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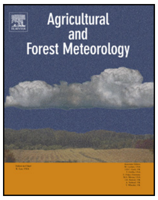

Aboveground biomass estimates of sagebrush using terrestrial and airborne LiDAR data in a dryland ecosystem

Aihua Li[a], Nancy F. Glenn[a,*], Peter J. Olsoy[a], Jessica J. Mitchell[b], Rupesh Shrestha[a]

[a] *Department of Geosciences, Boise State University, 1910 University Drive, Boise, ID 83725, USA*
[b] *Department of Geography and Planning, Appalachian State University, PO Box 32066, Boone, NC 28694, USA*

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ABSTRACT

Vegetation biomass estimates across drylands at regional scales are critical for ecological modeling, yet the low-lying and sparse plant communities characterizing these ecosystems are challenging to accurately quantify and measure their variability using spectral-based aerial and satellite remote sensing. To overcome these challenges, multi-scale data including field-measured biomass, terrestrial laser scanning (TLS) and airborne laser scanning (ALS) data, were combined in a hierarchical modeling framework. Data derived at each scale were used to validate an increasingly broader index of sagebrush (*Artemisia tridentata*) aboveground biomass. First, two automatic crown delineation methods were used to delineate individual shrubs across the TLS plots. Second, three models to derive shrub volumes were utilized with TLS data and regressed against destructively-sampled individual shrub biomass measurements. Third, TLS-derived biomass estimates at 5 m were used to calibrate a biomass prediction model with a linear regression of ALS-derived percent vegetation cover (adjusted $R^2 = 0.87$, $p < 0.001$, RMSE = 3.59 kg). The ALS prediction model was applied to the study watershed and evaluated with independent TLS plots (adjusted $R^2 = 0.55$, RMSE = 4.01 kg, normalized RMSE = 35%). The biomass estimates at the scale of 5 m is sufficient for capturing the variability of biomass needed to initialize models to estimate ecosystem fluxes, and the contiguous estimates across the watershed support analyzing patterns and connectivity of these dynamics. Our model is currently optimized for the sagebrush-steppe environment at the watershed scale and may be readily applied to other shrub-dominated drylands, and especially the Great Basin, U.S., which extends across five western states. Improved derived metrics from ALS data and collection of additional TLS data to refine the relationship between TLS-derived biomass estimates and ALS-derived models of vegetation structure, will strengthen the predictive power of our model and extend its range to similar shrubland ecosystems.

1. Introduction

Drylands are fragile and increasingly affected by changes in climate and land use that alter the woody plant mosaic, which resultantly exerts a major influence on ecosystem processes such as evapotranspiration and fire disturbance (Breshears, 2006; Yang et al., 2012). Drylands cover approximately 40% of earth's terrestrial surface resulting in a significant contribution to global carbon cycling. Sagebrush (*Artemisia tridentata*) is a dominant woody plant type in the sagebrush-steppe which covers approximately 62 million hectares of the western US. Understanding the structure and function of sagebrush at a regional scale is necessary for carbon cycle research (Harte et al., 2006), land management and policy decisions related to fuel loading (Frandsen, 1983), conservation and restoration of wildlife habitat (Davies et al., 2007), and estimating the resilience of sagebrush-steppe communities (Chambers et al., 2014). In addition, aboveground biomass is a key biophysical parameter for global carbon models (Hese et al., 2005; Houghton, 2005; Le Toan et al., 2011) and resolving dryland biomass contributions will improve the accuracy and applicability of these models.

When coupled with empirical data or physical models, remote sensing data can provide multi-scale contiguous biomass estimates ideally suited for terrestrial modeling over space and time. These indirect estimates of biomass can also be used in lieu of time-consuming field-based methods of biomass estimation. Vegetation

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* Corresponding author at: Department of Geosciences, Boise Center Aerospace Laboratory, Boise State University, 1910 University Drive, Boise, Idaho 83725, USA.
E-mail addresses: aihuali@boisestate.edu (A. Li), nancyglenn@boisestate.edu (N.F. Glenn), peterolsoy@gmail.com (P.J. Olsoy), mitchelljj@appstate.edu (J.J. Mitchell), rupeshshrestha@boisestate.edu (R. Shrestha).

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biomass can be estimated by relating it to attributes derived from multispectral (Gasparri et al., 2010; Lu et al., 2012; Doiron et al., 2013; Zandler et al., 2015), radar (Huang et al., 2010; Mitchard et al., 2012) and Light Detection and Ranging (LiDAR) data (Swatantran et al., 2011; Viana et al., 2012). Related studies of vegetation structure in semiarid ecosystems have also used airborne LiDAR (or airborne laser scanning, ALS) (Streutker and Glenn, 2006; Glenn et al., 2011). Laser altimetry data can provide the detailed vertical structure that spectral responses from optical data do not capture and help address the challenge of spectral mixing common with optical data in dryland systems (e.g., Okin et al., 2001). Importantly these two datasets are powerful when combined. Relating estimates of biomass from laser altimetry with spectral time-series data (e.g., Pascual et al., 2010) have the potential to estimate changes in biomass over time. Estimating structure and biomass with laser altimetry is also appealing as ALS datasets are becoming widely available and space-borne missions such as NASA's Ice, Cloud, and land Elevation Satellite (ICESat-2) and Global Ecosystem Dynamics Investigation (GEDI) are planned to provide new and repeat datasets of key ecosystems.

Biomass estimates of shrubs and grasses in dryland ecosystems with laser altimetry have largely been unexplored because developing robust structure metrics from ALS data is uniquely challenging for dryland vegetation types. For example, sagebrush are often represented by a limited number of laser pulses due to sparse cover and density, and an overall limited number of returns per pulse because of constraints related to laser pulse length (Glenn et al., 2011; Mitchell et al., 2011). Compared to the lower point density and larger coverage of ALS data, terrestrial laser scanning (TLS) data typically have higher point density and smaller geographic coverage. In forested environments previous studies used high density point clouds from TLS data to characterize canopy structure (Lovell et al., 2003; Hilker et al., 2010; Moorthy et al., 2011; Lin et al., 2012), leaf area index (Jupp et al., 2008; Zheng et al., 2013), aboveground biomass (Yao et al., 2011; Ku et al., 2012), and gap fraction (Hancock et al., 2014). Recent research in sagebrush-steppe has also demonstrated the use of TLS data to quantify shrub height and canopy cover at the plot scale (Vierling et al., 2013) and biomass at the individual shrub scale (Olsoy et al., 2014a,b). Field measurements and TLS and ALS data have complementary accuracy, point density (sampling) and spatial coverage, making these measurements ideal to integrate for estimating biomass at regional scales.

Regression methods have proven to be effective for modeling biomass with ALS-derived metrics (Zhao et al., 2009; Salas et al., 2010; Zolkos et al., 2013). For example, allometric equations are typically used to relate forest biomass field measurements with ALS-derived physical characteristics of trees. For shrub biomass estimates, studies have performed regression between shrub biomass and height metrics (median and standard deviation) derived from ALS data (Estornell et al., 2011, 2012) and between sagebrush biomass and volume derived from TLS data (Olsoy et al., 2014a,b).

Specific objectives of this study were to model biomass of sagebrush over the 238 km^2 Reynolds Creek Experimental Watershed with a robust error assessment, while demonstrating a hierarchical method to quantify biomass at multiple scales. Our hierarchical scaling method is based on regression techniques that combined field-measured and TLS data to derive Wyoming big sagebrush (*Artemisia tridentata* subsp. *wyomingensis*, hereafter sagebrush) biomass estimates for individual shrubs. These biomass estimates at the individual shrub scale were then extended to the watershed scale using an ALS-derived metric. Our intent was to derive biomass across the watershed scale at fine to moderate resolution (1-30 m). The motivation for this resolution is to capture relationships in the distribution and amount of soil and aboveground vegetation carbon, and to capture the variability of biomass when aggregating to coarser scales (e.g., 100 m resolution) for aboveground carbon storage and flux modeling, and distributed snow modeling (e.g Winstral et al., 2014).

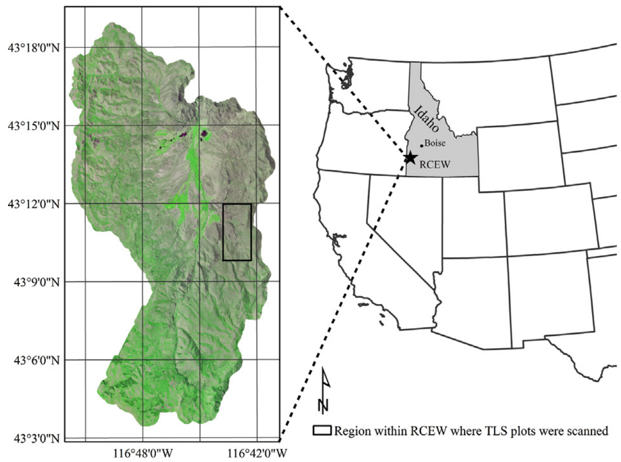

Fig. 1. Reynolds Creek Experimental Watershed (RCEW) study area, Idaho, USA.

2. Study area and data

2.1. Study area

The study area is Reynolds Creek Experimental Watershed (RCEW), located approximately 80 km southwest of Boise, Idaho, USA (Fig. 1). Large gradients in climate, precipitation, and hydrology occur across RCEW. The mean annual precipitation varies from about 250 mm in the north to over 1100 mm at the southern and southwestern watershed boundaries (Marks et al., 2007). Soils include Takeuchi-Kanlee, Nannyton-Larimer, Harmehl-Gabica, Searla-Bullrey, Farrot-Castlevale, Bakeoven-Reywat, Glasgow-Babington and Hoot-Nannyton (Seyfried et al., 2000). Vegetation types at our study areas within RCEW are dominated by sagebrush and bluebunch wheatgrass (*Pseudoroegneria spicata*) (Seyfried et al., 2001).

2.2. LiDAR and field data

Discrete return ALS data were acquired using an ALS50-II scanner (Leica Geosystems, Heerbrugg, Switzerland) operated by Watershed Sciences (Corvallis, OR) in November 2007. The average point density was 5 points/m^2 and pulse beam diameter at nadir was approximately 0.20 m. A Riegl VZ-1000 (Riegl, Horn, Austria) TLS instrument with a scan range of approximately 1 km, a beam divergence of 0.3 mrad and operating in the near infrared (1550 nm) was used to collect ground-based point cloud data in fall 2011 and 2012. Six TLS plots were scanned each year across a range of sagebrush densities (Fig. 2). The smallest and largest plot sizes were approximately 30 m × 30 m and 50 m × 50 m, respectively. For each plot, one scan was centered at a distance of 5 m from the nearest sampled sagebrush. A second scan was conducted from the opposite direction with the scan center at a distance of 5 m from the same nearest sampled sagebrush. The two scans from opposing directions ensured collection of the entire outer canopy structure. The scans were co-registered using four calibration targets which were placed at strategic positions. After scanning, the individual sagebrush plants ($n = 45$) were destructively sampled and oven-dried at 65 °C to get a constant dry weight for total aboveground biomass estimates (Olsoy et al., 2014b). Thirty sagebrush in 2011 ($n = 30$) and fifteen sagebrush in 2012 ($n = 15$) were sampled across dif-