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Michael A. White
University of Montana - Missoula

Gregory P. Asner
University of Colorado at Boulder

Ramakrishna R. Nemani
University of Montana - Missoula

Jeff L. Privette
NASA Goddard Space Flight Center

Steven W. Running
University of Montana - Missoula

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Measuring Fractional Cover and Leaf Area Index in Arid Ecosystems: Digital Camera, Radiation Transmittance, and Laser Altimetry Methods

Michael A. White, Gregory P. Asner,† Ramakrishna R. Nemani,* Jeff L. Privette,‡ and Steven W. Running**

Field measurement of shrubland ecological properties is important for both site monitoring and validation of remote sensing information. During the May 1997 NASA Earth Observing System Jornada Prototype Validation Exercise, we calculated plot-level plant area index, leaf area index, total fractional cover, and green fractional cover with data from four instruments: (1) a Dycam Agricultural Digital Camera (ADC), (2) a LI-COR LAI-2000 plant canopy analyzer, (3) a Decagon sunfleck Ceptometer, and (4) a laser altimeter. Estimates from the LAI-2000 and Ceptometer were very similar (plant area index 0.3, leaf area index 0.22, total fractional cover 0.19, green fractional cover 0.14), while the ADC produced values 5% to 10% higher. Laser altimeter values, depending on the height cutoff used to establish total fractional cover, were either higher or lower than the other instruments' values: a 10-cm cutoff produced values ~80% higher, while a 20-cm cutoff produced values ~30% lower. The LAI-2000 and Ceptometer are designed to operate in homogenous canopies, not the sparse and irregular vegetation found at Jornada. Thus, these instruments were primarily useful for relative within-site plant area index monitoring. Calculation of some parameters required destructive sampling, a relatively slow and labor-intensive activity that limits spatial and temporal applicability. Validation/monitoring campaigns therefore should be guided by consideration of the amount of time and resources required to obtain measurements of the desired variables. Our results suggest that the ADC is both efficient and accurate for long-term or large-scale monitoring of arid ecosystems.

INTRODUCTION

Shrublands exist in hot, dry areas where high evaporative demand greatly exceeds unpredictable and sparse precipitation (Evenari, 1985). Although estimates vary widely (Townshend et al., 1991), pure shrublands cover approximately 9% of the Earth's vegetated surface (Waring and Running, 1998). Within the past century, many arid to semiarid areas of the United States have experienced dramatic shrub increases, usually at the expense of native grasses (Smith et al., 1997). While some shrub expansion may be related to persistent drought (Herbel et al., 1972), evidence suggests that overgrazing and fire suppression are more important causes (Archer et al., 1995; Bryant et al., 1990; Grover and Musick, 1990). Such conversions can be detrimental to pastoral societies directly dependent on grassland extent and productivity. High shrub cover may also have beneficial effects, such as increasing runoff water for irrigation (Skarpe, 1990) or accelerating aquifer recharge (Leduc et al., 1997). Thus, depending on local priorities, increased or decreased shrub populations may be desired. Regardless of the goal, accurate monitoring of shrubland extent and vigor is important for natural resource managers and for the people they serve.

Satellite remote sensing provides the only technically consistent and temporally regular means of monitoring shrublands over large areas. In shrublands, remote sensing is hampered by a high proportion of bare soil, clump shad-

* Numerical Terradynamic Simulation Group, School of Forestry, University of Montana, Missoula, MO

† Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO

‡ NASA Goddard Space Flight Center, Code 923, Biospheric Sciences Branch

Address correspondence to Michael A. White, NTSG/School of Forestry, University of Montana, Missoula, MT 59812, USA. E-mail: mike@ntsg.umt.edu

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owing effects, and nonlinear relationships between the measured signal and the areal extent and leaf density of shrubs (Huete et al., 1992). Since vegetation cover is always low in shrublands, site variation in soil reflectance can lead to unpredictable errors in the quantification of shrubland ecological properties (van Leeuwen and Huete, 1996). Therefore, field measurement of shrubland ecological properties is often necessary to provide a context for the interpretation and quantification of satellite data. Although a wide variety of shrubland parameters are useful in specific applications, leaf area index (LAI) and fractional cover (F) are perhaps the most commonly used metrics.

LAI is the one-sided foliage area per ground area (m^2/m^2). Stem area index (SAI, m^2/m^2) is the one-sided stem area per ground area, where "stem" includes dead leaves, branches, and stems. The sum of LAI and SAI is plant area index (PAI, m^2/m^2), the one-sided plant area per ground area. In this paper, the terms PAI, LAI, and SAI refer to mean plot-level values (including bare ground and vegetation), while the terms shrub PAI, shrub LAI, and shrub SAI refer to individual plants within the landscape. Total fractional cover (FT, dimensionless) is the areal proportion of the landscape occupied by green or nongreen vegetation (=PAI/shrub PAI). Green fractional cover (FG, dimensionless) is the areal proportion of the landscape occupied by green vegetation (=LAI/shrub LAI). In these definitions of F, we assume that fractional cover within shrub perimeters is 1.

LAI, PAI, FG, and FT are each important for different purposes. Many climate and ecosystem models are strongly influenced by LAI (Bonan, 1993; Chase et al., 1996) and thus rely on accurate estimates. LAI and PAI are critical for research investigating the impacts of shrub populations on the partitioning of precipitation into runoff and evapotranspiration. Plot structural parameters, such as FT, are important in radiative transfer models (Bégué, 1993). FT is also required for calculating satellite estimates of sensible heat flux (Ricotta and Avena, 1997). Satellite remote sensing can be used to estimate LAI (Asrar et al., 1984; Spanner et al., 1990) and F (Duncan et al., 1993; Dymond et al., 1992; Pickup et al., 1993) through correlations with the normalized difference vegetation index (NDVI) or other spectral indices.

Consequently, ground estimates of shrubland ecological properties are important both for validation of remote sensing data and for long-term monitoring of site conditions. A wide variety of techniques are available for obtaining these estimates. Instruments that measure radiation transmittance, including the LI-COR LAI-2000 Plant Canopy Analyzer (LI-COR Inc., Lincoln, NE, USA) and the Decagon sunfleck Ceptometer quantum line sensor (Decagon Devices, Inc., Pullman, WA, USA), may be used to calculate PAI and/or shrub PAI. Ideally, transmittance instruments would measure LAI, the more ecologically relevant variable, but it is often difficult to separate green leaf from nongreen leaf vegetation. Many researchers have established empirical corrections to calculate LAI from recorded PAI values (Chen, 1996; Deblonde et al., 1994; Fassnacht et al., 1994; Gower and Norman, 1991). The consensus from these and other studies is that while transmittance methods can give consistent relative measurements at a given site, quantitatively accurate measurements require site-specific corrections factors. Digital cameras, to a lesser extent, have also been used to measure LAI. For example, Law (1994) measured LAI in artificially constructed shrub canopies, and Baker et al. (1996) measured LAI in *Pseudotsuga menziesii* trees.

The Prototype Validation Exercise (PROVE) campaign, an activity of the NASA Earth Observing System AM-1 validation program, is one of a series of field research projects designed to thoroughly, yet rapidly and economically, characterize site surface and atmospheric conditions. PROVE's goal is to provide field context for and validation of airborne and satellite data in a consistent fashion over a network of global validation test sites. To date, PROVE campaigns have been conducted in desert shrubland and moist temperate ecosystems. We participated in the May 1997 PROVE campaign conducted at the Jornada Long-Term Ecological Research site (see Privette, this volume, for project description). Our primary goal was to estimate plot-level LAI, PAI, FG, and FT from in situ field data. Our secondary goal was to investigate a digital camera's capability to measure ecologically relevant variables and to assess the camera's field reliability and ease of use. In this paper, we conduct an intercomparison of results and recommend the easiest and most reliable techniques for future field research seeking to measure the same variables in similar environments.

METHODS

Site Description

The Jornada Long-Term Ecological Research site is located in the northern Chihuahuan desert northeast of Las Cruces, New Mexico, USA (32.5°N, 106.8°W). Mean annual temperature is 16°C and mean annual precipitation is 21 cm with 52% falling between July and September (Schlesinger et al., 1990). In the late 19th century, grass cover was extensive. Since then, shrub canopy cover has increased while grass cover has decreased, possibly as the result of fire suppression and grazing (Buffington and Herbel, 1985; Schlesinger et al., 1990). The transitional site where we conducted our research is centered around a 26-m tower that was instrumented with meteorological sensors and a Cimel sunphotometer. The site is characterized by an open shrub canopy dominated by mesquite (*Prosopis grandulosa*), Mormon Tea (*Ephedra aspera*), and Yucca (*Yucca Glauca*). Mesquite is by far the dominant species, comprising approximately 70% of the canopy cover, with *Ephedra* (20%) and *Yucca* (10%) making up smaller portions of the landscape. Forb and grass species exist in small numbers.

Sampling

We sampled the Jornada transitional site on May 22 to May 24, 1997 with the five following approaches: (1) digital imagery with an Agricultural Digital Camera (ADC), (2) radiation transmittance with an LAI-2000 Plant Canopy Analyzer, (3) radiation transmittance with a Ceptometer quantum line sensor, (4) ecosystem height variation with airborne laser altimetry, and (5) destructive sampling with an LI-3000 leaf area meter and photographic analysis. We sampled with the instruments as follows: the ADC, LAI-2000, and Ceptometer at 5-m intervals along 100-m transects extending east, south, and west from the central tower; the LAI-2000 at individual component shrubs within the landscape; the ADC from a cherry picker 25 m above the surface; laser altimetry along four aerial transects at the tower site; and destructive sampling of single shrubs representative of the dominant species. In the next sections, we describe the use of each instrument and its range of application in our study.

To avoid future confusion, we first present a description of our variable naming convention. This paper contains an inevitably large number of variables; a complete variable list is presented in Appendix A. In general, the naming convention is as follows. When preceded by "shrub," variables refer to measurements made on individual shrubs; if not, variables refer to mean values from the transects or from the cherry picker. Subscripts are used to identify the instrument: "2000" for the LAI-2000; "cept" for the Ceptometer; "ADC" for the Agricultural Digital Camera; "laser" for laser altimetry; and "dest" for destructive sampling. In cases where one instrument was used for multiple purposes, superscripts are used to specify what was measured: "dest" refers to measurements of the destructively sampled shrubs; "component" refers to measurements of component shrubs throughout the landscape; and "mean" refers to species-weighted mean values compiled from component shrub data. Thus, $PAI_{2000}^{component}$ is an LAI-2000 plant area index measurement of a component shrub and PAI_{cept}^{dest} is a Ceptometer plant area measurement of a destructively sampled shrub.

Agricultural Digital Camera

We calculated FG from the ratio of red (R) to near-infrared (NIR) brightness as recorded in digital numbers by an Agricultural Digital Camera (ADC, Dycam Inc., Chatsworth, CA, USA). The ADC records images of dimension 496×365 pixels using an 8.5-mm lens and an 8.5-mm focal length. Brightness values are measured with a charge-coupled device (CCD) consisting of a color filter array sensitive to R and NIR wavelengths. The color filter array records radiation from 0.6 μm to 1.05 μm with 80% of the recorded value determined by radiation between 0.615 μm and 0.985 μm (S. Heinold, Dycam Inc., personal communication). Adjacent color filter array elements respond to different wavelengths: R between 0.6 μm and 0.75 μm and NIR between 0.75 μm and 1.05 μm. A Wratten 29 red filter is used to block radiation below 0.6 μm. The full CCD has an angular field-of-view of 31.5×24.25°. At a distance of 1 m, this equals an image size of 565×429 mm. Ideal conditions for ADC operation are constant radiation environments with view zenith angles close to 0°. Since images taken from nadir with a solar zenith angle less than one-half the field of view in the larger ADC dimension can produce hot spot effects, operation should be conducted with solar zenith angles of at least 15°.

For ground transect sampling, the ADC was mounted on a horizontal pipe attached to a ladder so that the ADC was 280 cm above the ground. Image area at this height was 160×120 cm. We used a portable computer to release the shutter. We moved the apparatus to each 5-m interval and completed each transect in about 20–25 minutes under bright, sunny conditions between 12:30 P.M. and 3:00 P.M. on May 23 (solar zenith angles between 15° and 29°). Additionally, we imaged the site from a cherry picker positioned roughly 20 m southwest of the tower on May 22 at 1:00 P.M. under bright, sunny conditions. We took 10 images in a circular pattern around the cherry picker basket at a height of 25 m (from approximately nadir angles), yielding images with a 14×11-m ground resolution.

While it was possible to calculate continuous vegetation indices with the ADC, NIR saturation in vegetated pixels reduced the dynamic range of this approach. Thus, a binary variable such as bright vs. dark was preferable to a continuous measure. FG was easily extracted from the ADC and met this criterion.

To calculate FG_{ADC}, we used the soil segmentation utility (Steve Heinold, Dycam Inc., Chatsworth, CA, USA). The program is a supervised classification. For each image, the user selects a training area of bare soil from which the soil segmentation utility calculates a soil ratio as the ratio of R to NIR brightness. Since bare soil usually has R brightness only slightly less than NIR brightness, the soil ratio is less than one, typically between 0.6 and 0.9 for Jornada soils. A threshold value is set as 99.5% of the soil ratio. Green vegetation, characterized by low R and high NIR brightness, will have an R:NIR ratio less than that of bare soil. The soil segmentation utility estimates FG as the percent of vegetated pixels below the 99.5% threshold. If the NIR response range had been greater, NIR values in otherwise saturated pixels would have been higher, leading to lower R:NIR ratios. Vegetated pixels at saturation therefore were not classified as soil. Use of FG, which is calibrated internally for each image using the soil ratio, obviates the absolute image calibration required for between scene comparison of NDVI or other vegetation indices.

Testing at Jornada showed that selection of different bare soil areas within one image resulted in soil ratio values varying by up to 35%. If an aberrantly high soil ratio were chosen, some bare soil would be classified as vegetation. Alternatively, selection of a low soil ratio would cause some vegetation to be classified as soil. To address this difficulty,

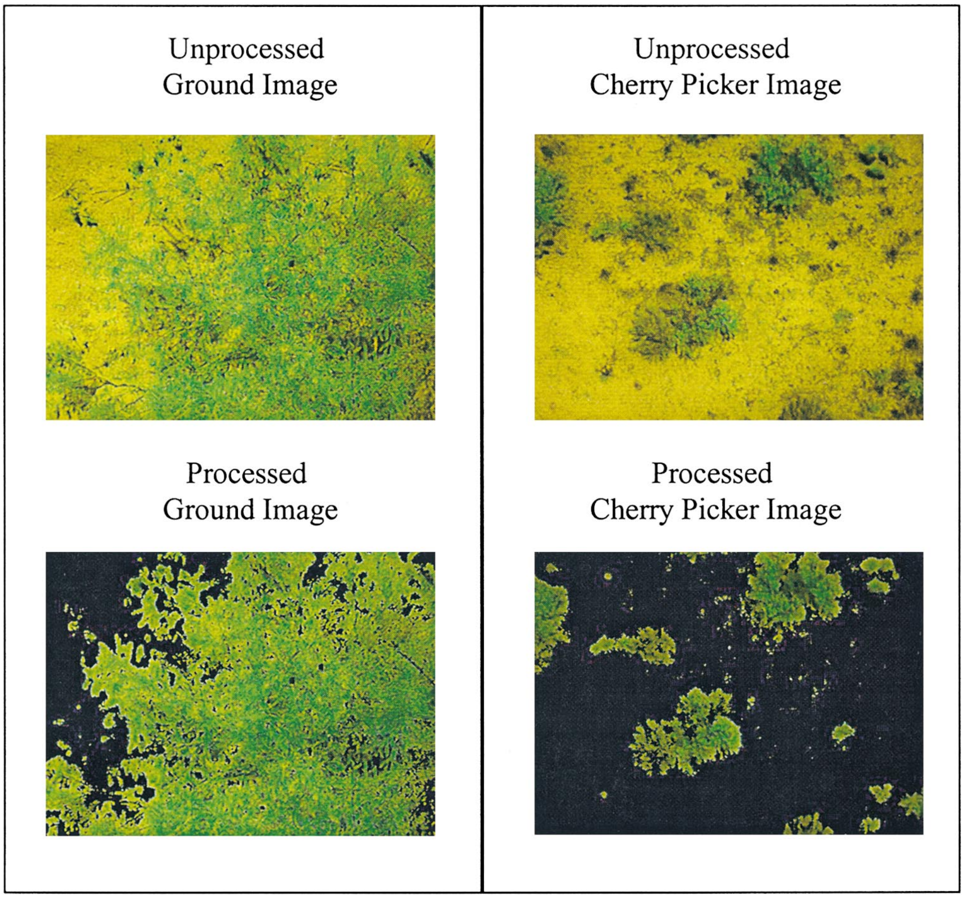

Figure 1. Application of the soil segmentation utility to ground and cherry picker images. Left panels show a sample unprocessed (top) and processed (bottom) ground transect image (280 cm height, 160×120-cm resolution, FG=0.77). Right panels show a sample unprocessed (top) and processed (bottom) cherry picker image (25 m height, 14×11-m resolution, FG=0.14). Areas classified as soil appear as black, while vegetated areas appear as in the unprocessed image.

we calculated the image soil ratio as the mean of five rectangular bare soil areas (approximately 50×30 pixels) within each image, one from each corner and one from the center. If most of the scene was vegetated, we still used five soil ratio values, but were forced to shift the location of individual samples within the scene. With this method, we calculated FG_{ADC} for: (1) individual ground images; (2) east, south, and west transects as the mean of the 20 component images per transect; (3) the plot as the mean of the three transects; and (4) individual and mean cherry picker images.

Figure 1 shows an example of the soil segmentation method for ground and cherry picker images. The left panels show an unprocessed (top) and processed (bottom) ground image mostly occupied by a single large shrub. Right panels show the same sequence but for a cherry picker image including numerous shrubs. In the bottom panels, areas classified as soil are black, while areas classified as green retain the appearance of the unprocessed images.

LAI-2000

The LI-COR LAI-2000 (LI-COR, Lincoln, NE, USA) integrates radiation transmittance through the canopy at 0.32 μm to 0.49 μm at five different view zenith angles (0–7°, 16–28°, 32–43°, 47–58°, and 61–74°) to calculate PAI_{2000}. See Welles and Norman (1991) for a discussion of the theoretical details.

We measured PAI_{2000} along the ground transects at twilight on May 23 under diffuse radiation conditions. To minimize the influence of canopy gaps and subsequent PAI_{2000} underestimation (LI-COR, 1992), we used a 45° view cap. After one above-canopy measurement, we sampled five intervals along the transect with the sensor pointed in the transect direction. We repeated this cycle four times per transect with each transect requiring approximately 10 minutes. Besides yielding PAI_{2000}, the data files from the LAI-2000, when used with the C2000 analysis package (LI-COR, Lincoln, NE, USA), can also be used to calculate the Beer's law extinction coefficient (k) for each of the five view angles as the fraction of foliage per unit LAI oriented toward the direction of incoming sky radiation. For each transect, we calculated the mean PAI_{2000} from the 20 points per transect and plot-level PAI_{2000} as the mean of the three transects. We also sampled shrub $PAI_{2000}^{component}$ for *Prosopis* (n=45), *Ephedra* (n=2), and *Yucca* (n=3) under diffuse radiation conditions at dawn or twilight. At each shrub, we took one above-canopy measurement and one measurement from each cardinal direction.

Ceptometer

The Ceptometer integrates instantaneous fluxes of photosynthetically active radiation (PAR, 0.4–0.7 μm) along a wand consisting of 80 1-cm^2 sensors. PAI_{cept} may be calculated based on methods described by Pierce and Running

Table 1. Experimental Design

	LAI-2000	*Ceptometer*	*ADC*	*LAI 3000/stem Photography*	*Laser Altimetry*
Transects	PAI	PAI	FG	–	–
Cherry picker	–	–	FG	–	–
Aircraft transects	–	–	–	–	FT
Component shrubs	shrub PAI	–	–	–	–
Destructive shrubs	shrub PAI	shrub PAI	–	shrub LAI shrub SAI	–

Component shrubs refer to individual shrubs sampled throughout the stand with the LAI-2000. Destructive shrubs refer to individual shrubs that were sampled first by the LAI-2000 and Ceptometer and then by destructive methods.

(1988) using the unitless ratio of below-canopy PAR (Q_i) to above-canopy PAR (Q_o), the extinction coefficient (k), and the Beer-Lambert law [see Eq. (1)]:

$$\mathrm{PAI_{cept}} = -1\mathrm{n}(Q_i/Q_o)/k \quad (1)$$

We derived k in two ways. First, we used the k value from the LAI-2000 7° ring, as calculated with the C2000 program. Second, following Pierce and Running (1988) we estimated k by inverting Eq. (1) and using $\mathrm{PAI_{2000}}$ [see Eq. (2)]:

$$k = -1\mathrm{n}(Q_i/Q_o)/\mathrm{PAI_{2000}} \quad (2)$$

We measured Q_i/Q_o along the ground transects on May 22 within 1 hour of solar noon in bright, sunny conditions. At each point, we took one above-canopy measurement, two below-canopy measurements along the transect, two below-canopy measurements perpendicular to the transect, and a final above-canopy measurement. Each transect required approximately 15–20 minutes. We calculated mean transect and mean plot $\mathrm{PAI_{cept}}$ as for $\mathrm{PAI_{2000}}$.

Destructive Sampling

We destructively measured $\mathrm{LAI_{dest}}$ for one representative shrub each of *Prosopis*, *Ephedra*, and *Yucca*. To do so, we manually harvested all green leaf material from the shrubs and measured their one-sided $\mathrm{LAI_{dest}}$ with a LI-COR LI-3000 leaf area meter (LI-COR, Lincoln, NE, USA). We calculated $\mathrm{SAI_{dest}}$ from photographs of the woody material remaining after leaf harvest. The sum of $\mathrm{SAI_{dest}}$ and $\mathrm{LAI_{dest}}$ is equal to $\mathrm{PAI_{dest}}$. Prior to harvest, we measured shrub $\mathrm{PAI_{2000}^{dest}}$ and shrub $\mathrm{PAI_{cept}^{dest}}$ for the three destructively sampled individuals, once at dawn and once at dusk ($n=8$ for both sets of measurements except for *Yucca* shrub $\mathrm{PAI_{cept}^{dest}}$ where $n=6$).

Laser Altimetry

Laser altimetry can be used to establish height variation along linear transects. FT is equal to the number of laser return signals greater than a specified height divided by the total number of signals. The method is well established and is described elsewhere (Ritchie et al., 1992; Weltz et al., 1994). Using pulsed galium arside laser altimetry data taken from small aircraft along four 300-m transects at the transitional site, two east–west and two north–south, J. Ritchie provided estimates of FT calculated from 10-cm, 20-cm, 30-cm, and 40-cm height thresholds (personal communication). Each transect was composed of 16,384 individual points with a 6-cm vertical precision. At 30-cm or 40-cm cutoff, numerous small shrubs would have been eliminated. Thus, we used both 10-cm and 20-cm cutoffs to calculate $\mathrm{FT_{laser}}$.

Intercomparison

Table 1 shows a summary of input data. We directly measured PAI, shrub PAI, shrub LAI, shrub SAI, and FG, and we obtained estimates of FT from laser measurements. It was then possible to estimate the full suite of variables (PAI, LAI, FG, and FT) for each instrument (see Table 2 for equations). Initially, two intermediate variables had to be calculated. First, the weighted ratio of total vegetation to green vegetation (T:G) was calculated as shown in Eq. (3):

$$\mathrm{T{:}G} = \frac{\sum_{i=0}^{2} w_i \text{ shrub } \mathrm{PAI}_{\mathrm{dest}_i}}{\sum_{i=0}^{2} w_i \text{ shrub } \mathrm{LAI}_{\mathrm{dest}_i}} \quad (3)$$

where w_i is the canopy percent dominance, assumed to be 70% for *Prosopis*, 20% for Ephedra, and 10% for Yucca.

Table 2. Intercomparison Scheme

	LAI-2000 and Ceptometer	*ADC*	*Laser Altimetry*
PAI	measured	(2) FT×shrub $\mathrm{PAI_{2000}^{mean}}$	(2) FT×shrub $\mathrm{PAI_{2000}^{mean}}$
LAI	(1) PAI/T:G	(3) PAI/T:G	(3) PAI/T:G
FT	(2) PAI/shrub $\mathrm{PAI_{2000}^{mean}}$	(1) FG×T:G	measured
FG	(3) FT/T:G	measured	(1) FT/T:G

Variables were either measured or derived. Numbers represent order in which variables were calculated.

Table 3. Measured Variables

	Soil Ratio	FG	LAI-2000 PAI	Ceptometer PAI	Laser FT >10 cm	Laser FT >20 cm
East transect	0.77 (0.038)	0.13 (1.14)	0.27 (0.99)	0.23 (1.28)	–	–
West transect	0.77 (0.030)	0.20 (1.18)	0.41 (1.09)	0.33 (1.60)	–	–
South transect	0.78 (0.023)	0.13 (1.20)	0.21 (1.06)	0.35 (1.21)	–	–
All transects[a]	0.77 (0.031)	0.15 (1.21)	0.30 (NA)	0.30 (1.40)	0.35 (0.062)	0.14 (0.065)
Cherry picker	0.77 (0.017)	0.18 (0.27)	–	–	–	–

Soil ratio (red/near-infrared digital number); green fractional cover (FG); PAI from the LAI-2000 and Ceptometer; and total fractional cover from laser altimetry (FT). Values in parentheses are the coefficient of variation.

[a] For laser FT, all transects refers to the mean of four 300-m aircraft transects at the transitional site (two east–west, two north–south); for all other variables, all transects refers to the mean of the east, south, and west 100-m transects.

We assumed that T:G was constant for the entire transitional site.

Second, the species-weighted, mean shrub PAI over the entire plot was required for calculation of several parameters. Several alternatives existed. Mean shrub PAI could have been set to the species-weighted shrub $PAI_{2000}^{component}$, but this would have assumed that using LAI-2000 data in equations based on other instruments was appropriate. In reality, this hybrid method might have translated errors created by unavoidable violation of LAI-2000 assumptions (see below) to equations based on other instruments. Mean shrub PAI could also have been calculated by assuming that shrub PAI_{dest} was valid for the entire site. However, shrub PAI_{dest} was based on only three data points. Neither method was entirely satisfactory. Given the available data, we adopted an alternative method capitalizing on the large number of individual shrub $PAI_{2000}^{component}$ values and the physical rigor of the destructive measurements. We assumed that differences between shrub PAI_{2000}^{dest} and shrub PAI_{dest} were caused by violation of LAI-2000 assumptions. We then calculated the ratio of shrub PAI_{2000}^{dest} to shrub PAI_{dest} (L:D). Both dawn and dusk shrub PAI_{2000}^{dest} data were used, resulting in two L:D values for each species. We then corrected all shrub $PAI_{2000}^{component}$ values for each species using both L:D values and calculated the mean, species-weighted, shrub PAI: shrub PAI_{2000}^{mean}.

RESULTS AND DISCUSSION

At the Jornada site, the ADC, LAI-2000, Ceptometer, and laser altimetry were used to produce estimates of PAI, LAI, FT, and FG. However, no one instrument was universally well suited for measuring every parameter. In reality, each instrument measured only one variable; the remainder were calculated with conversion factors, which were themselves subject to uncertainties. In the following sections, we present and discuss results for each instrument and discuss the most appropriate tools for shrubland monitoring.

ADC

The ADC produced consistent measurements of both the soil ratio and FG. Table 3 shows that the ADC soil ratio values used to calculate FG_{ADC} from both the transects and the cherry picker were essentially identical. Difference of mean tests showed that soil ratios were not significantly different within ground transects, among ground transects, within the cherry picker data, or between the ground and cherry picker data. Ground transect soil ratio coefficients of variation (CVs=standard deviation/mean) were around twice the cherry picker soil ratio CV. Since the images were not calibrated, we relied on the corrections for ambient radiation conditions inherent in individual image soil ratio calculations. Thus, despite the striking similarity in soil ratios, the mean value could not be used to calculate FG_{ADC} for all scenes.

The ADC's use of NIR information, as suggested by Law (1994) and implemented in the soil segmentation's calculation of FG_{ADC}, allowed for easy discrimination between soil (larger R:NIR ratio) and vegetation (smaller R:NIR ratio). Visual image analysis showed: (1) misclassification of dead vegetation as green material was minimal; (2) shadowed soil was correctly classified as soil; and (3) vegetation in deep shadow was classified as soil, leading to a possible underestimation of FG. However, due to limited self-shading in the sparse canopy and favorable illumination angles, misclassification of vegetation as soil was also minimal. Mean FG_{ADC} was 0.15 for the ground transects and 0.18 for the cherry picker (Table 3). Despite a factor of four difference in CVs between heights, FG_{ADC} was statistically indistinguishable between the cherry picker and ground transects.

Radiation Transmittance Instruments

The ground transects' PAI_{2000} and PAI_{cept} were both 0.30 (Table 3). In spite of the overall similarity, the ordinal relationships for the transects were not consistent: PAI_{2000} was highest in the west transect, while PAI_{cept} was highest in the south transect, near a transition to a more grassy canopy. The range in PAI_{2000} was 0.2, while the range in PAI_{cept} was only 0.12. Additionally, both instruments unavoidably violated major instrument assumptions.

The LAI-2000 assumes: (1) foliage is black (i.e., does not transmit or reflect radiation); (2) foliage is randomly distributed; (3) foliage elements are small in comparison to view areas; and (4) foliage is azimuthally randomly ori-

Table 4. Calculation of the Total Vegetation to Green Vegetation Ratio (T:G) and the Mean Plot-Level Shrub Plant Area Index

	Prosopis glandulosa	*Ephedra aspera*	*Yucca glauca*	*Weighted Mean*[a]
Shrub LAI_{dest}	1.71	0.70	1.38	–
Shrub SAI_{dest}	0.37	0.58	0.44	–
Shrub PAI_{dest}	2.08	1.28	1.82	–
T:G	1.22	1.83	1.32	1.36
L:D dawn	0.90	1.67	1.73	–
L:D dusk	0.83	1.54	1.43	–
Shrub $PAI_{2000}^{component}$	1.70 (0.33)	1.34 (0.014)	1.10 (0.51)	–
Shrub PAI_{2000}^{mean}	1.95 (0.38)	0.83 (0.040)	0.70 (0.30)	1.60 (0.27)

L:D is the ratio of shrub PAI_{2000}^{dest} to shrub PAI_{dest}, calculated from dawn and dusk PAI_{2000} data. Shrub $PAI_{2000}^{component}$ shows mean LAI-2000 measurements from individual component shrubs throughout the plot. Shrub PAI_{2000}^{mean} is shrub $PAI_{2000}^{component}$ corrected for L:D. Data is parentheses are one standard deviation.

[a] Weighted mean calculated with assumed 70% canopy cover for *Prosopis*, 20% for *Ephedra*, and 10% for *Yucca*.

ented. *Yucca*, with a regular distribution of large, planar, stalklike leaves, violated the random foliage distribution assumption. Effectively inserting the LAI-2000 wand under the *Yucca* foliage elements was difficult. Further, the relatively massive size of the *Yucca* stalks violated the assumption that foliage elements are small compared to view areas. *Ephedra*, containing photosynthetic stalks instead of true leaves, has a clumped distribution that also violated the random foliage assumption. *Prosopis*, which is more representative of broadleaf plants, did not seriously violate any assumptions.

The L:D ratio provided a measure of the severity of the LAI-2000's violations. Not surprisingly, since *Prosopis* had the least violation, its L:D was closest to unity. Both *Ephedra* and *Yucca* had L:D values well above one. Violation of random foliage distribution is routine in many applications and in some cases does not seem to introduce large errors (Martens et al., 1993), while in other cases, especially in highly clumped conifer vegetation, underestimation of PAI is common (Deblonde et al., 1994; Gower and Norman, 1991; Stenberg et al., 1994). In our case, the L:D ratios indicated that shrub LAI-2000 PAI should be corrected.

The Ceptometer was not an ideal instrument for Jornada's arid ecosystem. Major assumptions include: (1) spherical and random leaf inclination angle distribution, (2) random foliage distribution, and (3) a homogeneous media. Vegetation aggregation in sparsely distributed clumps violated the Beer's law assumption of a homogeneous media. The Ceptometer's major limitation was the requirement of an independent estimate of the Beer's law extinction coefficient (k). Calculated from the LAI-2000 7° lens, k was 0.35; from Eq. (2) using PAI_{2000} as an independent PAI estimate, k was 0.36 (we used 0.35). Despite the consistent results, calculation of k with either method was subject to the LAI-2000's assumptions, many of which were violated. Additionally, because we were measuring point transmittance in a highly irregular canopy, we were forced to use more samples than with the LAI-2000. Due to their unique canopy architecture, *Yucca* and *Ephedra* again represented the worst assumption violations.

Ultimately, since both instruments produced similar results, selection of one over the other may be guided by experimental conditions. The Ceptometer should be used in bright sunny conditions around solar noon, whereas the LAI-2000 functions best under diffuse radiation conditions (see Appendix B for discussion of instrument consistency and optimal times of observation). If working in a sunny environment, such as Jornada, there will be approximately 2 hours of useable time for the Ceptometer but only about 25–45 minutes for the LAI-2000 at dawn and dusk. In cloudy conditions, the LAI-2000 could be used throughout the day. At Jornada, though, consistently low CVs (Table 3) and an integrating transmittance-measuring technique requiring fewer measurements at each point made the LAI-2000 preferable to the Ceptometer.

Laser Altimetry

Laser altimetry data at the 10-cm cutoff produced high estimates, with FT_{laser} exceeding PAI_{2000} and PAI_{cept} (Table 3). However, the assignment of FT_{laser} is entirely dependent on the height cutoff used. By using the 10-cm cutoff, and especially considering the 6-cm vertical precision of the sensor, we were almost certain to include landscape elements unrelated to live or dead vegetation (Weltz et al., 1994). At the 20-cm cutoff, most nonvegetation ground elements and small forbs and grasses were probably excluded, leaving only fairly large shrubs. The ADC, on the other hand, detected even very small foliage elements. FT_{laser} was 0.35 with a 10-cm cutoff and 0.14 with a 20-cm cutoff (Table 3). The CV was very low and very similar for both height cutoffs.

Destructive Sampling

Up to now, we have considered the application and use of the instruments in reference to the single variable they

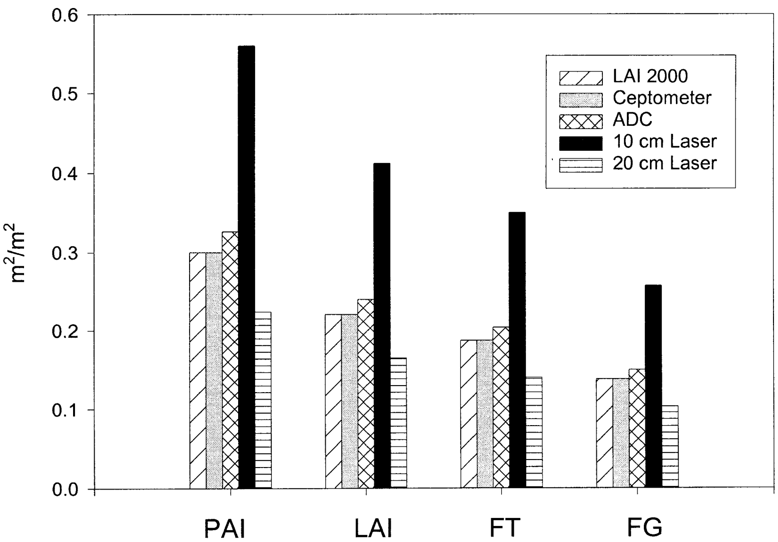

Figure 2. PAI, LAI, FG, and FG. LAI-2000 Plant Canopy Analyzer, Ceptometer quantum line sensor, and ADC data are the mean of three 100-m ground transects. Laser altimetry data are the mean of four 300-m aerial transects using 10-cm and 20-cm height cutoffs.

actually measured. Calculation of the other variables relied on conversion factors related to destructive sampling. We assumed that the shrub LAI_{dest} and shrub SAI_{dest} values were accurate. In reality, destructive sampling is notoriously difficult and inaccurate (e.g., Vertessy et al., 1995). For example, we were required to make subjective divisions between green and nongreen portions of *Yucca* and *Ephedra* vegetation. We further assumed that T:G and L:D, although calculated from single shrubs, were applicable to the entire plot. The shrubs selected for destructive sampling and the T:G and L:D ratios calculated from these shrubs may not have been representative of plot-level patterns. Shrub PAI_{2000}^{mean}, while based on LAI-2000 data, was considered to be a surrogate for a larger destructive sample (planned for future campaigns). However, as shown by Chen (1996), even a very large destructive sample can still yield inaccurate results.

Results from the destructive sampling and the calculation of T:G and shrub PAI_{2000}^{mean} are presented in Table 4. Weighted T:G, primarily controlled by the *Prosopis* T:G of 1.22, was 1.36. Component shrub sampling (shrub $PAI_{2000}^{component}$) showed highest values for *Prosopis* (1.70), followed by *Ephedra* (1.34) and *Yucca* (1.10). Correction for L:D slightly increased PAI for *Prosopis* (+15%) and reduced PAI for *Ephedra* (−38%) and *Yucca* (−36). This indicates that violation of the random foliage assumption in *Ephedra* and *Yucca* in this system tended to produce significantly inflated PAI measurements. Differences between shrub PAI_{2000}^{mean} and shrub $PAI_{2000}^{component}$ for *Prosopis* were within the likely error of destructive sampling. Final shrub PAI_{2000}^{mean} was 1.60.

Intercomparison

Results from the intercomparison scheme outlined in Table 2 and calculated with the intermediate variables in Table 4 are shown in Fig. 2. The basic relationship between variables is immediately apparent. Regardless of the instrument, values were highest for PAI, followed by LAI, FT, and FG. Within variables, relationships were also consistent. Values based on the LAI-2000 or Ceptometer were nearly identical. ADC-based data were slightly higher than the transmittance data, most likely because the ADC will detect low-lying grasses and forbs missed by both radiation transmittance methods. Laser altimetry variables at the 10-cm cutoff were by far the highest, nearly twice the LAI-2000 and Ceptometer variables. When the 20-cm cutoff was used, laser-based values were consistently the lowest. Indeed, Fig. 2 suggests that the laser results at the 20-cm cutoff tended to exclude small vegetation elements but that the 10-cm cutoff tended to include a large amount of nonvegetation material.

Shrubland Monitoring and Validation

Based on this study, we suggest that routine monitoring of PAI, FG, and FT is practical in shrublands, especially within a single site. The ADC was ideally suited for measuring shrubland FG, and at a cost of only about $1,000 was relatively economical. The ADC was simple to operate and based on our experiences was very durable. While similar values were obtained from ground and cherry picker measurements, ground transects are laborious and less efficient than imagery from a greater height (see Appendix C for discussion of scaling issues). We suggest that long-term ADC monitoring in shrublands will be optimized by mounting the ADC on a tower platform, such as the central tower at the transitional site, and automating data gathering. This design, if built with a weather-proof camera (DYCAM, personal communication), would provide beneficial inclusion of several landscape elements in each image (as described in Appendix C) and a temporally consistent methodology independent of operator error. Alternatively, we suggest imaging from a helicopter, tower, or cherry picker platform at a height >20 m above the surface. With the later approach, especially from helicopter, validation of remote sensing estimates of FG should be possible and comparable between numerous sites.

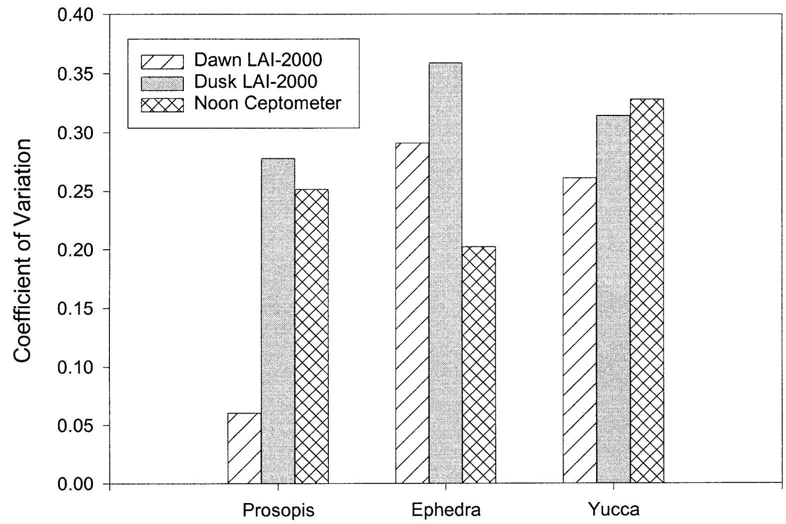

Figure 3. Coefficient of variation for *Prosopis*, *Ephedra*, and *Yucca* shrub PAI_{2000}^{dest} and shrub PAI_{cept}^{dest} from repeated measurements of one shrub per species. LAI-2000 data were taken under diffuse radiation conditions at dawn and dusk (n=8 for each species at each time). Ceptometer data were taken under bright sunlight (n=8 except for *Yucca* where n=6).

FT was easily calculated from laser altimetry data and the 20-cm cutoff produced values generally comparable to results from the ground-based instruments. For rapid FT estimation over large areas where the cost of aircraft operation is not a factor, laser altimetry is an excellent option. For rapid and inexpensive PAI estimates, the LAI-2000 appeared to be the best option. In an environment such as the Jornada transitional site, only 30 to 40 observations may be required (as described in Appendix C). Relative PAI comparisons, both temporally and spatially, should be possible with the LAI-2000.

Calculation of the full suite of variables from any one instrument or the calculation of LAI alone requires laborious destructive sampling. Worse, the T:G and shrub

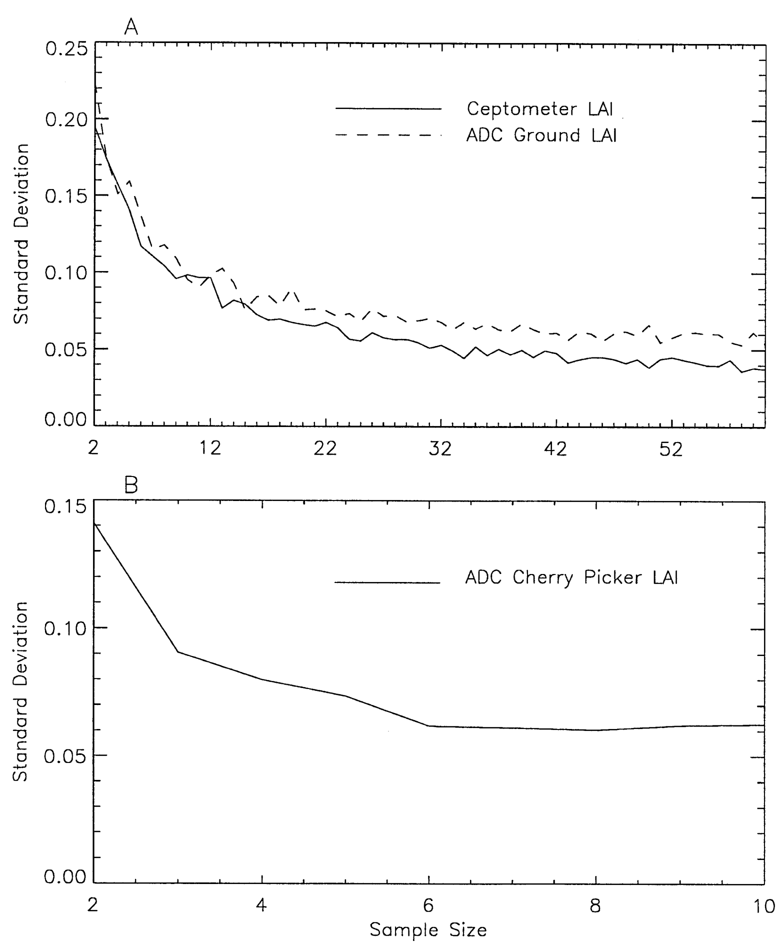

Figure 4. Bootstrap estimates of standard deviation from increasing sample size. (a) Ground-based LAI_{ADC} and LAI_{cept} standard deviations as sample size increased from 2 to 60. (b) LAI_{ADC} as estimated from the cherry picker as sample size increased from 2 to 10.

PAI_{2000}^{mean} conversion factors, as pointed out by Dufrêne and Bréda (1995), are not likely to be seasonally constant. Certainly for the deciduous *Prosopis*, T:G will not be constant. Thus, to rigorously monitor seasonal LAI, frequent destructive sampling would be required. At a site such as Jornada, this would be too intrusive for future long-term studies. Ideally, the ADC could be used to estimate LAI. However, the NIR saturation prevented us from accounting for even single scattering effects. If a more sensitive instrument were used in combination with species-specific radiative transfer models, it would theoretically be possible to establish optimal view and illumination angles and to establish correlations between destructively sampled LAI and ADC brightness values. This method would provide: (1) a one-time regression curve free of transmittance sensors' need for repeated destruction, and (2) a viable means of rapidly measuring LAI in the field. However, given current liabilities, LAI will be difficult to monitor routinely.

The methodologies we have presented here provide a simple and rapid means of validating estimates of FG throughout time and space and a somewhat more complicated means of validating LAI estimates at a single time and place. For instruments operating at a relatively fine spatial resolution, such as the Systeme Pour l'observation de la Terre (10 m) or the Thematic Mapper (30 m), operation of the ADC as outlined here could easily provide calibration of satellite fractional cover estimates at a large number of sites relatively quickly. Validation of coarser resolution satellite data will be best accomplished from a helicopter platform. Appendix C suggests that a Moderate Resolution Imaging Spectrometer 250-m pixel may be adequately characterized by nine observations, while an Advanced Very High Resolution Radiometer 1.1-km pixel will require about 150 observations. Moving to a height greater than the 25-m level used in this study should further reduce the required number of observations.

SUGGESTIONS FOR FUTURE WORK

In other short-canopy biomes, variation in canopy structure is likely to require a different combination of instruments for ecological monitoring and satellite validation. For crop canopies, typically with extremely small SAI, LAI can be directly measured with transmittance instruments (Hicks and Lascano, 1995). Since even at peak growing season biomass, grasslands can contain a large amount of dead vegetation mixed with green material (Singh and Gupta, 1993), transmittance LAI estimates must be corrected for T:G. In contrast to sparse shrub canopies, grassland T:G could be repeatedly calculated without destroying the plot. The ADC should be suitable for monitoring FG in both crop and grassland canopies.

While not specifically addressed in this paper, we speculate that the greatly different canopy structure of forest environments will necessitate different measurement strategies. Use of the ADC will be inappropriate in closed evergreen forests with FG approaching 1.0. In deciduous or open evergreen forests, the ADC could be used to monitor FG development, but obtaining a height great enough to include multiple canopy elements would be expensive and experimentally difficult. For forest canopies, we suggest one of two options for obtaining LAI. First, if measurements are required on a temporal scale of years, site-specific sapwood to leaf area allometric equations are fairly accurate (e.g., Keane and Weetman, 1987; O'Hara and Valappil, 1995; Vertessy et al., 1995). Second, if subannual data are required, transmittance instruments are the best alternative. If quantitative data are needed, correction factors must be applied (Chen, 1996; White et al., 1997). If only relative changes within a plot are desired, the transmittance data may be used without correction. Despite hopes to the contrary, there is "no one size fits all" validation or monitoring approach. Rather, variation in canopy structure mandates a biome-specific selection of both the most appropriate variable to measure and the measuring instrument.

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APPENDIX A: NOTATION LIST

	Shrub Parameters
Shrub LAI_{dest}	LI-3000 leaf area index measurements of the destructively sampled shrubs
Shrub SAI_{dest}	Photographic stem area index measurements of the destructively sampled shrubs
Shrub PAI_{dest}	Calculated plant area index of the destructively sampled bushes
Shrub PAI_{2000}^{dest}	LAI-2000 plant area index measurements of the destructively sampled shrubs
Shrub PAI_{cept}^{dest}	Ceptometer plant area index measurements of the destructively sampled shrubs
Shrub $PAI_{2000}^{component}$	LAI-2000 plant area index measurements of component shrubs
Shrub PAI_{2000}^{mean}	Mean, species-weighted, corrected LAI-2000 plant area index measurements of component shrubs

(*continued*)

Appendix A (Continued)

	Plot-Level Parameters[a]
PAI_{2000}	Plant area index measured with the LAI-2000
PAI_{cept}	Plant area index measured with the Ceptometer
PAI_{ADC}	Plant area index calculated from the Agricultural Digital Camera
PAI_{laser}	Plant area index calculated from laser altimetry
LAI_{2000}	Leaf area index calculated from the LAI-2000
LAI_{cept}	Leaf area index calculated from the Ceptometer
LAI_{ADC}	Leaf area index calculated from the Agricultural Digital Camera
LAI_{laser}	Leaf area index calculated from laser altimetry
FT_{2000}	Total fractional cover calculated from the LAI-2000
FT_{cept}	Total fractional cover calculated from the Ceptometer
FT_{ADC}	Total fractional cover calculated from the Agricultural Digital Camera
FT_{laser}	Total fractional cover measured with laser altimetry
FG_{2000}	Green fractional cover calculated from the LAI-2000
FG_{cept}	Green fractional cover calculated from the Ceptometer
FG_{ADC}	Green fractional cover measured with the Agricultural Digital Camera
FG_{laser}	Green fractional cover calculated from laser altimetry
	Ratios
T:G	The ratio of shrub PAI_{dest} to shrub LAI_{dest}
L:D	The ratio of shrub PAI_{2000}^{dest} to shrub PAI_{dest}

[a] "Measured" indicates variables immediately available from instrument data. "Calculated" indicates variables calculated with the equations in Table 2.

APPENDIX B: VARIABILITY OF LAI-2000 AND CEPTOMETER DATA.

Figure 3 shows the CVs for shrub PAI_{2000}^{dest} and shrub PAI_{cept}^{dest}. CVs from the Ceptometer showed no clear relationship with the LAI-2000 data, but were in the same general range. This suggests that within a single bush, neither instrument was inherently more consistent than the other. For all three species, the dawn shrub PAI_{2000}^{dest} had a lower CV (less variable) than the dusk shrubPAI_{2000}^{dest}. *Prosopis* showed the largest difference between dawn and dusk CVs. Differences in LAI-2000 wand placement might be expected to cause some variation in CV, but not the consistently observed lower dawn CVs. We speculate that the difference between dawn and dusk LAI-2000 could have been caused by differences in radiation environments. The east horizon at Jornada is formed by a nearby mountain range. Thus, after sunrise, there is a fairly long period of consistent diffuse radiation (~45 minutes). The west horizon is much farther away, resulting in a rapid transition from sunlight to dark with a shorter period of diffuse radiation (~25 minutes). Based on these divergent radiation conditions, it is likely that the dawn samples' more consistent radiation environment was manifested in lower CVs.

APPENDIX C: DEPENDENCE OF SAMPLE VARIABILITY ON SAMPLE SIZE AND SPATIAL RESOLUTION

We used a modified bootstrap analysis to assess the effects of increasing sample size and spatial resolution on the variability of mean plot-level estimates. The bootstrap methodology for ground transects was as follows. First, we randomly selected two samples from the total pool of 60 points (with replacement). We repeated this selection process for a total of 200 iterations. This produced a dataset of 200 samples with $n=2$. Second, we calculated the mean of each of the 200 samples. Third, we calculated the standard deviation of the 200 means. Fourth, we repeated steps one to three but with an increasing sample size until $n=60$. We completed the procedure for LAI, PAI, FT, and FG. For variables calculated with shrub PAI_{2000}^{mean} (Table 2), we used the normal approximation and randomly selected shrub PAI_{2000}^{mean} values for each of the 200 iterations. Unfortunately, since the point PAI_{2000} values were not retained, we were only able to use the bootstrap analysis for Ceptometer and ADC data.

Figure 4 shows the effect of increasing sample size on sample standard deviation. Results for FG, FT, PAI, and LAI all showed the same pattern. We present ground data for LAI_{ADC} and LAI_{cept} in Fig. 4. Increasing sample size from 2 to 12 resulted in a rapid decrease in standard deviation followed by a slower decrease up to around 30. Increasing sample size past 30 produced only minor reduction in standard deviation. Figure 4b shows the same phenomenon for the cherry picker LAI_{ADC}. Here, no reduction in standard deviation was obtained past a sample size of six. Both the ground and cherry picker LAI_{ADC} standard deviations reached a minimum of around 0.6, but at the ground resolution, approximately 30 images were required to approach the minimum. The cherry picker data, on the other hand, required only six images to reach the minimum.

Difference in ground resolution between the ground transects and the cherry picker revealed two patterns in the ADC data (Table 3). First, based on statistically indistinguishable soil ratios and FG_{ADC}, the ADC is not sensitive to variation in sensor height (to 25 m). Second, variability in FG_{ADC} estimates appeared to be dependent on the relationship between spatial resolution and landscape element size. Ground transect FG_{ADC} range was more than four times larger than the cherry picker FG_{ADC} range (Table 3), and FG_{ADC} CVs were vastly larger than the cherry picker CV. Evidently, a spatial resolution large enough to include multiple landscape elements resulted in more consistent image to image FG_{ADC} estimates. Ground images could either contain large portions of shrubs or virtually no plant material, while cherry picker images always contained multiple shrubs. The decreased data range and lower CVs strongly argue that ADC images should ideally be taken from a height that includes several landscape elements.

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