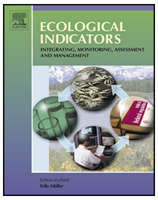
Ecological Indicators 61 (2016) 815–821

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



Estimation of big sagebrush leaf area index with terrestrial laser scanning

Peter J. Olsoy[a,1], Jessica J. Mitchell[b], Delphis F. Levia[c], Patrick E. Clark[d], Nancy F. Glenn[a,*]

[a] *Boise State University, Department of Geosciences, Boise Center Aerospace Lab, 1910 University Drive, Boise, ID 83725, USA*
[b] *Appalachian State University, Department of Geography and Planning, P.O. Box 32066, Boone, NC 28608, USA*
[c] *University of Delaware, Departments of Geography and Plant & Soil Sciences, Newark, DE 19716, USA*
[d] *USDA Agricultural Research Service, 800 Park Blvd, Suite 105, Boise, ID 83712, USA*

ARTICLE INFO

Article history:
Received 7 January 2015
Received in revised form 8 October 2015
Accepted 13 October 2015
Available online 10 November 2015

Keywords:
Artemisia tridentata
Convex hull volume
Ground-based LiDAR
Leaf area index
Terrestrial laser scanning
Voxel volume

ABSTRACT

Accurate monitoring and quantification of the structure and function of semiarid ecosystems is necessary to improve carbon and water flux models that help describe how these systems will respond in the future. The leaf area index (LAI, $m^2 m^{-2}$) is an important indicator of energy, water, and carbon exchange between vegetation and the atmosphere. Remote sensing techniques are frequently used to estimate LAI, and can provide users with scalable measurements of vegetation structure and function. We tested terrestrial laser scanning (TLS) techniques to estimate LAI using structural variables such as height, canopy cover, and volume for 42 Wyoming big sagebrush (*Artemisia tridentata* subsp. *wyomingensis* Beetle & Young) shrubs across three study sites in the Snake River Plain, Idaho, USA. The TLS-derived variables were regressed against sagebrush LAI estimates calculated using specific leaf area measurements, and compared with point-intercept sampling, a field method of estimating LAI. Canopy cover estimated with the TLS data proved to be a good predictor of LAI ($r^2 = 0.73$). Similarly, a convex hull approach to estimate volume of the shrubs from the TLS data also strongly predicted LAI ($r^2 = 0.76$), and compared favorably to point-intercept sampling ($r^2 = 0.78$), a field-based method used in rangelands. These results, coupled with the relative ease-of-use of TLS, suggest that TLS is a promising tool for measuring LAI at the shrub-level. Further work should examine the structural measures in other similar shrublands that are relevant for upscaling LAI to the plot-level (i.e., hectare) using data from TLS and/or airborne laser scanning and to regional levels using satellite-based remote sensing.

1. Introduction

Dryland ecosystems, including grasslands, shrublands, and savannas, occupy roughly 40% of the Earth's land surface (Meigs, 1953) and are particularly sensitive to climate and land use change (Backlund et al., 2008). Vegetation dynamics in dryland ecosystems such as the sagebrush-steppe in the Great Basin of the United States will likely be affected by climate change through elevated levels of CO_2, changes in air temperature, and the timing and distribution of precipitation (Bates et al., 2006; Kwon et al., 2008). In turn, woody plants such as sagebrush exert a major influence on dryland ecosystem processes such as evapotranspiration and carbon and nutrient cycling (Breshears, 2006; Yang et al., 2012a). Water and carbon fluxes in sagebrush are strongly related to plant leaf area index (LAI), a biophysical measure of the layers of leafy vegetation and an indicator of photosynthetic activity and net primary production (Bonan, 1993; Bussotti and Pollastrini, 2015; Smith et al., 1990). Changes in water and carbon cycling of the sagebrush-steppe in response to climate change will ultimately have land management consequences related to forage production, habitat quality and other ecosystem services (Polley et al., 2013). Importantly, measurement or accurate estimation of LAI is necessary for modeling and understanding water and carbon cycling in the sagebrush-steppe.

Due to their vast areal extent across North America, sagebrush (*Artemisia tridentata* Beetle)-dominated rangelands potentially represent a substantial carbon sink (Hunt Jr. et al., 2003; Prater and DeLucia, 2006). Understanding the spatiotemporal variability in sagebrush LAI is important for accurately predicting carbon budgets, even at the global scale (e.g., with global circulation models

---

* Corresponding author. Tel.: +1 208 426 2933.
E-mail addresses: peterolsoy@gmail.com (P.J. Olsoy), mitchelljj@appstate.edu (J.J. Mitchell), dlevia@udel.edu (D.F. Levia), pat.clark@ars.usda.gov (P.E. Clark), nancyglenn@boisestate.edu (N.F. Glenn).
[1] Present address: Washington State University, School of the Environment, 1228 Webster, Pullman, WA 99164, USA.

http://dx.doi.org/10.1016/j.ecolind.2015.10.034
1470-160X/© 2015 Elsevier Ltd. All rights reserved.

[GCMs]), under current and climate-change scenarios. Even within subspecies (e.g., Wyoming big sagebrush, *A. tridentata* subsp. *wyomingensis* Beetle & Young), sagebrush LAI likely varies among plants, stands, and even regions as well as among seasons and years. Data sets of sagebrush LAI for extensive areas and differing seasons are scarce because shrub LAI data are difficult and expensive to acquire with conventional field techniques (e.g., point-intercept sampling, light-intercept sensors, or destructive leaf harvest) and linkages that would promote upscaling between field measures and remotely sensed estimates have not been established for shrublands (Hufkens et al., 2008). Consequently, accurate modeling of the spatiotemporal variability of sagebrush LAI is inhibited by a paucity of data to develop and validate such models over space and time. Without a better understanding of this spatiotemporal variability in sagebrush leaf area, accurate predictions of climate-change effects on sagebrush itself, and on water and carbon flux responses in sagebrush-dominated rangelands are not possible.

Efficient and accurate assessment techniques are important for facilitating sagebrush LAI data collection over extensive areas and among differing time periods. Many methods have been developed to estimate LAI in a variety of ecosystems. The most accurate estimates come from direct measurements that require destructive sampling (Beerling and Fry, 1990). Despite the advantages in increased accuracy with destructive sampling, it is time-intensive and impractical at scales relevant to modeling the impacts of climate change. Other direct measurements involve developing allometric equations related to easily measured vegetation characteristics such as height or canopy cover, or field techniques such as point-intercept sampling (Bonham, 1989; Clark and Seyfried, 2001). Indirect measurements usually involve light interception techniques with hemispherical photography (Jonckheere et al., 2004), or commercially available instruments such as the Li-Cor® LAI-2000 Plant Canopy Analyzer (Mussche et al., 2001). However, indirect estimates have proven challenging in sagebrush-dominated ecosystems because light is disproportionately blocked by woody plant material, which leads to overestimation of LAI (Finzel et al., 2012).

Satellite remote sensing studies have demonstrated direct relationships between LAI and vegetation indices (Danson et al., 2003; Qi et al., 2000) such as the normalized difference vegetation index (NDVI) and the modified soil-adjusted vegetation index (MSAVI, Qi et al., 1994). These spectral indices leverage biophysical knowledge of the “red-edge” where photosynthetic absorption in the red spectrum and high reflectivity in the near-infrared correlate to green, leafy biomass or LAI (Turner et al., 1999). However, the relationship between vegetation indices and LAI breaks down in species with a large woody component (Hunt Jr. et al., 2003) and in dryland ecosystems in general because they contain weak vegetation signals overpowered by high soil reflectance and complex scattering (Kremer and Running, 1993; Mundt et al., 2006; Okin et al., 2001; Qi et al., 1994).

Terrestrial laser scanning (TLS) provides some advantages over standard field techniques for measuring or estimating sagebrush LAI, such as offering a link between ground-based measurements and airborne remotely sensed estimates (Hopkinson et al., 2013; Vierling et al., 2013) and reduced personnel time cost per unit area sampled. Consequently, TLS could provide an effective means of acquiring the sagebrush LAI data needed to scale to satellite-based remote sensing and thus properly develop and validate ecological and hydrological models required to accurately understand and predict the consequences of climate change. To investigate the use of TLS for estimating LAI of Wyoming big sagebrush, a dominant sagebrush subspecies in the Great Basin, we: (1) assess the accuracy of using TLS data to derive vegetation metrics for estimating sagebrush LAI by comparing TLS metrics to those derived from destructive harvesting and leaf area field measurements; and (2) contrast the accuracy of the TLS-derived sagebrush LAI with the field tested method of point-intercept sampling across three study sites in the Snake River Plain, Idaho, USA.

2. Methods

2.1. Study area

The study was conducted at three sites across the Snake River Plain in southern Idaho, USA that are characteristic of the Snake River Plain and Northern Basin and Range ecoregions of the Great Basin; Reynolds Creek Experimental Watershed (RCEW), Hollister, and Snaky Canyon Wash (SCW). These sagebrush-grassland sites are dominated by Wyoming big sagebrush, bluebunch wheatgrass (*Pseudoroegneria spicata* A. Löve), and Sandberg bluegrass (*Poa secunda* J. Presl). The RCEW study site is located in Owyhee County (43°10′32″N, 116°43′2″W; elevation: 1367 m) and has average annual precipitation of 271 mm and mean annual air temperature of 8.8 °C. Soils at RCEW consist of well-drained gravelly and silt loams from the Willhill-Cottle-Longcreek and Arbidge-Owsel-Gariper soil series complexes. The Hollister study site (Twin Falls County, Idaho, USA; 42°18′58″N, 114°41′34″W; elevation: 1448 m) has average annual precipitation of 256 mm and mean annual temperature of 8.8 °C. The soil at Hollister is well-drained and consists of Chuska very stony loam and Shabliss silt loam. The SCW study site (Clark County, Idaho, USA; 44°4′23″N, 112°38′14″W; elevation: 1529 m) has average annual precipitation of 206 mm, and mean annual temperature of 6.5 °C. Soils at SCW are somewhat excessively drained, gravelly loams from a complex of the Whitecloud, Simeroi, and Paint soil series. Climate data were sourced from the Western Regional Climate Center operated by the Desert Research Institute (WRCC, 2009), and soil data from Web Soil Survey of the Natural Resources Conservation Service (Soil Survey Staff, 2013).

2.2. Field sampling

Terrestrial laser scanning, LAI point-intercept measurements, and destructive biomass sampling of Wyoming big sagebrush (hereafter referred to as sagebrush) was conducted at RCEW, Hollister and SCW from September to October 2012. Terrestrial laser scanning and destructive biomass sampling methods are detailed in Olsoy et al. (2014). Scanning was performed with a Riegl VZ-1000 TLS instrument with a 1550 nm near-infrared laser with waveform processing, 8 mm accuracy at 100 m range (Riegl, 2015), and a beam diameter of 2 mm at 6.67 m range (Yang et al., 2012b). Three plots were established at each study site and each plot contained two 25 m^2 sub-plots. The sub-plots all included two or three marked sagebrush ($n = 15$ per site, total $n = 45$) and were scanned from two opposing scan positions at a mean distance of 5.7 m from each sagebrush plant with laser pulse rate set to 300 kHz and an angular stepwidth of 0.01°, resulting in a minimum point spacing of 2 mm (Fig. 1). Scans were georeferenced using four reflective targets whose positions were captured using a survey-grade GPS unit. After scanning the sub-plots, a 1-m^2 quadrat ($n = 42$) was fit around each sagebrush within the sub-plots and point-intercept sampling was applied to estimate LAI (Clark and Seyfried, 2001). The sagebrush LAI point-intercept sampling approach uses a 20-pin frame with five equally spaced frame locations within the 1 m^2 quadrat for a total of 100 attempts m^{-2}. This method uses a sharpened pin that is pushed through the sagebrush canopy and one records the number of pin-point contacts or “hits” with green foliage. The number of green hits is divided by the number of attempts to give an estimate of LAI (Fig. 2). Multiple point frames may be used for shrubs larger than 1 m^2. However, in this study, shrubs that did not fit within