased point density and attention to canopy penetration will be necessary to accurately model biomass.

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