Accuracy and Precision of Two Indirect Methods for Estimating Canopy Fuels

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Abstract—*We compared the accuracy and precision of digital hemispherical photography and the LI-COR LAI-2000 plant canopy analyzer as predictors of canopy fuels. We collected data on 12 plots in western Montana under a variety of lighting and sky conditions, and used a variety of processing methods to compute estimates. Repeated measurements from each method displayed considerable variability, but hemispherical photography proved to be the more precise method. To evaluate the accuracy of the different methods, we correlated measurements with allometrically derived estimates of canopy bulk density and available canopy fuel. Measurements from both methods were more highly correlated with available canopy fuel than canopy bulk density. Hemispherical photography emerged as the superior methodology, displaying greater precision and accuracy, at least when measurements must be collected under sub-par lighting conditions.*

In order to assess the potential risk of crown fires, accurate estimates of canopy fuel loads are needed. Direct met hods for measuring these loads are often difficult and time consuming, involving destructive sampling of the forest canopy or, alternatively, detailed allometric measurements on individual trees. As a result, indirect methods are being used increasingly to exploit the relationship between the amount of biomass in the forest canopy and the amount of light that gets transmitted to the forest floor. By measuring the relative amount of light reaching the forest floor, canopy fuels can be estimated indirectly.

This paper examines two indirect methods for measuring canopy fuels, the LI-COR LAI-2000 and hemispherical photography. Both of these methods have been used extensively to measure leaf area index (LAI), and are much less time consuming than direct methods (see Jonckheere and others 2004, or Chen and others 1997, for reviews of different methods for estimating LAI). Defined as the one sided leaf area per unit ground area, LAI is used frequently as a measure of canopy structure, and LAI has also been correlated with important metrics of canopy fuels loads, for example canopy bulk density (Keane and others, 2005). Thus these indirect methods could potentially provide an efficient method for estimating canopy fuel loads.

However, because these indirect methods rely on light transmittance, the resulting estimates can be highly sensitive to the ambient lighting conditions. Ideally measurements should be taken only at dawn or dusk with the sun below the horizon. Less ideally, data can also be collected under uniformly cloudy skies. In the former case, data collection is limited to only a few hours each day, while in the latter, data collection hinges on weather conditions. In practice these constraints may be too prohibitive, greatly limiting the time available for data collection. As a result they are often disregarded, and data are collected under a wide variety of lighting and sky conditions.

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In this paper, we evaluate the accuracy and precision of these two indirect methods with measurements taken under a variety of less than ideal lighting conditions. Using repeated measurements from 12 sites, we evaluate the precision of the estimates obtained using each method, and then compare these estimates with two allometrically derived metrics of canopy fuel loads: canopy bulk density (CBD) and available canopy fuel (ACF).

Background and Theory

Hemispherical photography and the LAI-2000 present different ways to measure the *gap fraction* in a stand: the proportion of sky visible under the canopy. With digital hemispherical photography, a digital camera with a fish eye lens is used to take a photograph of the canopy from which the gap fraction is computed. Usually this is accomplished by converting the color photograph to a black and white image: a threshold is chosen and all pixels darker than the threshold are declared to be not-sky and painted black, while all those brighter than the threshold are declared sky and painted white. The gap fraction is then equivalent to the proportion of white pixels in the image. Hemispherical photography requires little specialized equipment, simply a tripod, a digital camera, a fish eye lens, and software for processing the images.

The LAI-2000, on the other hand, is a specially produced piece of equipment for measuring LAI (LI-COR 1992). It consists of a light sensor mounted on a wand that is attached to an electronic control box. To compute gap fractions, the LAI-2000 needs to take two measurements of light intensity with the light sensor. The first measurement is taken above the forest canopy under open sky (usually in a clearing) while the second is taken below the canopy. The gap fraction is then computed by taking the ratio of these two measurements. Both measurements must be taken with the light sensor leveled and facing the same compass direction.

There is extensive theory detailing the relationship between gap fractions, leaf area index, and other canopy structure statistics (Welles and Norman 1991). Briefly, in an idealized homogenous full cover forest stand with small, randomly distributed foliage, the Beer Lambert law can be used to compute leaf are index, L, from gap fraction measurements as

$$L = 2\int_0^{\pi/2} -\ln(G(\theta))\cos\theta\sin\theta d\theta. \tag{1}$$

Here θ denotes zenith angle and $G(\theta)$ is the gap fraction as a function of the zenith angle. In practice, this integral is usually approximated by dividing the continuous range of zenith angles $(0,\frac{\pi}{2})$ into a number of concentric rings or sectors. The gap fraction is measured at specific zenith angles (or over a range of zenith angles) and then L is given by a weighted sum,

$$L = 2\sum_{i=1}^{n} -\ln(G(\theta_i))W_i, \tag{2}$$

Where n is the number of zenith angles (or number of rings) used, and W_i is the weighting term. The light sensor on the LAI-2000 has 5 rings centered at zenith angles of 7, 23, 38, 53, and 68 degrees. With hemispherical photography the number of rings and their locations can be controlled by the experimenter.

The LAI estimates derived from Hemi-photos and the LAI-2000 are very sensitive to lighting conditions. Both methods are best used under certain restricted light conditions: before sunrise, after sunset, or, less preferably, under uniformly cloudy skies (LI-COR 1992; Pepper 1998; Frazer 2001). Direct sunlight in a hemispherical photograph often leads to lens flare, and brightly lit foliage can be mistakenly classified as sky when hemispherical photographs are converted to black and white images for analysis. Similarly direct sunlight can lower resulting estimates from the LAI-2000 by up to 40% because of sunflects (Welles and Norman 1991). In practice appropriate lighting conditions can be difficult to obtain, greatly limiting the time available for data collection. As a result, these constraints are often neglected, or less data is collected. In this study, we examine how collecting data under sub-optimal lighting conditions affects the precision and accuracy of the measurements obtained.

Materials and Methods

Study Area and Sampling Methodology

The study area, located in Lolo National Forest in western Montana, consisted of 11 sample units, each 13m in radius. Each sample unit was either homogenously Douglas-fir (*Pseudotseuga menziessi*) or homogenously ponderosa pine (*Pinus ponderosa*). The tree densities varied substantially between plots (table 1). Nine of the plots were on south aspects, and 2 were on north aspects (plot codes DF-N and PP-N). Two of the Douglas-fir plots were open grown (DF-O-1 and DF-O-1) and located several miles from the others, in an area with thinner soil and higher winds.

Height, diameter and crown ratio measurements were collected on each tree in the study units, and then these tree lists were used to compute stand level canopy fuel load and bulk density, using methods described in Reinhardt and others (this proceedings).

Table 1—Fuel characteristics of the plots used in the study. Plots beginning with DF are homogenously Douglas fir, whereas those beginning with PP are homogenously ponderosa pine. All plots are circular with a radius of 13 m.

Plots					
Index	Plot Code	Canopy Bulk Density (Kg/m^3)	Available Canopy Fuel (Tons/Acre)	Canopy Cover (%)	Tree per acre
1	DF-2	0.0801	5.587	48.68	137
2	DF-3	0.1290	5.444	46.32	107
3	DF-4	0.2752	9.567	68.40	244
4	DF-N	0.0633	3.718	35.13	84
5	DF-0-1	0.0122	0.891	9.27	8
6	DF-0-2	0.0703	3.518	33.90	84
7	PP-1	0.0895	2.239	37.18	274
8	PP-2	0.0922	2.533	39.21	305
9	PP-3	0.0244	0.508	9.73	53
10	PP-4	0.1082	2.750	42.06	290
11	PP-N	0.0848	4.127	42.87	198

Hemispherical photographs and readings with the LI-COR LAI-2000 were collected in early September 2004. Data were collected under a variety of lighting and sky conditions, and in total measurements were taken 12 times with each instrument on each sample area.

A Nikon Coolpix 9000 digital camera with a fisheye lens was used for taking hemispherical photographs. The camera was attached to a leveled tripod and aligned so that the camera body pointed north. On each visit to a plot, two photographs were taken sequentially: one with proper exposure as determined by the camera's automatic metering and one underexposed by two f-stops. All photographs were taken using the highest resolution setting.

Two LICOR LAI-2000 units were used to obtain the above and below canopy measurements. The first unit was set up in a centrally located clearing, leveled, aligned to the North, and automatically logged above canopy readings every 30 seconds. The other unit was used to record the below canopy readings, and on each visit to a plot two below-canopy readings were taken immediately after the hemispherical photographs. The wand on the below canopy unit was leveled and aligned to the north for each measurement. Each LAI-2000 unit used a 90° view cap.

Data Processing

To compute gap fractions for the LAI-2000, we individually matched each below canopy reading with the above canopy reading that was closest in time, and computed gap fractions at each of the five zenith angles. Computing gap fractions for the hemispherical photographs was more complicated, as the color photographs first had to be converted to black and white images. Usually this is accomplished by choosing a threshold and coloring all pixels darker than the threshold black (vegetation) and all others white (sky). However, under uneven lighting conditions this approach can result in substantial misclassifications because foliage near the sun appears brighter than the sky far from the sun.

Instead, we used a two-stage supervised clustering algorithm to convert the color photographs to black and white images. The algorithm is an example of a commonly used iso-clustering algorithm from the image processing literature (Richards 1996), and was implemented in ARC-GIS. Briefly, the algorithm uses an automated procedure to assign each pixel in the image to one of a user-specified number of bins, based on the color and brightness attributes of the pixels in the image. In the first stage of processing, the photograph was divided into ten bins and the user was then prompted to classify each bin as not-sky (black), sky (white), or unknown (red). Often a single bin contained both vegetation and sky, and these bins were classified as unknown in the first stage. Any pixels classified as unknown during the first stage were then further subdivided into seven bins for a second stage of classification. The result was a black and white image with generally more fine detail than was obtainable using the traditional single threshold approach.

The resulting black and white images were then input into the commercial software HemiView for analysis. HemiView divides each image into a user-specified number of concentric circles (rings) of equal width, corresponding to different zenith angles, and then computes the average gap fraction in each ring. To facilitate comparison with estimates from the LAI-2000, five rings were used, centered at zenith angles of 9, 27, 45, 63, and 81 degrees. Note that the zenith angles from the two techniques are different, since the rings in the LAI-2000 are of unequal width.

There are potentially many ways to combine the individual gap fractions at each zenith angle into estimates of the overall LAI or fuel on a plot. The standard method is to compute LAI using all five zenith rings by taking a weighted sum of the logarithm of the gap fractions, i.e. equation 2. Not all rings need to be included in the sum however, and we also computed LAI values using different subsets of the zenith rings.

Moreover, it may be that the raw un-weighted gap fractions prove to be better indicators of canopy fuel loads. In this case the average gap fraction, $\bar{G}$, will be a useful statistic:

$$\bar{G} = \frac{1}{n}\sum_{i=1}^{n} G(\theta_i). \tag{3}$$

As with the LAI based statistics, this sum can be computed over different subsets of the zenith rings. In the following analysis, we utilized several different sets of zenith rings and computed predictions using both the raw gap fractions and the log transformed and weighted LAI as the predictive statistic (table 2).

Results

Comparing the Different Methods

We computed the mean, variance, and coefficient of variation (CV), for each method on each plot (table 3). The mean variance and CV per plot are both consistently larger for the LAI-2000 estimates than for the hemi-photo estimates. There is also a tendency for the CV and variance to increase as the number of rings used in the analysis is reduced. Note, however, that the estimates derived using only the 3rd ring do not conform to this pattern, suggesting that the number of rings is less important than the zenith angles of the rings used. Estimates derived using the smaller zenith angles exhibit more variation than do estimates derived from the larger angles.

Table 2—Factors in the analysis. Gap fractions were obtained with either the Licor unit or hemispherical photographs. Either the mean gap fraction or the log transformed and weighted leaf area index was used to derive predictions. The different analysis schemes used between and five zenith rings to derive predictions.

Methods	
Licor	LAI-2000 plant canopy analyzer
Hemi	Hemispherical photography
Statistics	
GF	Mean gap fraction (unweighted)
LAI	Leaf area index (weighted mean of the logarithm of individual gap fractions)
Analysis Scheme	
1	Only third zenith ring
2	Top two zenith rings
3	Top three zenith rings
5	All five zenith rings

Table 3—Summary statistics of the LAI estimates produced using different methods. The average variance and CV per plot represent the variance (CV) in measurements on each plot averaged across all the plots. Similarly the variance (CV) across plots denotes the variance (CV) in the mean value of the measurements for each plot. Note that these are the results using the LAI statistic.

Method	Mean	Average Variance Per Plot	Average CV Per Plot	Variance Across Plots	CV Across Plots
LAI-2000					
LAI-5	1.04	0.18	0.46	0.16	0.38
LAI-3	1.13	0.32	0.71	0.37	0.54
LAI-2	0.90	0.33	1.05	0.52	0.80
LAI-1	1.33	0.56	0.70	0.42	0.49
Hemi					
LAI-5	1.80	0.04	0.09	0.33	0.32
LAI-3	1.69	0.09	0.15	0.52	0.43
LAI-2	1.55	0.13	0.19	0.88	0.61
LAI-1	1.82	0.08	0.14	0.33	0.32

For the hemi-photos, the variance and CV across plots is substantially larger than the average variance and CV per plot, suggesting that the method can consistently distinguish between some of the plots. However, the LAI-2000 readings have roughly similar variances between and across plots, and the CV across plots is actually smaller than the average CV per plot. The mean estimates of LAI from the LAI-2000 are consistently lower than those from the hemi-photos for all of the different ring choices. Also, the mean estimated LAI values from the hemi-photos decrease as the rings with larger zenith angles are removed from the analysis.

To examine the correlation between the LAI-2000 estimates and the hemi-photo estimates, we computed simple correlation coefficients for each pair of estimates (table 4). The correlation between the LAI-2000 and hemi-photo estimates increases as the rings with the larger zenith angles are excluded from the analysis. Measurements were most correlated when only the top two zenith rings were used.

Table 4—Correlation coefficients between the hemi-photo and Licor LAI values.

	Licor LAI-2000			
Hemi-Photo	LAI-5	LAI-3	LAI-2	LAI-1
LAI-5	0.561	0.618	0.673	0.429
LAI-3	0.602	0.659	0.667	0.499
LAI-2	0.594	0.683	0.717	0.496
LAI-1	0.560	0.570	0.543	0.459

Relationship with Allometric Data

For all processing methods, we computed regressions using both available canopy fuel (ACF) and canopy bulk density (CBD) as computed from the stand data as response variables. We tested three different regression models. The simplest, the reduced model, used only the measured LAI or GF statistic as a predictor variable, but the other two regressions incorporated additional predictor variables. The second regression model introduced tree type (Douglas fir or Ponderosa pine) into the reduced model as a categorical predictor variable, including an interaction term. This approach is justified due to the homogenous nature of the stands in the study and the common use of species specific clumping factors for modifying LAI estimates (White and others 1998). Finally the third regression model further added canopy base height as an additional predictor variable. Canopy base height is defined as the average height within a stand from the ground to the canopy bottom. While more difficult to assess than tree type, canopy base height can be measured or estimated relatively easily.

To simply the presentation, we use R^2 values to measure goodness of fit (figure 1). For each of the two instruments there were two possible statistics (GF or LAI), four analysis schemes, two response variables, and three types of regression models, for a total of 2x2x4x2x3 = 96 different regression models.

Several clear patterns emerge from figure 1. The reduced regression model, using a single predictor, performs uniformly poorly for both instruments and both predictor variables. The third regression model, which includes canopy base height, performs substantially better than the other two, especially for hemispherical photography with CBD as the response variable. For all of the

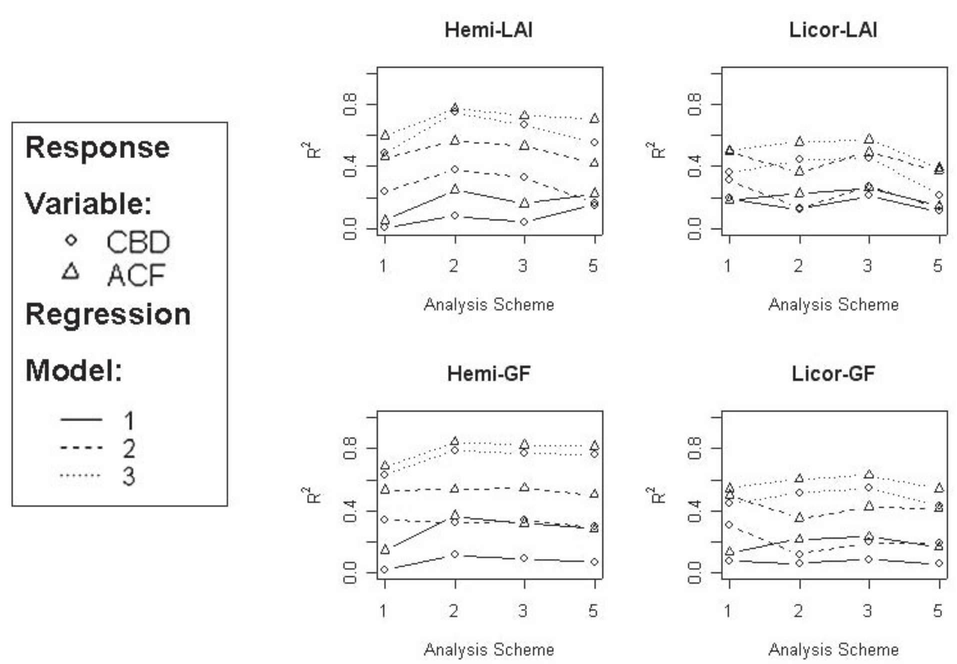

Figure 1—R^2 values from the different regressions. The x-axis shows the number of zenith rings used to derive predictions. Regression model 1 (solid lines) is the reduced model, model 2 (dashed lines) includes tree type as a predictor, and model 3 (dotted lines) also includes canopy base height. Results are shown with available canopy fuel (ACF) or canopy bulk density (CBD) as the response variable.

regression models, the fit was better using ACF as the response variable than it was with CBD as the response variable. The LAI-2000 estimates derived using only the third ring (analysis scheme 1), as well as those derived using the top 3 rings (analysis scheme 3), produced the best fits for both CBD and ACF. Conversely, the hemi-photo estimates derived using the top two rings consistently had the largest R^2 values, although only marginally larger than those derived using the top 3 rings. For the hemi-photos, correlations generally increase as the zenith angles increase, but for the LAI-2000 correlations appear to peak around the third zenith angle. Overall, there appears to be little overall difference in performance between the estimates produced using LAI and those produced using average GF.

With the simplest regression model, the hemi-photos and LAI-2000 both performed similarly. In the more complex regression models, however, the hemi-photo results were clearly dominant, with consistently larger R^2 values than the corresponding LAI-2000 based estimates. This suggests that hemi-photo based estimates of CBD and ACF are more accurate.

Discussion and Conclusions

As is clear from table 2, the hemi-photo measurements are more precise than the LAI-2000 measurements, with substantially smaller variances and CVs on each plot. The hemi-photos also provided more accurate measures of canopy fuels, as indicated by the R^2 values from the regressions against CBD and ACF.

The number of rings used in the analysis had a somewhat significant impact on the accuracy of the different estimates (table 4). The tendency towards increased accuracy with reduced zenith angles may be due to the relatively small size (13m radius) of the plots used. In any case, as the zenith angles used for analysis decreased, the CV of the measurements on each plot tended to increase. Taken together these results suggest that accuracy can be increased, at least on smaller plots, by only using the smaller zenith angles, but at the cost of decreasing the precision of the measurements.

The lower precision of the LAI-2000 estimates is not surprising: the LAI-2000 is not intended to derive estimates from individual measurements. Indeed, part of the attraction of using the LAI-2000 is the ease of taking repeated measurements on a single plot. Whereas repeated measures using hemi-photos require analyzing each photograph individually, the LAI-2000 can automatically combine repeated measures into a single estimate. Thus the lower precision of individual measurements is offset by the ease of repeating measurements. The large processing time needed to derive estimates from the hemi-photos, and the relative ease of incorporating multiple measurements into a single estimate using the LAI-2000, makes the LAI-2000 more competitive than the preceding analysis might suggest. Nonetheless, this analysis demonstrates that the hemi-photo method is preferable from the standpoint of both accuracy and precision. If the processing of the hemi-photos could be completely automated, the processing time would be more comparable for the two methods, and the hemi-photo methodology would be more clearly preferable.

Surprisingly the hemi-photos provided decent measures of canopy fuels despite the variety of less than ideal lighting and sky conditions under which the photographs were taken. In this study we used a very labor intensive processing methodology that allowed for more detailed black and white photographs even under poor lighting conditions such as direct sunlight. Apparently more labor intensive processing in the lab was able to compensate for less than ideal sampling conditions in the field. Hemispherical photography thus has the potential to reduce the labor, time, and environmental constraints in the field, in exchange for more time and labor spent in the lab.

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