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Research Note

Indirect Measurement of Leaf Area Index in Sagebrush-Steppe Rangelands

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Abstract

Leaf area index (LAI) is defined as the one-sided area of leaves above a unit area of ground. It is a fundamental ecosystem parameter that is a required input of process-based plant growth and biogeochemical models. Direct measurement of LAI is the most accurate method, but is destructive, time-consuming, and labor-intensive. LAI is highly variable in time and space on sagebrush-steppe rangelands, and a rapid, nondestructive method is desirable to understand ecosystem processes. The point-intercept method is nondestructive and has been demonstrated to provide accurate LAI estimates, but the method is time-consuming. LAI measurement with the Accupar ceptometer (Decagon Devices, Pullman, WA) is nondestructive and faster than the point-intercept method, but has not been evaluated on sagebrush-steppe rangelands. The objective of this study was to evaluate the ceptometer for measurement of LAI in sagebrush-steppe rangelands. Ceptometer and point-intercept LAI data were collected at six sites in sagebrush-steppe rangelands and the values were compared. We found that 1) ceptometer LAI data were consistently greater than point-intercept LAI data, 2) ceptometer data were much more variable than the point-intercept data based on standard deviations, and 3) the overall correlation between the two methods was very weak ($r^2 = 0.15$). The much greater ceptometer LAI values were, at least partly, due to the large woody component of the vegetative cover. We attribute the high variability of ceptometer-measured LAI to high instrument sensitivity of the angle of the instrument relative to the sun.

Resumen

El índice de área foliar (IAF) se define como el área de hoja verde (un solo lado) por unidad de área de suelo. Este es un parámetro fundamental en los ecosistemas que requiere un proceso basado en el crecimiento de la planta y modelos bio-geoquímicos. Mediciones directas de IAF es el método más preciso pero es destructivo, consume tiempo y mucho trabajo. IAF es muy variable en tiempo y espacio en los pastizales de matorrales de estepa, por lo que se requiere un método no destructivo para entender el proceso del ecosistema. El método del punto de intercepción es no destructivo y ha demostrado en proveer estimaciones de IAF precisas. El Accuper ceptometor (Decagon Devices, Pullman, WA) es un método no destructivo que es más rápido que el punto de intercepción pero no ha sido evaluado en pastizales de estepa con artemisa. El objetivo de este estudio fue evaluar el ceptometro para medir el IAF en pastizales de estepa con artemisa. Se recolectaron datos de IAF del ceptometro y del punto intercepto en seis sitios de pastizal de estepa de artemisa y los valores fueron comparados. Encontramos que 1) los datos de IAF del ceptometro fueron más consistentes que los del punto intercepto, 2) los datos del ceptometro fueron mucho más variables que los del punto intercepto y 3) la correlación general entre los dos métodos fue muy endeble ($r^2 = 0.15$). Los valores de IAF mayor con el ceptometro el menos en parte se debió a la gran composición de material leñoso de la cubierta vegetal. Atribuimos la alta variabilidad de las medidas de IAF del ceptometro a la alta sensibilidad del ángulo del instrumento relativo al sol.

Key Words: ceptometer, gap-intercept, LAI, point-frame, quadrat, shrubs

INTRODUCTION

Leaf area index (LAI) is defined as the one-sided area of leaves above a unit area of ground (Kirkham 2005), and is related to plant–atmosphere gas exchange and plant growth (Kirkham 2005). The leaf is the location of many of the plant's most vital processes and is the primary organ on vascular plants that absorbs sunlight energy for conversion to glucose, absorbs carbon dioxide from the atmosphere, and releases oxygen and water into the atmosphere (Barbour et al. 1999). The measurement of LAI is critical for the study of many biogeochemical cycles in ecosystems (Breda 2003) and is also an essential input parameter in many process-based plant

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production and ecosystem models (Arora 2002; Jonckheere et al. 2004).

Direct measurement of LAI through destructive sampling is considered highly accurate, but requires a significant commitment of time and labor and is, therefore, of limited use for field characterization of LAI (Clark and Seyfried 2001). Indirect methods of measuring LAI, such as point-intercept sampling (Levy and Madden 1933), facilitate more extensive study of LAI under field conditions. Point-intercept sampling is also called point quadrat or point/pin sampling and was developed to measure vegetation dynamics in grasslands. The point-intercept method has been used extensively in many types of rangeland vegetation and is suited for use in any vegetation under about 1.5 m tall (Coulloudon et al. 1996; Clark and Seyfried 2001). Clark and Seyfried (2001), working at Reynolds Creek Experimental Watershed (RCEW) in southwestern Idaho, tested inclined and vertical point-frames and determined that point-intercept sampling using vertical point-frames accounted for 96% of the variability of LAI in sagebrush. Goodall (1952) reviewed the point-intercept method and concluded that it is "one of the most trustworthy methods available." Although point-intercept can be used over a greater area than the direct, destructive measurement of LAI, it is still time and labor intensive and an alternative, more efficient method would be useful for field characterization of LAI.

Gap-fraction analysis is an indirect method of measuring LAI that uses light to determine the fraction of unvegetated background detected from a viewpoint either above or below the vegetation (Breda 2003; Jonckheere et al. 2004). The Accupar ceptometer (Decagon Devices, Pullman, WA) uses gap-fraction analysis to estimate LAI by measuring direct incident photosynthetically active radiation (PAR; 400–700 nm) above and below the plant canopy. The LAI is calculated using the Beer–Lambert extinction law, which is

$$I_z = I_o e^{-k\mathrm{LAI}} \quad [1]$$

where I_z ($\mathrm{W \cdot m^{-2}}$) is the intensity of radiation at a certain depth from the top of the canopy, I_o ($\mathrm{W \cdot m^{-2}}$) is the incident radiation at the top of the canopy, k is the extinction coefficient and LAI is the estimated leaf area above the level of I_z per unit area of ground (Breda 2003). The ceptometer was designed for use with crops and is most effective in strong sunlight, within 2 h of solar noon.

The ceptometer method is rapid and nondestructive and has been successfully used to measure LAI for plant growth modeling of agronomic crops and some natural vegetation (Running and Gower 1991; Kiniry 1994, 1998; Kiniry et al. 1999). It is not clear, however, that the ceptometer is well adapted for use in sagebrush-steppe vegetation, because unlike agronomic crops, sagebrush-steppe vegetation has a significant woody component and highly uneven spatial distribution. The objective of this research was to evaluate the application of the ceptometer for LAI measurement in sagebrush-steppe vegetation as an alternative to the point-intercept method.

METHODS

This study was conducted over 2 yr, with work beginning in the fall of 2008 and ending in early summer 2010. Data were collected at six sagebrush-steppe sites, three in Idaho and three in California, representing a wide range of vegetative conditions within sagebrush-steppe rangelands. The Idaho sites were located on the RCEW, which is administered by the Agricultural Research Service. The California sites were located on Marble Creek, a grazing allotment managed by the Bureau of Land Management, north of Bishop, California at the base of the western side of the White Mountains. All sites were grazed on a seasonal rotation throughout the study period.

Site Description

The three sites in Idaho (ID-Flats, ID-Nancy Gulch [ID-NG], and ID-Lower Sheep Creek [ID-LSC]), range from 1 200 m to 1 600 m in elevation, and represent differing climatic conditions and vegetative communities. At an elevation of 1 190 m, ID-Flats has a mean annual precipitation (MAP) of 240 mm and a mean annual temperature (MAT) of 9°C. The soil at ID-Flats is a Hardtrigger–Enko complex (2–15% slopes), classified as a fine-loamy, mixed, superactive, mesic Xeric Haplargid with a parent material of volcanic ash and loamy alluvium. Dominant species are Wyoming big sagebrush (*Artemisia tridentata* Nutt. subsp. *wyomingensis* Beetle & Young), shadscale saltbush (*Atriplex confertifolia* [Torr. & Frem.] S. Watson), bottlebrush squirreltail (*Elymus elymoides* [Raf.] Swezey), and Sandberg bluegrass (*Poa secunda* J. Presl). The ID-NG study site is at an elevation of 1 400 m, has a MAP of 300 mm and a MAT of 9°C. ID-NG soil is the Arbidge–Owsel–Gariper complex (1–15% slopes), classified as a fine-silty, mixed superactive mesic durinodic Xeric Haplargid with a parent material of volcanic ash, mixed alluvium, or loess. Vegetation at ID-NG is characterized by Wyoming big sagebrush, bluebunch wheatgrass (*Pseudoroegneria spicata* Pursh), bottlebrush squirreltail, and Sandberg bluegrass as the dominant species. The ID-LSC study site is at 1 627 m, with a MAP of 340 mm and a MAT of 8°C. The soil is a Vitale–Itca–Rubble land complex (2–60% slopes), classified as a loamy-skeletal, mixed, superactive, frigid Typic Argixeroll with a parent material of Tephra, alluvium, or colluvium over bedrock. Dominant species at ID-LSC are low sagebrush (*Artemisia arbuscula* Nutt.), lupine (*Lupinus* L. sp.), milkvetch (*Astragalus* L. sp.), and Sandberg bluegrass.

The three California sites (CA-North, CA-Middle, and CA-South) are all at about the same elevation, 1 850 m, and were laid out parallel to the north–south trend of the White Mountains and spaced about 1 km apart. The MAP at the California sites is 190 mm (NOAA 2011); MAT was not available for the California sites. Wyoming big sagebrush, Nevada ephedra (*Ephedra nevadensis* S. Watson), and antelope bitterbrush (*Purshia tridentata* [Pursh] DC) are dominant components of the vegetation at all three California sites. Soil at CA-South is an Ulymeyer–Rovana complex (5–15% slopes) and classified as a sandy-skeletal, mixed, mesic Xeric Torriorthent with a parent material of alluvium derived from granite. Soil at CA-Middle is Bairs boulder loamy coarse sand (5–15% slopes) and classified as loamy-skeletal, mixed mesic Xeric Haplargids with a parent material of alluvium derived from granite. Soil at CA-North is a Warrior very gravelly sandy loam (5–15% slopes) and classified as loamy-skeletal, mixed (calcerous), mesic Xeric Torriothents with a parent material of alluvium derived from mixed material.

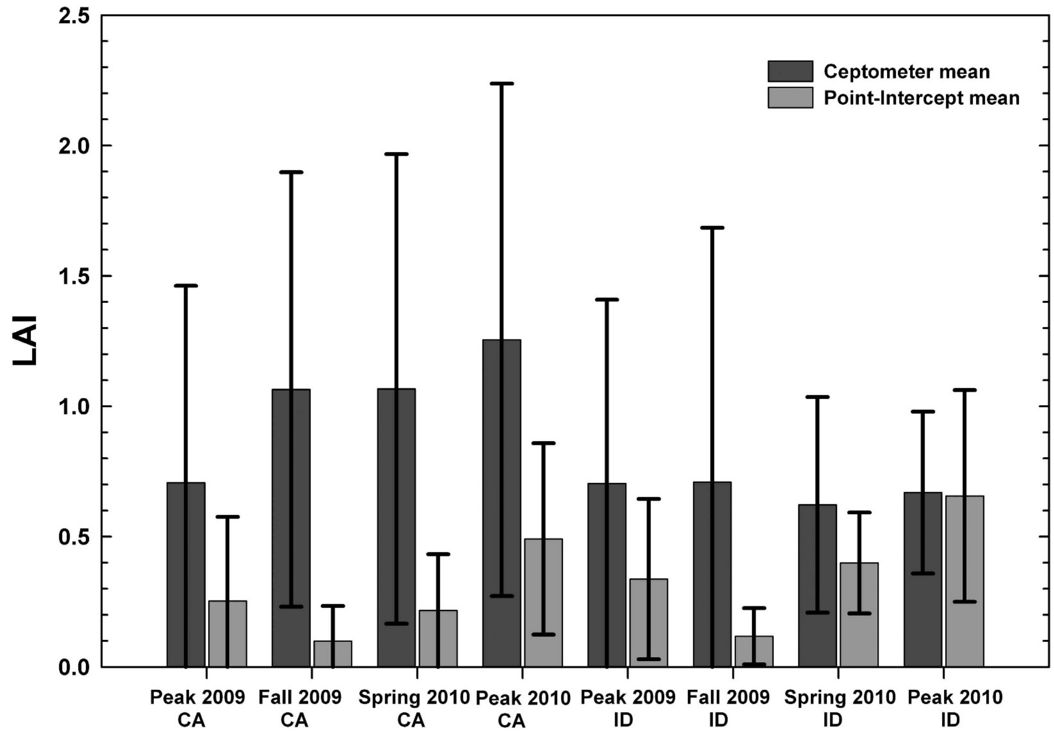

Figure 1. Mean ceptometer and point-intercept leaf area index ($m^2 \cdot m^{-2}$) values. Error bars represent standard deviation.

Experimental Layout

Four 50-m transects were installed at each site. Half-meter (0.5 m × 1 m) quadrats were established on the south side of each transect, offset by 5 m, beginning at 3 m and continuing every 5 m, for a total of 10 quadrats per transect. With 40 quadrats per site, there were a total of 120 quadrats in Idaho and 120 quadrats in California. Quadrats were moved to the north side of each transect for the second year to avoid interference with a different study.

Measurement of Leaf Area Index

The laser point-frame, used to collect point-intercept data, was designed in a T shape with three adjustable legs used to support a 1-m-long frame that held 10 lasers, spaced 10 cm apart in a nadir orientation (VanAmburg 2005; Seefeldt and Booth 2006). Point-intercept data were collected by placing the frame above the plant canopy, parallel to the 1-m side of each quadrat, at distances of 10 cm, 20 cm, 30 cm, and 40 cm from the edge of the quadrat, resulting in 40 sample points per quadrat. At each point, the number of times the laser struck vegetation between the canopy top and ground was recorded. Vegetation hits were recorded by species and noted as green or brown; upper leaves were pushed aside as necessary to read lower canopy levels. Point-intercept data were collected in 2009 at peak standing crop and in the fall, and in 2010 in early spring to midspring and at peak standing crop. All quadrats were sampled at each site every time data were collected. LAI calculations from point-intercept data were made by counting the number of green hits per sample area and dividing by the total number of sample points for the same sample area. For example, there were 40 sample points per quadrat; if there were a total of 41 green hits in a quadrat the LAI would be 1.025 (i.e., 41/40 = 1.025).

The ceptometer is 80 cm long and consists of 80 linear sensors; it is lightweight, and self-contained. Each measurement integrates the PAR from all 80 sensors. It is critical that the instrument be level when data are collected so the instrument is provided with a bubble level. Calculation of LAI using the ceptometer requires the determination of k, the extinction coefficient (Equation 1). The value of k was calculated by taking measurements of I_z and I_o from 10 Wyoming big sagebrush plants at the CA-North site. The value of I_o was determined by taking measurements above the selected plants. The value of I_z was determined by taking measurements below the selected plants. After I_z and I_o measurements were taken, the 10 plants were harvested and weighed. Branches were taken as subsamples from each of the 10 plants, and all green leaves from the subsamples were removed and processed in a leaf area meter to determine LAI. Subsampled branches and corresponding leaves were weighed to determine a leaf to branch ratio, which was used to calculate overall LAI for each harvested plant. An average k value of -0.45, with a standard deviation of 0.15, was determined to be appropriate for the vegetation at all study sites.

During sampling, the value of I_o was determined from the average of five measurements made above each quadrat, prior to the I_z measurement. Measurements of I_z were taken parallel to the 1-m leg of the quadrat, every 10 cm across the width of the quadrat for a total of five measurements, and averaged into a single value. This was repeated three times. The average of these three values was used to calculate LAI for each quadrat.

All 40 quadrats were not sampled at each site due to data collection time constraints and constraints associated with the optimum time-frame for collecting data using the ceptometer. At peak standing crop in 2009, the quadrats along two of the four transects at each site were sampled, resulting in 20 quadrats per site for a total of 120 quadrats. In the fall of 2009, this method was repeated on the newly established quadrats on the north side of each transect. In the spring of 2010, ceptometer data were collected twice, once in early to midspring and a second time at peak standing crop.

At all sites large interspaces occurred between plants resulting in a substantial number of quadrats for which $I_o \approx I_z$. To account for this, the measurement protocol was adjusted in 2010 to emphasize relatively high LAI quadrats. As a result 9 to 15 quadrats were sampled at the midspring and peak 2010 sampling periods for each site, depending on the number of quadrats with shrub cover.

Regression analyses in Microsoft Excel plotted point-intercept LAI data against ceptometer LAI data to define a linear relationship between the two datasets. Site- and date-specific data were used to examine the effect of season on the LAI relationship. Error was estimated by calculating standard deviation for point-intercept and ceptometer-measured LAI values.

RESULTS AND DISCUSSION

A comparison of ceptometer- and point-intercept–measured LAI data, as shown in Figure 1, illustrates large differences between the two datasets. The ceptometer LAI data mean was 0.85 and the point-intercept LAI data mean was 0.33, indicating that ceptometer LAI measurements were about 2.5 times greater than point-intercept LAI measurements. Regression analysis revealed high variation in regression equations defining the linear relationship between ceptometer and point-intercept measured LAI, with r^2 values ranging from 0.0008 to 0.94, slopes ranging from -17.03 to 4.21, and y-intercepts ranging from 0 to 1.32. In addition, measurement variability, as indicated by standard deviation, was about 2.5 times greater for ceptometer LAI data than for point-intercept data. As a result, the ceptometer method requires more measurements than the point-intercept method to obtain a comparable standard deviation. Finally, the temporal trends observed with the two methods were different. For example, ceptometer LAI measurements showed essentially no difference between the LAI measured at peak standing crop in 2009 and the LAI measured post–ephemeral leaf drop in the fall of 2009 (Fig. 1), while point-intercept data indicated a dramatic drop in measured LAI over the same time period. These results may be partly due to the high variability of ceptometer measurements.

The results described above raise serious concerns regarding the use of the ceptometer for estimating LAI in sagebrush-steppe rangelands. However, such an application may be effective if the ceptometer could be effectively calibrated to mimic point-intercept results. Unfortunately, regression analysis of the data indicated a very weak overall relationship ($r^2 = 0.15$) and no consistent relationship between LAI measured by the two methods when sampling site and season were considered. The extreme variability in ceptometer data as well as the tendency to overestimate LAI relative to point-intercept values is evident in Figure 2a.

The large variability in the ceptometer LAI data may be partly due to the difficulty of obtaining a level measurement. Ceptometer measurements are highly sensitive to the orientation of the instrument relative to incident solar radiation. This is a small problem when the user is standing upright, but becomes an issue when crawling on the ground threading the instrument through woody shrubs. The problem is further exacerbated when operating on uneven, sloping terrain in which it is important to have the instrument as close to the soil surface as possible to measure the effects of low-lying vegetation.

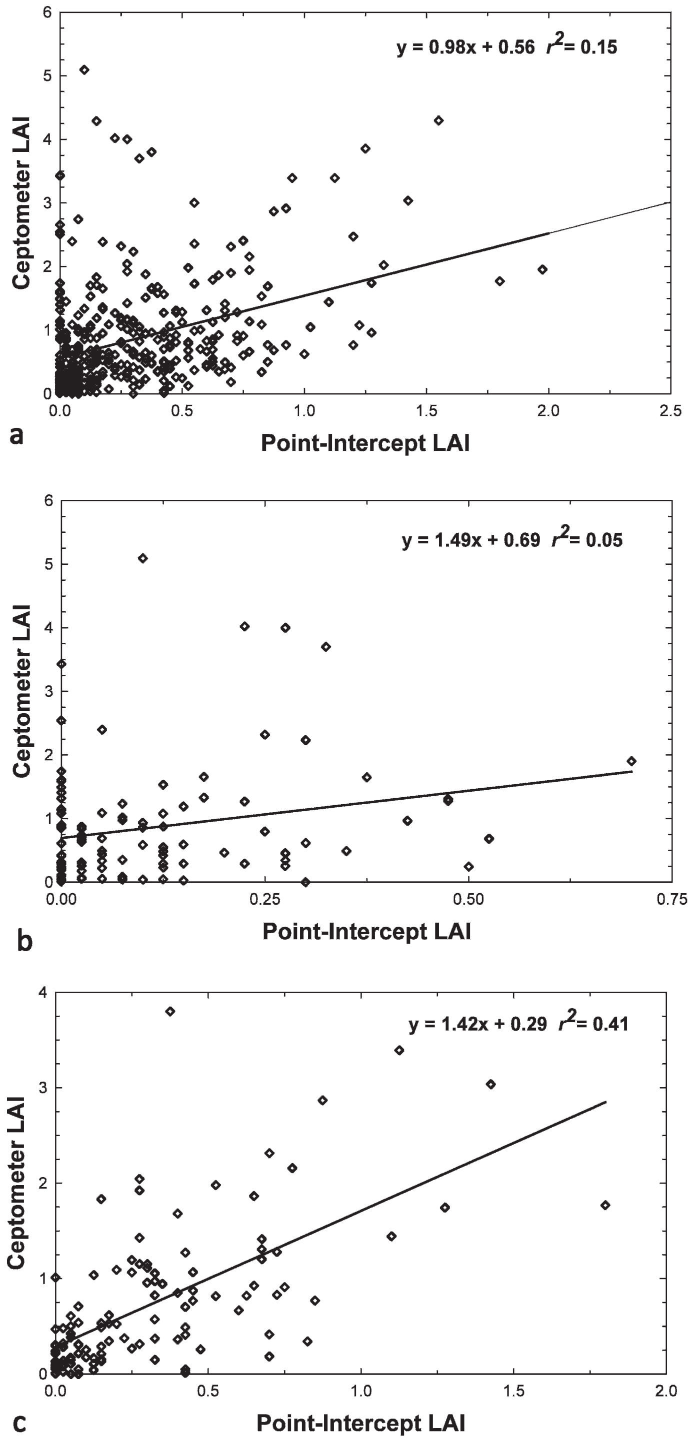

Figure 2. a, Regression analysis of point-intercept and ceptometer leaf area index (LAI; $m^2 \cdot m^{-2}$) estimates from six sites in Idaho and California and four sampling periods over a 2-yr time-span. **b,** Regression analysis of point-intercept and ceptometer LAI ($m^2 \cdot m^{-2}$) values collected in the fall of 2009 from six study sites in Idaho and California. **c,** Regression analysis of point-intercept and ceptometer LAI ($m^2 \cdot m^{-2}$) values collected at peak standing crop in 2009 from six study sites in Idaho and California.

The upward bias of ceptometer measurements was not unexpected because a substantial portion of the surface cover at these sites consists of woody perennial vegetation (e.g., sagebrush). For this reason, ceptometer LAI data would be better represented if referred to as plant area index data (Breda 2003; Jonckheere et al. 2004) because the ceptometer does not distinguish between leaves and other, nonphotosynthetic, plant parts, such as woody stems and branches. This problem is most apparent in the fall, when green vegetation is near its minimum, but the woody vegetation remains, and least evident at peak standing crop, when green leaf area exceeds that of the wood. In this study, correlations between ceptometer and point-intercept values were low for every measurement except at peak standing crop (Figs. 2b and 2c). These results suggest that one possible strategy for use of the ceptometer in sagebrush-steppe vegetation is to make repeated measurements at the same location through time, thus focusing on the change in cover, which is almost entirely due to green vegetation. We were unable to evaluate this approach with the data collected because of destructive sampling done to obtain vegetation production once LAI had been determined. A second approach for the use of the ceptometer in sagebrush-steppe vegetation would be to complete more extensive destructive sampling of shrubs to determine k at each site. This approach was not pursued in this study because the goal was to find a quick, efficient method for determining LAI in situ, using the minimum amount of destructive sampling required.

IMPLICATIONS

Because of the role of LAI in regulating the rate of photosynthesis, accurate measurements of LAI are critical to the understanding and modeling of plant growth and other biogeochemical ecosystem processes. A quick and accurate method of measuring LAI in a variety of ecosystem types would benefit scientific investigations by facilitating the collection of a large volume of LAI data without requiring an unfeasible commitment of field time and labor. This study tested the ceptometer as a method of measuring LAI in sagebrush-steppe ecosystems, an ecosystem type for which it was not originally designed. The results of this study demonstrated that the ceptometer method produces inaccurate and imprecise LAI data and, therefore, provides a poor estimate of LAI in sagebrush-steppe ecosystems.

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