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Aboveground total and green biomass of dryland shrub derived from terrestrial laser scanning

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ABSTRACT

Sagebrush (*Artemisia tridentata*), a dominant shrub species in the sagebrush-steppe ecosystem of the western US, is declining from its historical distribution due to feedbacks between climate and land use change, fire, and invasive species. Quantifying aboveground biomass of sagebrush is important for assessing carbon storage and monitoring the presence and distribution of this rapidly changing dryland ecosystem. Models of shrub canopy volume, derived from terrestrial laser scanning (TLS) point clouds, were used to accurately estimate aboveground sagebrush biomass. Ninety-one sagebrush plants were scanned and sampled across three study sites in the Great Basin, USA. Half of the plants were scanned and destructively sampled in the spring ($n = 46$), while the other half were scanned again in the fall before destructive sampling ($n = 45$). The latter set of sagebrush plants was scanned during both spring and fall to further test the ability of the TLS to quantify seasonal changes in green biomass. Sagebrush biomass was estimated using both a voxel and a 3-D convex hull approach applied to TLS point cloud data. The 3-D convex hull model estimated total and green biomass more accurately ($R^2 = 0.92$ and $R^2 = 0.83$, respectively) than the voxel-based method ($R^2 = 0.86$ and $R^2 = 0.73$, respectively). Seasonal differences in TLS-predicted green biomass were detected at two of the sites ($p < 0.001$ and $p = 0.029$), elucidating the amount of ephemeral leaf loss in the face of summer drought. The methods presented herein are directly transferable to other dryland shrubs, and implementation of the convex hull model with similar sagebrush species is straightforward.

1. Introduction

Drylands constitute 40% of global land area and 37% of the world's human population occupy drylands (White and Nackoney, 2003). Increased temperatures and more frequent drought associated with climate change and degradation from improper land use stress dryland ecosystems, increasing the likelihood of fire and desertification (Reynolds et al., 2007). In dryland ecosystems, fire can cause type conversions where a new stable state of invasive annual grasses is created, replacing the native perennial grasses (Tausch et al., 1995) and shrubs (Knick and Rotenberry, 1997).

Sagebrush (*Artemisia tridentata*) is a dryland shrub that dominates large portions of the western US. As a consequence of fire, invasive plants, and other disturbances, the distribution of sagebrush has declined from historic levels (Rowland et al., 2006). Juniper (*Juniperus* spp.) encroachment at higher elevations and cheatgrass (*Bromus tectorum*) invasion at lower elevations have led to reduction of sagebrush cover and fragmentation of the sagebrush steppe (Knick, 1999; Miller and Rose, 1999). The presence of cheatgrass, a highly flammable, exotic annual grass increases fire potential, leading to more frequent and larger fires (Knapp, 1996). Intact sagebrush communities typically require 35–100 years to fully recover from fire (Baker, 2006) and the introduction of cheatgrass has modified the fire return interval on former sagebrush steppe rangelands to as little as 3–5 years (Balch et al., 2013). Some estimates show that 50–60% of areas that were once sagebrush-dominated now have understories dominated by exotic annual grasses or have been converted to near-monocultures of annual grasses (West, 2000).

Other threats to sagebrush-dominated rangelands include changes in land use as rising human populations require more space and natural resources (Foley et al., 2005). Historically, urban development, increased agricultural development, and

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poorly-managed livestock grazing (Anderson and Inouye, 2001) have caused large decreases in sagebrush-dominated rangelands (Knick, 1999).

Sagebrush ecosystems provide habitat and forage for many threatened or endangered animals or animal species of concern such as the greater sage grouse (*Centrocercus urophasianus*) (Knick and Connelly, 2011; Knick et al., 2003) and pygmy rabbits (*Brachylagus idahoensis*) (Rachlow et al., 2005). Intact sagebrush communities promote nutrient cycling and infiltration of precipitation thus influencing soil *C*/*N* ratios and soil carbon storage while also minimizing runoff and soil erosion relative to sites dominated by exotic grasses (Chen and Stark, 1999; Gill and Burke, 1999; Moffet et al., 2007; Pierson et al., 2008). Monitoring and quantifying sagebrush biomass change is essential for enabling managers to make knowledge-based decisions and to adaptively adjust to altered ecosystem function as global climate change processes occur in dryland systems.

Sagebrush are evergreen plants, but the total leaf weight fluctuates greatly throughout the year. In the spring, with warming temperatures and increased moisture, sagebrush produce ephemeral leaves. Drought stress during the summer causes the plant to drop the ephemeral leaves and only maintain 33% of their leaf weight (Miller and Schultz, 1987). Despite this loss of leaf weight, the contribution of sagebrush to wildlife forage in the winter is significant. As examples, pygmy rabbit diets increase from 10–51% sagebrush in the summer to 82–99% in winter (Green and Flinders, 1980; Thines et al., 2004) and summer sage grouse diets consist of only 1–19% sagebrush compared to 100% in winter (Wallestad et al., 1975). Ecosystem management of sagebrush and other dryland shrubs and their use for wildlife forage, requires a current understanding of total aboveground shrub biomass and, more critically, of available green or photosynthetically-active biomass as seasons progress and as drought, normal, and wet years occur. Furthermore, accurate quantifications of sagebrush biomass under varying climatic and edaphic conditions are needed by researchers developing predictive understandings of how sagebrush ecosystems and their services will respond to future climate-change conditions (Shaw and Harte, 2001).

Aboveground biomass is most accurately estimated with destructive sampling, which is expensive and time consuming. Estimating green biomass demands even more time as sorting of the leaves and green stems from the woody plant material is required. Less expensive methods involving surrogate estimates have been proposed, but still involve taking multiple field measurements for each shrub of interest. Remote sensing approaches may offer a solution. Determining relationships between sagebrush biomass and remotely-sensed variables can provide researchers and managers with the ability to estimate biomass at extensive scales and across multiple time intervals.

Remote sensing methods, such as airborne laser scanning (ALS), have proven effective at assessing tree volume (Kato et al., 2009) and biomass (Drake et al., 2002) in forested environments. Airborne laser scanning of sagebrush-dominated rangelands, however, can be problematic, tending to underestimate shrub height and volume by as much as 30–50% (Glenn et al., 2011; Mitchell et al., 2011). This underestimation is due to the low point density of ALS, typically less than 10 pts m^{-2}, relative to shrub size (Bork and Su, 2007).

Terrestrial laser scanning (TLS), or ground-based LiDAR, provides a method for collecting much higher density (1000 pts m^{-2}) point clouds than ALS. TLS point clouds have been used to accurately estimate parameters in forest vegetation (Huang and Pretzsch, 2010; Lefsky and McHale, 2008; Loudermilk et al., 2009) but also offer potential for assessments of short-stature vegetation such as species found in the sagebrush steppe (Vierling et al., 2013). Olsoy et al. (in press) demonstrated TLS-derived voxel volume can be used to accurately predict sagebrush biomass; however, the method was only tested at a single study site during a single season. Further testing over space and time is required to establish TLS as a robust technology to assess condition and trends in sagebrush biomass and to provide groundwork for scaling from plot to landscape levels. Exploring alternate methods for volume estimation is also necessary for efficient use and processing of the TLS data for sagebrush and other dryland vegetation communities.

The objectives of this study were to expand the Olsoy et al. (in press) study of estimating sagebrush biomass from TLS-derived volume to: (1) contrast the accuracy of convex hull volume and voxel volume models for predicting total and green biomass; (2) test the robustness of the relationship between sagebrush volume and biomass over space (study sites) and time (seasons); and (3) apply the best relationship between TLS-derived volume and green biomass and determine if this relationship can detect actual seasonal differences in sagebrush biomass.

2. Methods

2.1. Study area

The study area spans across southern Idaho (Fig. 1) and is representative of the xeric, sagebrush-dominated ecosystems of the Snake River Plain and Northern Basin and Range ecoregions in the Great Basin. Three sites within the study area were sampled, including the Reynolds Creek Experimental Watershed (RCEW), Hollister, and Snaky Canyon Wash (SCW). These study sites provide an increasing elevation gradient and increasingly drier climate from west to east (Table 1; WRCC, 2009). Vegetation at all study sites is dominated by Wyoming big sagebrush (*A. tridentata* subsp. *wyomingensis*), bluebunch wheatgrass (*Pseudoroegneria spicata*), and Sandberg bluegrass (*Poa secunda*).

The RCEW is a mountainous landscape in southwestern Idaho. The study site within RCEW (lat 43°10′32″N, long 116°43′2″W) is hilly, with elevations ranging from 1310 m to 1452 m. Soils consist of well-drained gravelly and silt loams from the Willhill-Cottle-Longcreek and Arbidge-Owsel-Gariper soil series complexes (Soil Survey Staff, 2013). The RCEW has the highest mean annual precipitation rate but has the lowest percentage of precipitation occurring as snow of any of the three sites (Table 1).

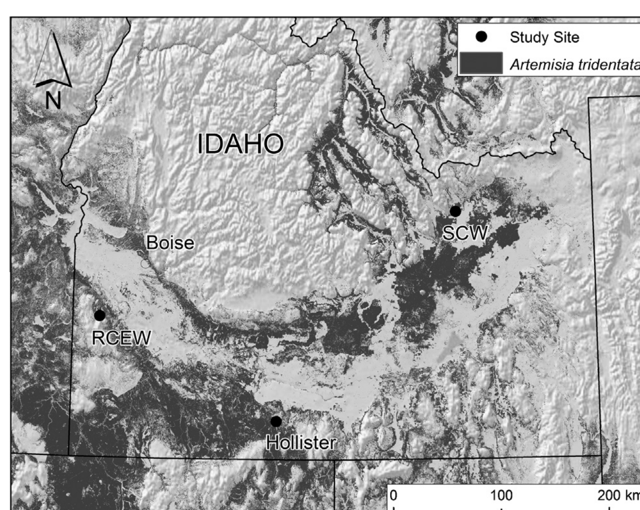

Fig. 1. Distribution of study sites across the Northern Basin and Range and Snake River Plain ecoregions of Idaho, USA. The shaded areas are dominated by big sagebrush.