2-1-2014

Aboveground Total and Green Biomass of Dryland Shrub Derived from Terrestrial Laser Scanning

Peter J. Olsoy
Boise State University

Nancy F. Glenn
Boise State University

Patrick E. Clark
USDA Agricultural Research Service

DeWayne R. Derryberry
Idaho State University

NOTICE: this is the author's version of a work that was accepted for publication in ISPRS Journal of Photogrammetry and Remote Sensing. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in ISPRS Journal of Photogrammetry and Remote Sensing, Vol. 88, (2014)] DOI: 10.1016/j.isprsjprs.2013.12.006

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

Peter J. Olsoy[a], Nancy F. Glenn[a,*], Patrick E. Clark[b], and DeWayne R. Derryberry[c]

[a]Department of Geosciences, Boise State University, Boise Center Aerospace Lab, 1910 University Drive, Boise, ID 83725, USA, peterolsoy@boisestate.edu, nancyglenn@boisestate.edu

[b]USDA Agricultural Research Service, 800 Park Blvd, Suite 105, Boise, ID 83712, USA, pat.clark@ars.usda.gov

[c]Department of Mathematics, Idaho State University, PO Box 8085 Pocatello, ID 83209, USA, derrdewa@isu.edu

[*]Corresponding author at: Department of Geosciences, Boise State University, Boise Center Aerospace Laboratory, 1910 University Drive, Boise, Idaho 83725-1535, USA, Tel.: +1 208 373 1819. E-mail address: nancyglenn@boisestate.edu (N.F. Glenn).

Keywords: terrestrial LiDAR; sagebrush steppe; seasonal change; fire; Great Basin

NOTICE: this is the author's version of a work that was accepted for publication in *ISPRS Journal of Photogrammetry and Remote Sensing*. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in I*SPRS Journal of Photogrammetry and Remote Sensing*, Vol. 88, (2014)] DOI: 10.1016/j.isprsjprs.2013.12.006

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

NOTICE: this is the author's version of a work that was accepted for publication in *ISPRS Journal of Photogrammetry and Remote Sensing*. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in I*SPRS Journal of Photogrammetry and Remote Sensing*, Vol. 88, (2014)] DOI: 10.1016/j.isprsjprs.2013.12.006

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 & 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 & Stark, 1999; Gill & 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 & 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 & 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

NOTICE: this is the author's version of a work that was accepted for publication in *ISPRS Journal of Photogrammetry and Remote Sensing*. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in I*SPRS Journal of Photogrammetry and Remote Sensing*, Vol. 88, (2014)] DOI: 10.1016/j.isprsjprs.2013.12.006

sagebrush ecosystems and their services will respond to future climate-change conditions (Shaw & 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 & 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 & Pretzsch, 2010; Lefsky & 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 review) 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 review) 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 (*Artemisia 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**).

The Hollister study site is located in southcentral Idaho (lat 42°18'58"N long 114°41'34"W) with elevation ranging from 1417 m to 1476 m and the only appreciable elevation gain coming from a gradual, continuous slope from south to north. The soil is well-drained and consists of Chuska very stony loam and Shabliss silt loam (Soil Survey Staff, 2013).

The Snaky Canyon Wash study site is located at the foot of the Beaverhead Mountains (lat 44°4'23"N long 112°38'14"W) in eastern Idaho. SCW, with elevations ranging from 1518 m to 1550 m, has the highest elevation of the 3 study sites. Soils are somewhat excessively drained, gravelly loams from a complex of the Whitecloud, Simeroi, and Paint soil series (Soil Survey Staff, 2013). Annual precipitation at SCW is the lowest of the 3 study sites, however, the percentage of annual precipitation coming as snowfall is nearly twice that compared to the other study sites (**Table 1**).

2.2. Field Sampling

In May 2012, six plots containing 5 sagebrush plants each (or in one case, 6 sagebrush plants) were established at each study site (n = 91 total plants). The sagebrush plants in each plot were chosen based on a stratified approach to sample a range of sagebrush volumes from approximately 0.01 m^3 to 2 m^3. Each plot was scanned using a Riegl VZ-1000 TLS from two opposing scan positions at a mean distance of 5.7 m (total range of 3 to 9 m) from each sagebrush plant resulting in a beam diameter of 2 mm. The Riegl VZ-1000 uses a near infrared laser (1550 nm) and has a range up to 1500 m for objects with 90% reflectivity or 700 m for objects with 20% reflectivity, with accuracies of 8 mm at 100 m range (Riegl, 2013). The two scans from each plot were georeferenced together using four reflective targets, whose positions were captured using real-time kinematic (RTK) GPS. Collection, registration, and processing of the TLS point cloud were performed in the RiSCAN Pro software package (Riegl, Horn, Austria). After scanning was completed, half of the sagebrush plants at each study site (n = 45) were destructively sampled by cutting the sagebrush at the ground and collecting the plant matter into plastic bags for temporary storage. The following fall, October 2012, the same sites were revisited and the remaining sagebrush (n = 45) were scanned again from the same scan locations as the spring 2012 scans. These remaining sagebrush plants were then destructively sampled as described above. The groups of shrubs identified for destructive sampling in both spring and fall were chosen using the same stratified random approach to sample a range of sagebrush volumes as mentioned above. An additional thirty sagebrush plants were scanned and destructively sampled in October 2011 (i.e., fall-only sampled) at 6 plots in RCEW (n=30) increasing the total sample size to 121 sagebrush plants. All samples were sorted to separate the green biomass; which included leaves, green stems, and seeds, from the woody biomass. The sorted samples were oven-dried at 65°C for 48 h or until a constant dry weight was reached. Separate dry weights of green and woody biomass were recorded for each sagebrush plant.

2.3. Volumetric Analysis

This study used the TLS point cloud to calculate shrub volume based on two different approaches, voxel-derived volume and 3-D convex hull-derived volume. The TLS point cloud was first subset into points from green and non-green or woody parts of the sagebrush canopy.

These subsets were then used to calculate the volumes of both the green canopy and total sagebrush canopy. These volumes were then used to estimate green and total sagebrush biomass. The efficacy of the voxel and convex hull approaches for accurately estimating the green and total sagebrush biomass was then contrasted.

Subsetting the TLS point cloud into green and non-green fractions was performed based on differences in reflectivity of the laser energy (1550 nm) between the green and woody biomass of the sagebrush canopy. A reflectivity threshold value of -4.5 dB was used to separate the green from the woody points. The higher water content present in green biomass absorbs laser energy while the drier, woody biomass tends to more strongly reflect laser energy at 1550 nm (Gao, 1996; Sims & Gamon, 2003). The reflectivity threshold we used was intended to represent the maximum difference between green biomass absorption and woody biomass reflectance.

Voxels, or volumetric pixels, were first developed for medical imagery (Kaufman, 1990; Levoy, 1988). The 3-D space is divided into voxels (1 cm^3), which either contain points representing laser returns (1) or are empty (0). This simple classification allows for voxels to represent multiple canopy levels (Z values) at the same X, Y coordinate. Voxels are able to model discontinuous surfaces unlike surface models such as Triangulated Irregular Networks (TINs) or digital elevation models (DEMs), which only provide a single Z value for each X,Y coordinate (Stoker, 2009). Provided the inner vegetation structure is detected by the TLS, voxels can provide a highly accurate estimation of volume where the inner branches and leaves of the shrub canopy are represented as present (1) and the canopy gaps are represented by empty voxels (0) (**Fig. 2A** and **Fig. 2C**). The green subset of points is used to calculate green voxel volume, while all points are used to calculate total voxel volume. However, if the TLS fails to penetrate

NOTICE: this is the author's version of a work that was accepted for publication in *ISPRS Journal of Photogrammetry and Remote Sensing*. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in I*SPRS Journal of Photogrammetry and Remote Sensing*, Vol. 88, (2014)] DOI: 10.1016/j.isprsjprs.2013.12.006

deeply into the sagebrush canopy; as may occur in large, densely-canopied sagebrush plants, the voxel-based approach will treat the lack of laser returns or points from the canopy interior as empty voxels or canopy voids. Consequently, the voxel-based approach could substantially underestimate the canopy volume of large, densely-canopied sagebrush or other dryland shrubs.

The 3-D convex hull approach was applied to the TLS point clouds as an alternative to the voxel-volume approach. A convex hull is defined by an outer set of facets, which contain the entire point cloud. Facets are merged to guarantee the result is convex and does not contain errors caused by non-convex solutions. The convex hull volume is then calculated using the facets as boundaries and filling in the inner gaps to produce a solid object (**Fig. 2B** and **Fig. 2D**). The convex hull processing in this study was completed using the Quickhull algorithm (QHULL) developed by Barber et al. (1996), which returns the smallest convex subset of exterior points from the point cloud. For any vegetation with extensive gaps in the canopy, this method overestimates the true volume that the vegetation occupies, as these gaps are ignored. The voxel method assumes the TLS penetrates fully into the canopy, while the convex hull method assumes a consistent biomass-to-volume ratio across all sizes of plants.

2.4. Statistical Analysis

The first objective was to contrast the accuracy of sagebrush volume methods (X) for predicting biomass (Y), which was addressed using ordinary least squares (OLS) regressions. These regressions required a log-log transformation of both the volume (X) and biomass (Y) variables to normalize the residuals. The general form of this regression model is presented in Eq. (1):

$$\ln(AGB) = \beta_0 + \beta_1 \ln(V) + \beta_2 \ln(V)^2 \qquad (1)$$

where, *AGB* is the predicted aboveground biomass (g) of the shrub, *V* is the estimated volume (m^3) of the shrub, and β_i are the regression parameters. Statistical analyses were conducted using the R statistical package (R Core Team, 2012). Coefficient of determination (R^2) values from the regressions were used to evaluate relative predictive power of the two biomass estimation methods. Cross validation for all models was completed using the leave-one-out (LOOCV) method (Brovelli et al., 2008).

The second objective of testing the robustness of the relationship between volume and biomass over space and time was addressed by expanding the model presented in Eq. 1 to include site and season variables. Interactions between predictor variables were also considered in the most complex model. The variable with the lowest contribution was removed in a stepwise fashion until all the remaining predictor variables were significant ($\alpha = 0.05$) and a highly predictive yet parsimonious model was achieved. This "best" model was compared to the simplest model, where only sagebrush volume was used as a predictor.

After evaluating the robustness of the TLS-based approaches, the most robust approach was applied to determine if seasonal variation in the actual green biomass values at each study site could be detected based on TLS-derived, green volume estimates (Objective 3). Using the convex hull relationship developed from **Eq. 1**, the predicted green biomass was calculated for each plant that was scanned in the spring and fall (fifteen sagebrush at each site [n=45]). The values were differenced and a paired t-test was used to evaluate if seasonal changes were detected. All t-tests were one-sided with an alternative hypothesis that ephemeral leaf loss would be detected. As a comparison, the seasonal changes in green biomass based on destructive sampling at each study site (from spring and fall), were assessed using a two-sample t-test (thirty or thirty-one sagebrush at each site [n=91]). The individual p-values from the three sites were combined using meta-analysis with Fisher's method (Hedges & Olkin, 1985) to assess overall seasonal change.

3. Results

3.1. Biomass Estimation

Regression coefficients and model selection results for the 3-D convex hull and voxel-based models are presented in **Fig. 3**. The 3-D convex hull model estimated total biomass more accurately (R^2_{LOOCV} = 0.919) than the voxel-based model (R^2_{LOOCV} = 0.862). Green biomass predictions from the convex hull model (R^2_{LOOCV} = 0.834) greatly outperformed voxel (R^2_{LOOCV} = 0.731) estimates. Season, site, and variable interactions were included as further predictor variables for biomass (**Table 2**), but contributed modest to no gains in predictive power over the simple, univariate models. For example, the best convex-hull models that included site and season variables explained only 0.5% and 1.1% more variation for total and green biomass than did the univariate models. Predictions from bi- or multi-variate voxel volume models improved by only 2.6% and 2.4% for total and green biomass, respectively, over those from univariate models. The univariate voxel models for green biomass which included a quadratic volume parameter (V^2) provided an improved regression fit and more normalized residuals relative to the simplest model with only the linear form (V) of the volume parameter (**Fig. 3D**).

3.2. Seasonal Differences

Seasonal differences in sagebrush green biomass were measured with destructive sampling and were detected by our TLS-based biomass predictions. The mean value for destructively-harvested samples of green sagebrush biomass at the Hollister study site during

NOTICE: this is the author's version of a work that was accepted for publication in *ISPRS Journal of Photogrammetry and Remote Sensing*. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in I*SPRS Journal of Photogrammetry and Remote Sensing*, Vol. 88, (2014)] DOI: 10.1016/j.isprsjprs.2013.12.006

spring was larger than for fall samples (**Fig. 4**; $p = 0.019$). Actual green biomass at SCW exhibited marginally significant seasonal differences ($p = 0.060$). Spring and fall green biomass means at RCEW were similar ($p = 0.887$). Combining the results from all three sites using Fisher's method revealed overall seasonal differences in actual green biomass ($X^2 = 13.76$; $p = 0.032$). The convex hull relationship developed from **Eq. 1** was used to test for seasonal change in green biomass at each site. The results were similar to the destructive sampling. The Hollister study site exhibited significant spring to fall decreases in green biomass (**Fig. 5**; $p < 0.0001$), as did the SCW site ($p = 0.029$), while RCEW did not show significant seasonal change ($p = 0.899$). The combined test for seasonal differences in TLS-derived green biomass estimates also yielded a significant result ($X^2 = 27.95$; $p < 0.0001$).

4. Discussion

4.1. Biomass Estimation

The simple, univariate models accurately predicted Wyoming big sagebrush biomass across a broad spatiotemporal scope, spanning two seasons at three study sites across a 400-km extent. Adding site and season predictor variables to the model yielded little additional predictive power (< 3%). Consequently, these results indicate that the model can be accurately applied to other Wyoming big sagebrush-dominated regions in the Great Basin, without requiring a site or seasonal correction variable. We hypothesize that minimal destructive sampling will be necessary to apply the relationships developed here for other big sagebrush subspecies, such as mountain big sagebrush (*A. tridentata ssp. vaseyana*), and possibly, basin big sagebrush (*A. tridentata ssp. tridentata*). This conclusion is based on subspecies similarities in the ratio between woody and green biomass. However, shorter-stature sagebrush species, such as low sagebrush (*A. arbuscula*) and stiff sagebrush (*A. rigida*) may have substantially different canopy structure and ratios between woody and green biomass (Rosentreter, 2005). As such, the relationships developed here may not hold for these species. Destructive sampling in different big sagebrush subspecies, other sagebrush species, and other dryland shrub species (e.g., bud sagebrush [*Picrothamnus desertorum*] and fourwing saltbush [*Atriplex canescens*]) will be necessary to test this hypothesis.

The convex-hull volume method left only 8% of total biomass (R^2 = 0.92) and 16% of green biomass (R^2 = 0.84) variation unexplained. These accuracy values are quite similar to those reported from previous research using TLS to predict aboveground biomass tree growth forms. Yao et al. (2011) reported accurate prediction of conifer biomass (R^2 = 0.85) while Lin et al. (2010) obtained even higher accuracies for conifers (R^2 = 0.97) but slightly lower for deciduous trees (R^2 = 0.88). Our method for estimating shrub biomass can be combined with already established methods for tree biomass to comprehensively estimate vegetation biomass across a region.

Our validated methods and allometric equations (**Fig. 3** and **Eq. 1**) are well suited for a variety of applications such as tracking changes in rangeland carbon stocks (Fang et al., 2001), assessing fuel loads (Thaxton & Platt, 2006), and evaluating food availability for threatened or endangered animal species (Hobbs & Swift, 1985). Our work indicates TLS can be confidently used for biomass assessments at the individual plant or small-plot scale, however, additional work is needed to scale the TLS methodologies and equations from these relatively smaller scales to broader, landscape-scale applications. Using the TLS methodologies produced here at the plot-scale will require significant effort in improving and automating the classification methods of the point cloud, and proper segmentation of individual shrubs. For example, Brodu and Lague (2012) developed a method to use multi-scale dimensionality to classify a complex TLS point cloud of a streambed with large boulders, finer rocks, and various vegetation types. In their method, the individual points are classified based on the distribution of surrounding points in 1-dimension, a 2-dimensional circle, and a 3-dimensional sphere (Brodu & Lague, 2012). This and other geostatistical approaches may be applicable to automatically classifying the point cloud between shrubs and grasses in dryland environments. Once sagebrush plants or plants from other targeted shrub species are individually classified, the methods presented here to calculate volume can be used to predict plot-level biomass. If individual shrubs cannot be delineated due to high shrub density, or technological limitations, multiple sagebrush could be grouped and treated as a single unit or patch. Testing at the plot-scale is needed to assess the errors that this grouping could introduce. Additionally, further work needs to explore the effects of scan distance on beam divergence, incidence angle, partial hits, and the reflective properties of the plant to improve the green and non-green classification method. Our work minimized some of these effects by measuring shrubs close to the scanner (average of 5.7 m).

To obtain biomass estimates at the landscape-scale, a combination of TLS and airborne and/or satellite-based LiDAR will be required (Vierling et al., 2013). Airborne LiDAR of forested environments has been used to estimate biomass, with Drake et al. (2003) achieving fairly high accuracies in tropical forests (R^2 = 0.89), but lower accuracies in deciduous forests (R^2 = 0.66). Shrub biomass estimates using ALS in the Mediterranean by Estornell et al. (2011) proved less accurate when all shrubs were included (R^2 = 0.37-0.48), but selecting only shrubs with a higher density of points increased the accuracy (R^2 = 0.73), suggesting that future advances in ALS technology to obtain higher point densities will make ALS more viable. While the shrubs in the Estornell et al. (2011) study were 0.8-2.5 m, the current state of ALS technology is not yet sufficient for accurate estimation of biomass for low-height (<1 m) vegetation.

4.2. Seasonal Differences

Results from repeated scanning over different seasons indicate our TLS methodologies are sensitive enough to detect seasonal differences in Wyoming big sagebrush biomass. The Hollister and SCW sites showed significant measureable differences in destructively sampled green biomass and these differences were also predicted by our TLS convex hull-based approach. The climatic conditions at RCEW may explain why no differences in biomass were measured at that site. Future work should use knowledge of the climate, soils, and phenology at study sites to plan sampling according to the goals of capturing different peak seasonal events.

4.3. Implications

Technology and methods presented here for assessing biomass of Wyoming big sagebrush can, almost certainly, be transferred to other dryland shrubs as long as scale dependencies, scan acquisitions and canopy density are considered. Shrubs with higher canopy density or higher stand density may require more scans to properly model the entire shrub. Deciduous shrubs or completely evergreen shrubs require different sampling strategies, and the timing of scans should be adjusted accordingly. The amount of destructive sampling required to develop TLS volume-biomass relationships for other shrub species will probably be quite small.

By distinguishing between TLS points that represent green, or photosynthetically-active, parts of the plant from points representing woody parts, this methodology shows promise in predicting other vegetation characteristics such as leaf area index (LAI) in shrub-dominated ecosystems. Point cloud classification is desirable to reduce the woody contribution to the overestimation of LAI in gap fraction analysis. The methods and equations here are also complimentary as ground validation for ALS or satellite-based measurements of biomass at the landscape-scale. The rapid, non-destructive nature of TLS allows for targeting of short-duration vegetation events such as peak primary production, as well as repeated monitoring across multiple years to assess net carbon storage for climate modeling, seed production for plant community recovery and sustainability, and long-term animal forage and browse biomass predictions.

5. Acknowledgements

Research was funded by the NOAA OAR Earth Systems Research Laboratory/ Physical Sciences Division (ESRL/PSD) Awards NA09OAR4600221 & NA10OAR4680240, Idaho National Laboratory, and the NSF Idaho EPSCoR Program and by the National Science Foundation under award number EPS-0814387. We thank Mr. Randy Lee at Idaho National Laboratory for his assistance with the TLS, and Mr. Lucas Spaete, Dr. Rupesh Shrestha, Mr. Kyle Gochnour and numerous other students for providing field and lab assistance.

6. References

Anderson, J. E., & Inouye, R. S. (2001). Landscape-scale changes in plant species abundance and biodiversity of a sagebrush steppe over 45 years. *Ecological Monographs*, *71*(4), 531–556.

Baker, W. L. (2006). Fire and Restoration of Sagebrush Ecosystems. *Wildlife Society Bulletin*, *34*(1), 177–185.

Balch, J. K., Bradley, B. A., D'Antonio, C. M., & Gómez-Dans, J. (2013). Introduced annual grass increases regional fire activity across the arid western USA (1980–2009). *Global Change Biology*, *19*(1), 173–183.

Barber, C. B., Dobkin, D. P., & Huhdanpaa, H. (1996). The quickhull algorithm for convex hulls. *ACM Transactions on Mathematical Software*, *22*(4), 469–483.

Bork, E. W., & Su, J. G. (2007). Integrating LIDAR data and multispectral imagery for enhanced classification of rangeland vegetation: A meta analysis. *Remote Sensing of Environment*, *111*(1), 11–24.

Brodu, N., & Lague, D. (2012). 3D terrestrial lidar data classification of complex natural scenes using a multi-scale dimensionality criterion: Applications in geomorphology. *ISPRS Journal of Photogrammetry and Remote Sensing*, *68*(1), 121–134.

Brovelli, M. A., Crespi, M., Fratarcangeli, F., Giannone, F., & Realini, E. (2008). Accuracy assessment of high resolution satellite imagery orientation by leave-one-out method. *ISPRS Journal of Photogrammetry and Remote Sensing*, *63*(4), 427–440.

Chen, J., & Stark, M. S. (2000). Plant species effects and carbon and nitrogen cycling in a sagebrush-crested wheatgrass soil. *Soil Biology and Biochemistry*, *32*(1), 47-57.

Drake, J. B., Dubayah, R. O., Clark, D. B., Knox, R. G., Blair, J. B., Hofton, M. A., … Prince, S. (2002). Estimation of tropical forest structural characteristics using large-footprint lidar. *Remote Sensing of Environment*, *79*(2), 305–319.

Drake, J. B., Knox, R. G., Dubayah, R. O., Clark, D. B., Condit, R., Blair, J. B., & Hofton, M. (2003). Above-ground biomass estimation in closed canopy neotropical forests using lidar remote sensing: factors affecting the generality of relationships. *Global Ecology and Biogeography*, *12*(2), 147–159.

Estornell, J., Ruiz, L. A., Velázquez-Martí, B., & Fernández-Sarría, A. (2011). Estimation of shrub biomass by airborne LiDAR data in small forest stands. *Forest Ecology and Management*, *262*(9), 1697–1703.

Fang, J., Chen, A., Peng, C., Zhao, S., & Ci, L. (2001). Changes in forest biomass carbon storage in China between 1949 and 1998. *Science*, *292*(5525), 2320–2322.

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., ... & Snyder, P. K. (2005). Global consequences of land use. *Science*, *309*(5734), 570-574.

Gao, B. (1996). NDWI—A normalized difference water index for remote sensing of vegetation liquid water from space. *Remote Sensing of Environment*, *58*(3), 257–266.

Gill, R. A., & Burke, I. C. (1999). Ecosystem consequences of plant life form changes at three sites in the semiarid United States. *Oecologia*, *121*(4), 551-563.

Glenn, N. F., Spaete, L. P., Sankey, T. T., Derryberry, D. R., Hardegree, S. P., & Mitchell, J. J. (2011). Errors in LiDAR-derived shrub height and crown area on sloped terrain. *Journal of Arid Environments*, *75*(4), 377-382.

Green, J. S., & Flinders, J. T. (1980). Habitat and dietary relationships of the pygmy rabbit. *Journal of Range Management*, *33*(2), 136-142.

Hedges, L. V., & Olkin, I. (1985). *Statistical methods for meta-analysis*. London: Academic Press.

Hobbs, N. T., & Swift, D. M. (1985). Estimates of habitat carrying capacity incorporating explicit nutritional constraints. *Journal of Wildlife Management*, *49*(3), 814–822.

Huang, P., & Pretzsch, H. (2010). Using terrestrial laser scanner for estimating leaf areas of individual trees in a conifer forest. *Trees*, *24*(4), 609–619.

Kato, A., Moskal, L. M., Schiess, P., Swanson, M. E., Calhoun, D., & Stuetzle, W. (2009). Capturing tree crown formation through implicit surface reconstruction using airborne lidar data. *Remote Sensing of Environment*, *113*(6), 1148–1162.

Kaufman, A. (1990). *Volume visualization*. Los Alamitos: IEEE Computer Society Press.

Knapp, P. A. (1996). Cheatgrass (*Bromus tectorum L*) dominance in the Great Basin Desert: History, persistence, and influences to human activities. *Global Environmental Change*, *6*(1), 37–52.

Knick, S. T. (1999). Requiem for a sagebrush ecosystem? *Northwest Science*, *73*(1), 53-57.

Knick, S. T., & Connelly, J. W. (2011). *Greater Sage-Grouse: Ecology and Conservation of a Landscape Species and Its Habitats, Published for the Cooper Ornithological Society* (Vol. 38). Los Angeles: University of California Press.

Knick, S. T., Dobkin, D. S., Rotenberry, J. T., Schroeder, M. A., Haegen, W. M. V., & van Riper III, C. (2003). Teetering on the Edge or Too Late? Conservation and Research Issues for Avifauna of Sagebrush Habitats. *The Condor*, *105*(4), 611–634.

Knick, S. T., & Rotenberry, J. T. (1997). Landscape characteristics of disturbed shrubsteppe habitats in southwestern Idaho (U.S.A.). *Landscape Ecology*, *12*(5), 287–297.

Lefsky, M. A., & McHale, M. R. (2008). Volume estimates of trees with complex architecture from terrestrial laser scanning. *Journal of Applied Remote Sensing*, *2*(1), 023521.

Levoy, M. (1988). Display of surfaces from volume data. *IEEE Computer Graphics and Applications*, *8*(3), 29–37.

Lin, Y., Jaakkola, A., Hyyppä, J., & Kaartinen, H. (2010). From TLS to VLS: Biomass Estimation at Individual Tree Level. *Remote Sensing*, *2*(8), 1864–1879.

Loudermilk, E. L., Hiers, J. K., O'Brien, J. J., Mitchell, R. J., Singhania, A., Fernandez, J. C., … Slatton, K. C. (2009). Ground-based LIDAR: a novel approach to quantify fine-scale fuelbed characteristics. *International Journal of Wildland Fire*, *18*(6), 676–685.

Miller, R. F., & Rose, J. A. (1999). Fire history and western juniper encroachment in sagebrush steppe. *Journal of Range Management*, *52*(6), 550–559.

Miller, R. F., & Schultz, L. M. (1987). Development and longevity of ephemeral and perennial leaves on *Artemisia tridentata* Nutt. ssp. *wyomingensis*. *Great Basin Naturalist*, *47*(2), 227–230.

Mitchell, J. J., Glenn, N. F., Sankey, T. T., Derryberry, D. R., Anderson, M. O., & Hruska, R. C. (2011). Small-footprint LiDAR estimations of sagebrush canopy characteristics. *Photogrammetric Engineering and Remote Sensing*, *77*(5), 521–530.

Moffet, C. A., Pierson, F. B., Robichaud, P. R., Spaeth, K. E., & Hardegree, S. P. (2007). Modeling soil erosion on steep sagebrush rangeland before and after prescribed fire. *Catena*, *71*(2), 218-228.

Olsoy, P. J., Glenn, N. F., & Clark, P. E. (in press). Estimating sagebrush biomass using terrestrial laser scanning (TLS). *Rangeland Ecology and Management*.

Pierson, F. B., Robichaud, P. R., Moffet, C. A., Spaeth, K. E., Hardegree, S. P., Clark, P. E., & Williams, C. J. (2008). Fire effects on rangeland hydrology and erosion in a steep sagebrush-dominated landscape. *Hydrological Processes*, *22*(16), 2916-2929.

R Core Team. (2012). *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from http://www.R-project.org/

Rachlow, J. L., Sanchez, D. M., & Estes-Zumpf, W. A. (2005). Natal burrows and nests of free-ranging pygmy rabbits (*Brachylagus idahoensis*). *Western North American Naturalist*, *65*(1), 136–139.

Reynolds, J. F., Smith, D. M. S., Lambin, E. F., Turner II, B. L., Mortimore, M., Batterbury, S. P., … Herrick, J. E. (2007). Global desertification: building a science for dryland development. *Science*, *316*(5826), 847–851.

Riegl Laser Measurement Systems. (2013). Riegl VZ-1000 datasheet. Retrieved April 17, 2013, from http://www.riegl.com/

Rosentreter, R. (2005). Sagebrush identification, ecology, and palatability relative to sage-grouse. USDA Forest Service Proceedings RMRS-P-38, 3-16.

Rowland, M. M., Wisdom, M. J., Suring, L. H., & Meinke, C. W. (2006). Greater sage-grouse as an umbrella species for sagebrush-associated vertebrates. *Biological Conservation*, *129*(3), 323–335.

Shaw, M. R., & Harte, J. (2001). Control of litter decomposition in a subalpine meadow-sagebrush steppe ecotone under climate change. *Ecological Applications*, *11*(4), 1206-1223.

Sims, D. A., & Gamon, J. A. (2003). Estimation of vegetation water content and photosynthetic tissue area from spectral reflectance: a comparison of indices based on liquid water and chlorophyll absorption features. *Remote Sensing of Environment*, *84*(4), 526–537.

Soil Survey Staff. (2013). Web Soil Survey. Natural Resources Conservation Service, United States Department of Agriculture. Retrieved April 17, 2013, from http://websoilsurvey.nrcs.usda.gov/

Stoker, J. (2009). Visualization of Multiple-return Lidar Data: Using Voxels. *Photogrammetric Engineering and Remote Sensing*, *75*(2), 109–112.

Tausch, R. J., Chambers, J. C., Blank, R. R., & Nowak, R. S. (1995). Differential establishment of perennial grass and cheatgrass following fire on an ungrazed sagebrush-juniper site. In Roundy, B. A., McArthur, D. E., Haley, J. S., & Mann D. K. (Compilers). Proceedings: Wildland Shrub and Arid Land Restoration Symposium. General Technical Report INT-GTR-313. USDA, Forest Service, Intermountain Research Station, Ogden, UT, 116-118.

Thaxton, J. M., & Platt, W. J. (2006). Small-scale fuel variation alters fire intensity and shrub abundance in a pine savanna. *Ecology*, *87*(5), 1331–1337.

Thines, N. J. S., Shipley, L. A., & Sayler, R. D. (2004). Effects of cattle grazing on ecology and habitat of Columbia Basin pygmy rabbit (*Brachylagus idahoensis*). *Biological Conservation*, *119*(4), 525-534.

Vierling, L. A., Xu, Y., Eitel, J. U. H., & Oldow, J. S. (2013). Shrub characterization using terrestrial laser scanning and implications for airborne LiDAR assessment. *Canadian Journal of Remote Sensing*, *38*(6), 709–722.

Wallestad, R., Peterson, J. G., & Eng, R. L. (1975). Foods of adult sage grouse in central Montana. *Journal of Wildlife Management*, *39*(3), 628-630.

West, N. E. (2000). Synecology and disturbance regimes of sagebrush steppe ecosystems. In Entwistle, P. G., DeBolt, A. M., Kaltenecker, J. H., & Steenhof, K. (Compilers), Proceedings: Sagebrush Steppe Ecosystems Symposium. USDI Bureau of Land Management Publication BLM/ID/PT-0010011150, Boise, ID, 15–26.

White, R. P., & Nackoney, J. (2003). Drylands, People, and Ecosystem Goods and Services: A Web-based Geospatial Analysis. *World Resources Institute Publications*. Retrieved from http://pdf.wri.org/drylands.pdf

WRCC. (2009). Idaho Climate Summaries. Western Regional Climate Center, Desert Research Institute. Retrieved from http://www.wrcc.dri.edu/summary/climsmid.html

Yao, T., Yang, X., Zhao, F., Wang, Z., Zhang, Q., Jupp, D., … Strahler, A. (2011). Measuring forest structure and biomass in New England forest stands using Echidna ground-based lidar. *Remote Sensing of Environment, 115*(11), 2965-2974.

Tables

Table 1. Summary of study area climate data for RCEW, Hollister, and SCW. Data are from the Western Regional Climate Center (WRCC) operated by the Desert Research Institute (DRI).

Site	**Mean Elevation (m)**	**Precipitation (mm/yr)**	**Snowfall (mm/yr)**	**July Mean Temp (°C)**	**Dec Mean Temp (°C)**
RCEW	1367	271	241	20.8	-1.2
Hollister	1448	256	391	21.5	-1.2
SCW	1529	206	417	20.4	-6.7

Table 2. Model variables for explaining total and green biomass. The first model in each group includes all variables and their interactions (noted by *). In each subsequent model, the variable with the highest p-value was removed until all remaining variables were significant ($p < 0.05$[b]). The final model is the simplest, with only volume as a predictor, and is provided for comparison. V = Convex hull or Voxel Volume (m^3), Se = Season (Spring or Fall), Si = Site (RCEW, Hollister, or SCW).

Model	**Parameters**	R^2	R^2_{LOOCV}
Total Convex Hull Volume			
V^2 + V + Se + Si + V*Se + V*Si + Se*Si	11	0.927	0.918
V^2 + V + Se + Si + V*Si + Se*Si	10	0.928	0.921
V^2 + V + Se + Si + V*Si	8	0.928	0.920
V^2 + V + Se + Si	6	0.927	0.920
V + Se + Si	5	0.930	0.924[a]

NOTICE: this is the author's version of a work that was accepted for publication in *ISPRS Journal of Photogrammetry and Remote Sensing*. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in I*SPRS Journal of Photogrammetry and Remote Sensing*, Vol. 88, (2014)] DOI: 10.1016/j.isprsjprs.2013.12.006

V + Si	4	0.928	0.923[b]
V	2	0.921	0.919[c]
Total Voxel Volume			
V^2 + V + Se + Si + V*Se + V*Si + Se*Si	11	0.901	0.886
V^2 + V + Se + Si + V*Se + Se*Si	9	0.899	0.887
V^2 + V + Se + Si + Se*Si	8	0.899	0.888[a]
V^2 + V + Se + Si	6	0.888	0.875
V^2 + V + Se	4	0.890	0.880[b]
V^2 + V	3	0.873	0.862
V	2	0.867	0.861[c]
Green Convex Hull Volume			
V^2 + V + Se + Si + V*Se + V*Si + Se*Si	11	0.852	0.839
V^2 + V + Se + Si + V*Se + Se*Si	9	0.853	0.841
V^2 + V + Se + Si + V*Se	7	0.853	0.842
V^2 + V + Se + Si	6	0.854	0.845[a]
V^2 + V + Se	4	0.852	0.845[ab]
V + Se	3	0.847	0.841
V	2	0.839	0.834[c]
Green Voxel Volume			
V^2 + V + Se + Si + V*Se + V*Si + Se*Si	11	0.770	0.753
V^2 + V + Se + Si + V*Se + Se*Si	9	0.770	0.755[a]
V^2 + V + Se + Si + V*Se	7	0.754	0.740
V^2 + V + Se + Si	6	0.756	0.745

V^2 + V + Si	5	0.756	0.746
V^2 + V	3	0.738	0.731[b]
V	2	0.703	0.690[c]

[a]Best overall model (highest R^2_{LOOCV})

[b]Best model with all significant p-values ($p < 0.05$)

[c]Simplest model

Figure Captions

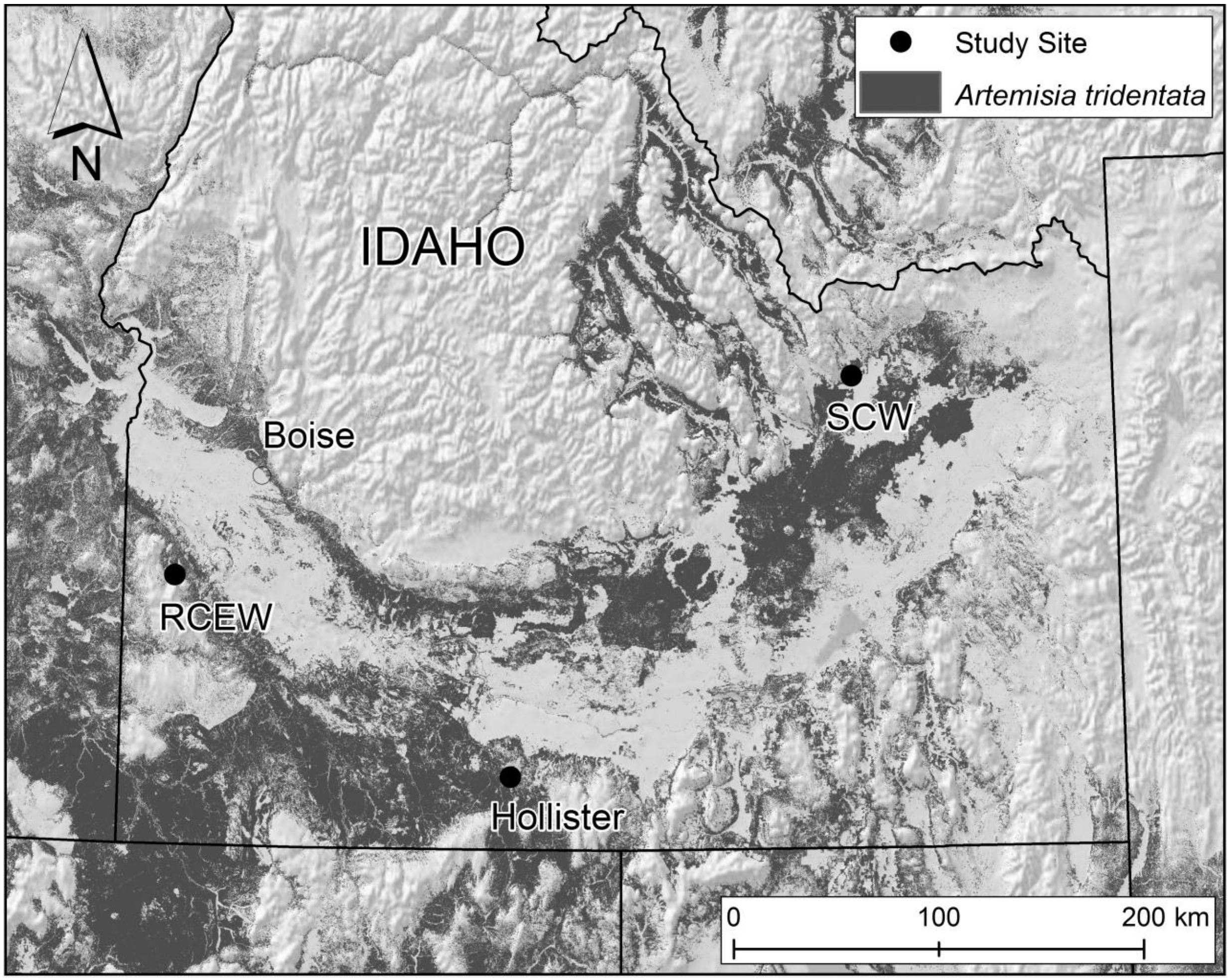

Fig. 1. Distribution of study sites across the Northern Basin and Range and Snake River Plain ecoregions of Idaho, USA. The shaded areas are dominated by big sagebrush.

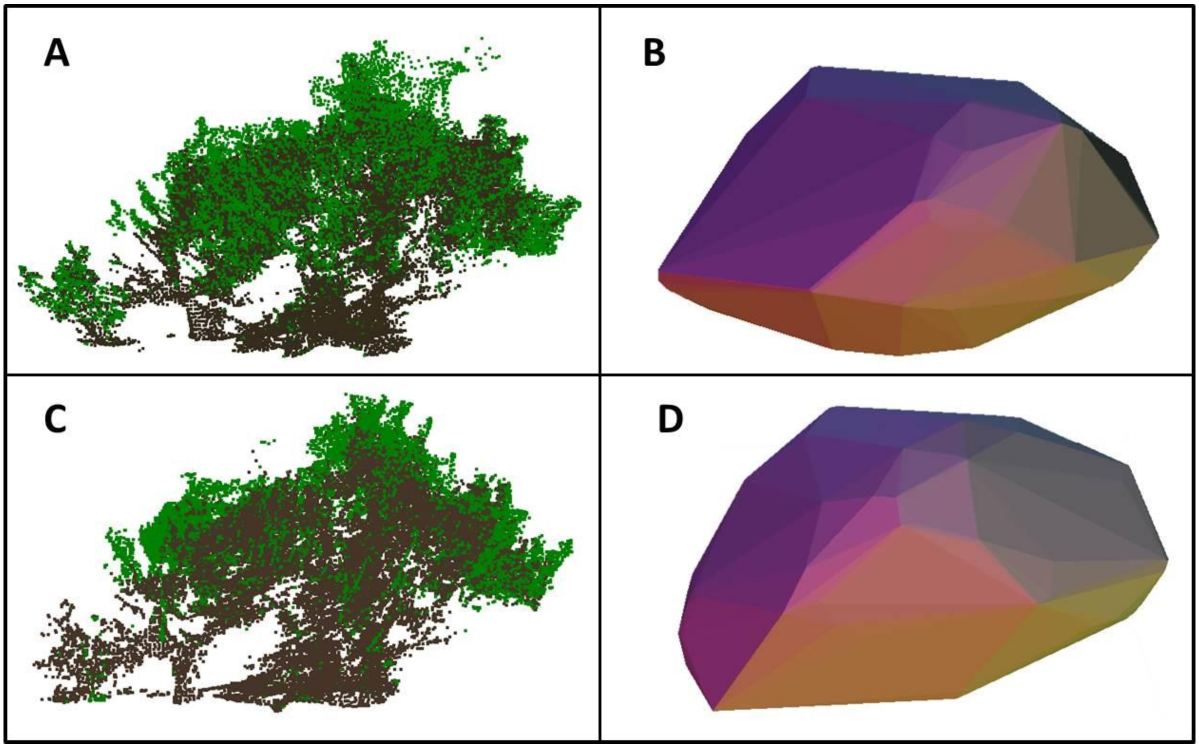

Fig. 2. Similar perspectives of sagebrush point clouds modeled with the voxel method in spring (**A**) and fall (**C**), and the convex hull method in spring (**B**) and fall (**D**). Green and brown represent green and woody biomass respectively in (**A**) and (**C**).

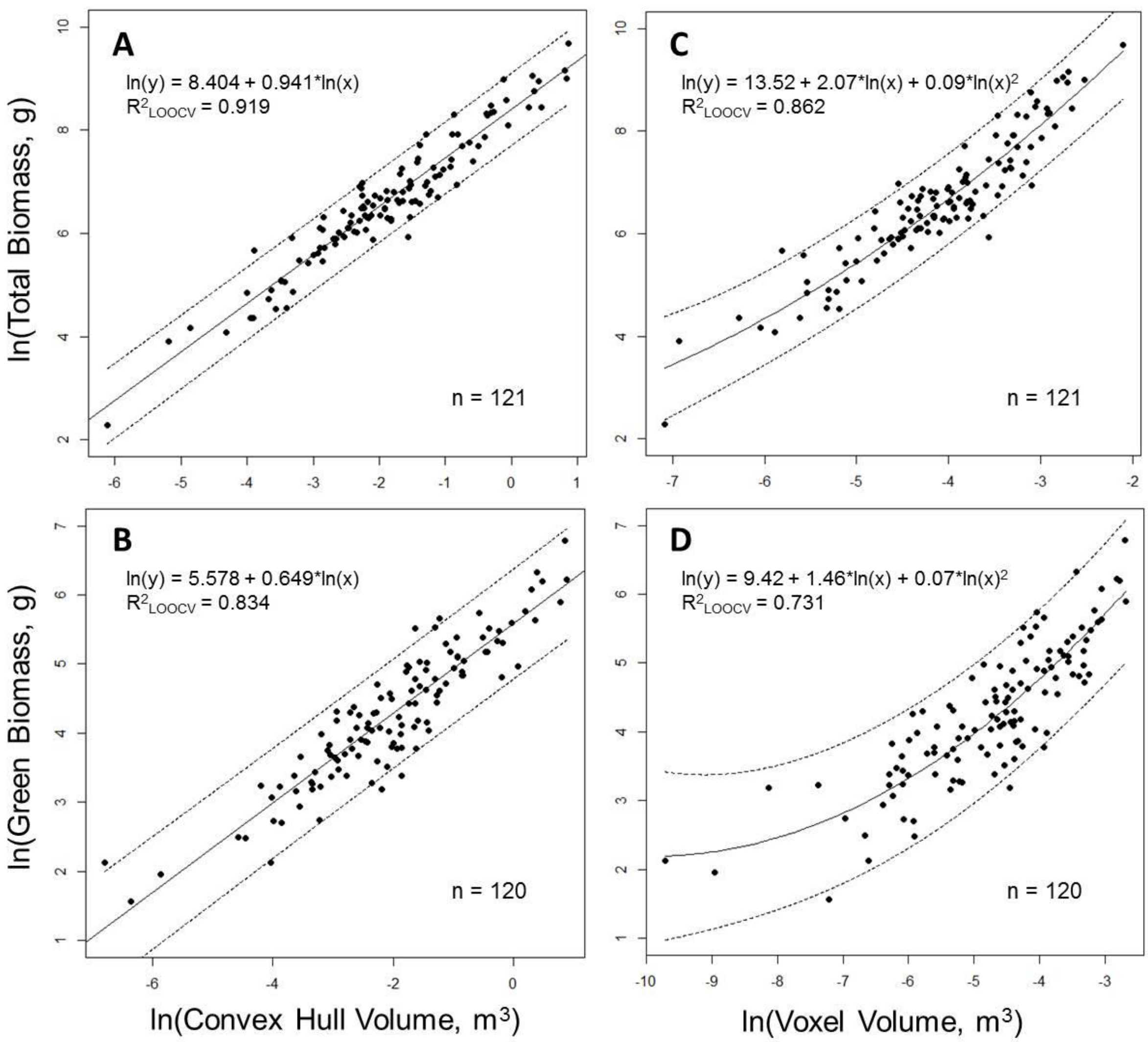

Fig. 3. Regression using convex hull volume to predict (**A**) total biomass and (**B**) green biomass, and using voxel volume to predict (**C**) total biomass and (**D**) green biomass. Dotted lines are 95% prediction interval; solid line shows regression fit.

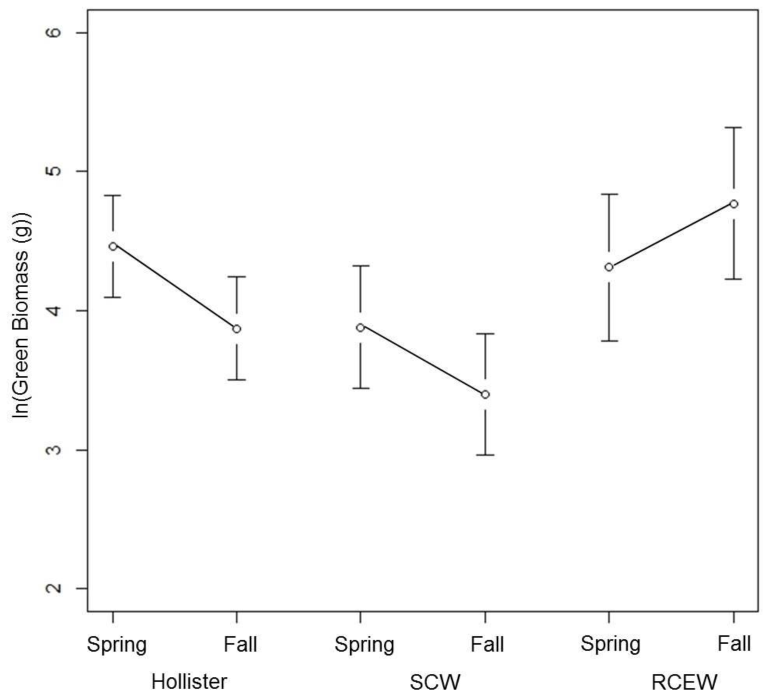

Fig. 4. Mean and 95% confidence interval for green biomass of destructive samples for each season and site (n=15 for each season in both Hollister and SCW; n=16 for spring and n=15 for fall in RCEW). Hollister showed a significant difference in green biomass (p = 0.019) and SCW showed a marginally significant difference (p = 0.060).

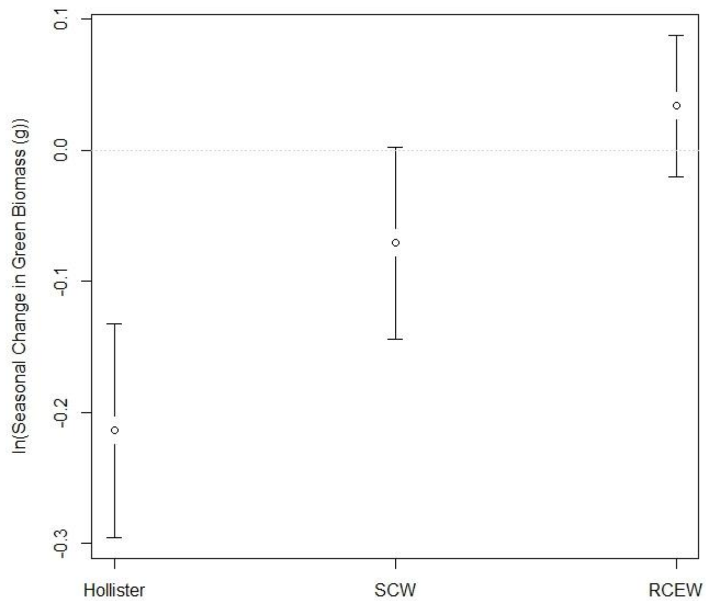

Fig. 5. Mean and 95% confidence interval for predicted seasonal change in green biomass using the convex hull relationship developed from Eq. 1. Sample size is n=15 per site. Hollister and SCW showed significant decreases in green biomass ($p < 0.0001$ and $p = 0.029$, respectively).