A COMPARISON OF TOOLS FOR REMOTELY ESTIMATING LEAF AREA INDEX IN LOBLOLLY PINE PLANTATIONS

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Abstract—Light interception is critical to forest growth and is largely determined by foliage area per unit ground, the measure of which is leaf area index (LAI). Summer and winter LAI estimates were obtained in a 17-year-old loblolly pine (Pinus taeda L.) spacing trial in Mississippi, using three replications with initial spacings of 1.5, 2.4, and 3.0 m. Direct estimates of summer LAI were made in August of 2001 using allometric methods. Monthly litter trap collections were used to determine the change in LAI between August and January; winter LAI was derived by subtraction from summer values. Indirect estimates of LAI were made using a LI-COR LAI-2000 Plant Canopy Analyzer (PCA) and hemispherical photography in conjunction with Delta-T HemiView 2.1 software. As remote estimators of LAI, both the PCA and hemispherical photographs underestimated summer maximum LAI, and neither tool appeared to be sensitive to seasonal change in LAI.

INTRODUCTION

Estimates of leaf area index (LAI) have been used to measure radiation interception, photosynthetic capacity, forested stand stress levels, net canopy carbon gain, and stand productivity. Stand management decisions and stand growth predictions require accurate determination of LAI, thus a rapid inexpensive estimation of LAI is desirable. Numerous methods have been employed to estimate LAI: destructive biomass harvesting, allometric relationships based on tree and stand attributes, litterfall collections, remote sensing approaches, instantaneous measures of light transmittance (such as the LI-COR LAI-2000 or light ceptometer), and gap fraction analysis of canopy hemispherical photographic images. Several workers have compared methods of LAI estimation, (Chason and others 1991; Chen and others 1991, 1997; Fassnacht and others 1994; Gatch and others 2002; Gower and Norman 1991; Hebert and Jack 1998; Lopez-Serrano and others 2000; Machado and Reich 1999; Macfarlane and others 2000; Sampson and others 2003; Sampson and Allen 1995; Wang and others 1992), and most agree that a number of these methods have site-specific limitations.

Loblolly pine (Pinus taeda L.) canopies present a unique set of challenges to the measurement of LAI. LAI in loblolly pine stands varies annually with foliage cohort. In a study of loblolly pine in North Carolina, Sampson and others (2003) reported that foliage development occurred in three distinct stages, each transpiring over a 4-month growth cycle. LAI should thus peak around August, prior to fall foliage abscission. Minimum LAI should occur during the winter months, prior to needle accretion. Compounding seasonal variations in LAI are variations associated with climatic regime. In loblolly pine stands, the rate and quantity of foliage abscission may be a function of water availability (Albaugh and others 1998, Sampson and others 2003, Sampson and Allen 1998), while nutrient availability can strongly influence shoot-clumping (Hebert and Jack 1998, Sampson and Allen 1995, Sampson and Allen 1998). Additionally, estimates of LAI may be influenced by stand basal area (Gatch and others 2002), and thus these estimates may also be influenced by stand management and/or mortality in mature stands. The net result is that the timing of LAI measurement will influence the measurement outcome, and the ability to accurately estimate LAI in mature loblolly pine stands tends to decrease with increasing LAI.

Sampson and others (2003) hypothesized that of the methods available to estimate LAI in forest stands, instantaneous methods such as those using the PCA should provide the best estimates of seasonal variations in LAI. Rich (1990) suggested that hemispherical photography might also be effectively used to measure seasonal changes in foliage densities. Few studies have actually compared seasonal values in loblolly pine stands (Harrington and others 2002, Hebert and Jack 1998, Sampson and others 2003). Our objectives were: (1) to compare the capabilities of two remote estimators of LAI relative to summer maximum LAI estimates derived from standard allometric approaches, and (2) to compare the sensitivity of remote estimators of LAI to seasonal changes in LAI as estimated from litter trap collections.

METHODS

Site Descriptions

The study is located in Winston County, MS, on the Mississippi State University John W. Starr school forest (33°16' N, 88°52' W). The study area is situated in an interior flatwood site with an average precipitation of 1,430 mm and a site index of 23 m in 25 years for loblolly pine (Roberts and others 2003). The study was conducted in a 17-year-old loblolly pine plantation (established in 1986). Average heights ranged from 16 to 20 m, and stands generally had closed canopies with the exception of localized mortality gaps. The study design included three replicates of three treatments consisting of loblolly pine at initial square spacings of 1.5 m, 2.4 m, and 3.0 m. Twenty-four 149 m^2 plots of each spacing, for a total of 72 plots, were included in the study.

Direct Estimates

Direct measurements of LAI were obtained through allometric approaches. Summer maximum individual tree leaf areas (LA) were calculated from diameter at breast height (d.b.h.) and tree height (HT) using locally derived (based on destructive sampling) allometric equations. In August, 2001, all trees from each plot (n range = 4 to 50 trees, average = 22 trees)

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were measured for d.b.h. and HT. Tree HT and d.b.h. were used to calculate individual tree LA in m^2 as follows:

$$LA = 0.000313 \times dbh^{2.2919} \times height^{-0.1971} \qquad (1)$$

Total LA for the plot was obtained by summing the LA of all trees on the plot. Summer maximum LAI was obtained by dividing total plot LA by plot area.

Winter LAI values were derived from summer allometric data and litterfall data for 5 months. Three 0.5 m^2 litter traps were placed at random within each plot. Litter was collected monthly from August, 2001, to January, 2002. Litter collections were combined to yield a single composite sample per plot. Samples were pre-dried in preparation for sorting. Samples were sorted into needles and other materials (twigs, bark, catkins, and other debris) to remove all material except whole needles and needle fragments. The pine needles were then dried at 70 °C for a minimum of 48 hours to achieve constant weight and weighed to the nearest 0.1 g. Total per-plot monthly weights were summed to provide needle-fall weights on a per-plot basis for the interval of August 2001-January 2002. Seasonal change in leaf area (ΔLA) was calculated as:

$$\Delta LA = [\text{dry weight (g)/trap area (m}^2)] \times [43\text{cm}^2/\text{g}] \times [1\text{m}^2/10000\text{cm}^2] \qquad (2)$$

Winter LAI was determined by subtracting ΔLA from the summer maximum LAI values.

Indirect Estimation of LAI using Plant Canopy Analyzer (PCA)

In September, 2001, and January, 2002, LAI was estimated using a pair of Licor LAI-2000 plant canopy analyzers (PCA, LiCOR Inc., Lincoln, NE). Simultaneous readings were taken inside and outside of the canopy. All readings were taken in the early morning hours, from dawn until direct sunlight began reflecting from the tops of the crowns. LAI-2000 readings were taken with a 45° view cap attached to the lens and the center of the 45° view cap facing due north at 1.37 m above ground. Within the canopy, readings were taken along the southern border of the plot, with a sampling range of 4.75 m in the east-west direction and 1.0 m in the north-south direction. Five readings were taken within the sampling range: two readings within tree rows and three readings between tree rows.

Data were processed using LI-COR C2000 software. Data were filtered for "bad pairs" (for example pairs in which the ratio of sensor A to sensor B differed from other pair readings within the same ring), which may result from sensor obstruction or deviation from level position. The results of the outside-plot values were examined and, when determined to deviate from zero, a correction multiplier was applied to simultaneous within-plot readings. All data were processed with a mask on ring five. LAI was calculated using the LI-COR software.

Indirect Estimation of LAI using Hemispherical Photography

In summer 2001 and winter 2002, hemispherical photographic images were taken following general procedural recommendations for vertical photographs in forest canopies (Becker and others 1989, Chen and others 1991). Images were taken from plot center at a height of 1.37 m above ground level with a Nikon Coolpix990 digital camera equipped with a fisheye lens. The camera was mounted on a self-leveling tripod and aligned to magnetic north. Images were photographed at a resolution of 2,048 x 1,536 pixels, with focus set at infinity and shutter speed and aperture set automatically. Images were taken using three image quality settings: fully automatic color, black and white with high-sharpness, and color with reduced-contrast and high-sharpness. It was later determined that the reduced-contrast, high-sharpness images yielded the best images for processing; i.e., sky appeared as white and foliage elements appeared as black. All images were taken in early morning hours or in overcast conditions, so the sky background was evenly illuminated, and no sunlight was reflected by vegetation.

Prior to analysis, images were processed using Adobe Photoshop 7.0. Images were examined for evidence of "washed-out" areas due to reflected sunlight. Washed-out areas, which occurred in 10 of 144 images, were adjusted to match the rest of the image using Photoshop's lasso tool and image adjustment features. An opaque circle overlay was created to exclude portions of the image outside of a 58° zenith angle which was the portion of the image determined trigonometrically to be outside of the plot area. Images were saved as jpeg files and imported into HemiView 2.1 canopy analysis software (Delta-T Devices Ltd.) for analysis. The HemiView software was used to estimate LAI from the images based on image gap fraction, using eight azimuth and seven zenith sectors within the unmasked portion.

RESULTS AND DISCUSSION

Comparison of the Capabilities of Two Remote Estimators of LAI Relative to Summer Maximum LAI Estimates Derived from Standard Allometric Approaches

Most reported LAI values are understood to have been acquired at maximum leaf area display, which for loblolly pine would be during August in normal years (Sampson and others 2003) and up to 2 months earlier during dry years (Hebert and Jack 1998). August summer maximum estimates of LAI in this study derived from standard allometric approaches ranged from 1.50 to 5.41, which is within the expected range for loblolly pine (Sampson and Allen 1995). Summer LAI for 1.5 m, 2.4 m, and 3.0 m spacings averaged 4.20, 4.13, and 3.99, respectively, with an overall mean of 4.07 (fig. 1). Differences were not significant at $\alpha = 0.05$.

Estimates of summer LAI from the PCA (range = 1.57 to 5.57) and hemispherical photography (range = 2.73 to 4.55) were also within the expected range for loblolly pine (Sampson and Allen 1995). The two remote estimators compared well with each other: means for the PCA and hemispherical photography were 3.39 and 3.33, respectively. However, the remote methods underestimated the allometric mean by 17 and 18 percent, respectively (fig. 2). This is typical of remote estimates in most conifer stands (Chen 1996, Fassnacht and others 1994, Gower and Norman 1991). Both methods have been reported to be biased due to blockage of light by boles and non-random distribution of foliage elements (Barclay and others 2000, Chen 1996, Fassnacht and others 1994, Gower and Norman 1991). Gower and Norman (1991) developed a procedure for determining a stand-specific "clumping factor" which could be used to ameliorate this effect; however, we made no attempt to correct the remote estimates as the method is costly to estimate and has not performed well in

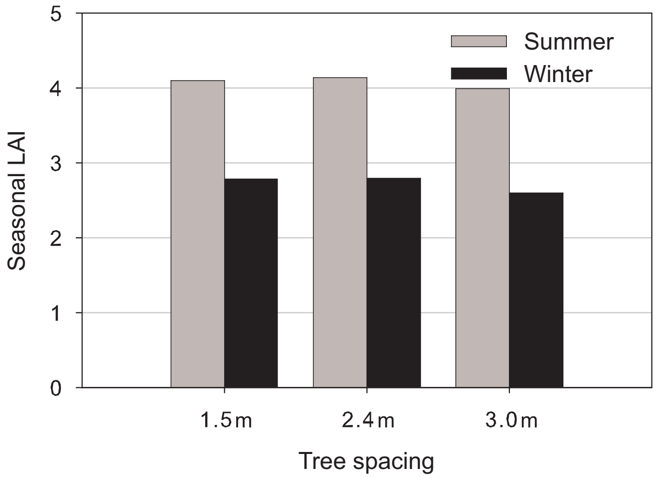

Figure 1—Direct estimates of mean summer and winter LAI (m^2/m^2) by initial spacing. Differences among spacing within seasons were not significant at $\alpha = 0.05$.

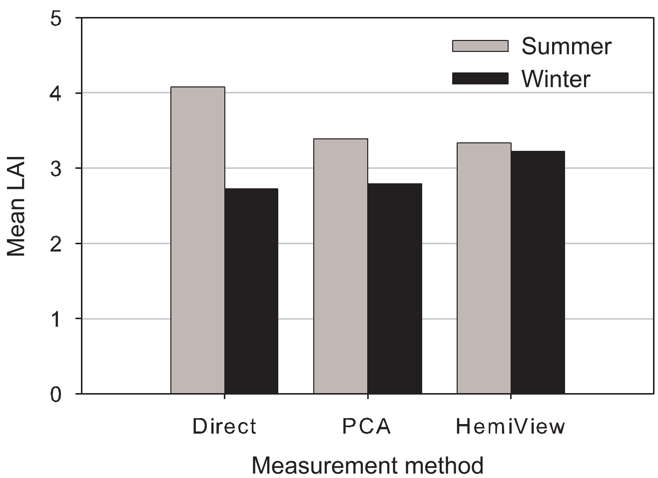

Figure 2—Comparison of means for direct and remote estimates of LAI (m^2/m^2), for summer and winter measurements, combined across plots.

some studies (Fassnacht and others 1994, Hebert and Jack 1998).

Comparison of the Sensitivity of Two Remote Estimators of LAI to Seasonal Changes in LAI as Estimated from Litter Trap Collections

Litterfall-based estimates of seasonal change in LAI by spacing treatment yielded ΔLAI values of 1.32, 1.34, and 1.39 for 1.5 m, 2.4 m, and 3.0 m spacings, respectively. Winter estimates of LAI ranged from 0.85 to 3.97. Mean winter LAI for 1.5 m, 2.4 m, and 3.0 m spacings were 2.78, 2.79, and 2.60, respectively, with an overall mean of 2.73. Differences were not significant at $\alpha = 0.05$.

Estimates of winter LAI from the PCA (range = 1.49 to 5.06) and hemispherical photography (range = 2.71 to 4.00) were also within the expected range for loblolly pine (Sampson and Allen 1995); however, in contrast to the underestimated summer values (fig. 2), neither the PCA nor hemispherical photographs underestimated winter values. Winter versus summer correlation plots for all three methods are presented in figure 3.

The PCA overestimated winter LAI by 2 percent (overall mean = 2.79). Mean winter LAI values for 1.5 m, 2.4 m, and 3.0 m spacings were 2.92, 2.79, and 2.67, respectively. Differences were not significant at $\alpha = 0.05$. A strong relationship, though not 1:1, was found between the direct estimates for summer and winter LAI with little scatter (fig. 3a). Summer and winter LAI values, as measured by the PCA, had a weaker correlation ($r^2 = 0.7554$) than that of the direct estimates, and the slope and y-intercept were lower (fig. 3b). Sampson and others (2003) hypothesized that of the methods available to estimate LAI in forest stands, instantaneous methods such as the PCA should prove the best estimate of seasonal variations in LAI. In this loblolly pine stand, the PCA was a weak estimator of summer LAI but appeared to provide reliable estimates of winter LAI.

Underestimation of LAI by the PCA is often attributed to clumping and nonrandom distribution of foliage (Fassnacht and others 1994, Gower and Norman 1991, Sampson and Allen 1995, van Gardingen and others 1999). Workers have attempted to apply correction factors to the results, with limited success. Sampson and others (2003) stated that while site-specific corrections to PCA estimates may be valid and necessary, there is insufficient evidence that the corrections are easily and reliably applicable. The results from this study suggest that there is a threshold level of LA above which the LAI-2000 is unreliable, and that the threshold level lies somewhere between the winter and summer values for these loblolly pine stands. As needle abscission increases, the canopy appears to approach a more random distribution of foliage elements. This is consistent with the findings of Sampson and Allen (1995).

Hemispherical photography overestimated winter LAI by 18 percent (mean = 3.22); mean winter LAI values for 1.5 m, 2.4 m, and 3.0 m spacings were 3.22, 3.12, and 3.22, respectively. Differences were not significant at $\alpha = 0.05$. There was no correlation between winter and summer LAI estimates obtained from hemispherical photography (fig. 3c). The change in mean LAI from summer to winter represented a decrease of only 0.11, indicating that the hemispherical photography was not sensitive to seasonal changes in these loblolly pine stands. There is typically a roughly 40 percent drop in LAI from summer to winter for loblolly pine. LAI values obtained from hemispherical photography were 18 percent lower than direct estimates in the summer and 18 percent higher than direct estimates in the winter. This suggests that mean LAI as determined from hemispherical photography may represent a value midway between “true” summer and winter LAI.

SUMMARY AND CONCLUSIONS

Spacing effects on LAI were not seen for any of the estimation approaches used: allometry, LAI-2000 plant canopy analyzer, or hemispherical photography. Both the PCA and hemispherical photographs were comparable as estimators of summer LAI in these loblolly pine stands, although both methods underestimated LAI by approximately 20 percent. This result is most likely the result of foliage clumping in these closed-canopy loblolly pine stands.

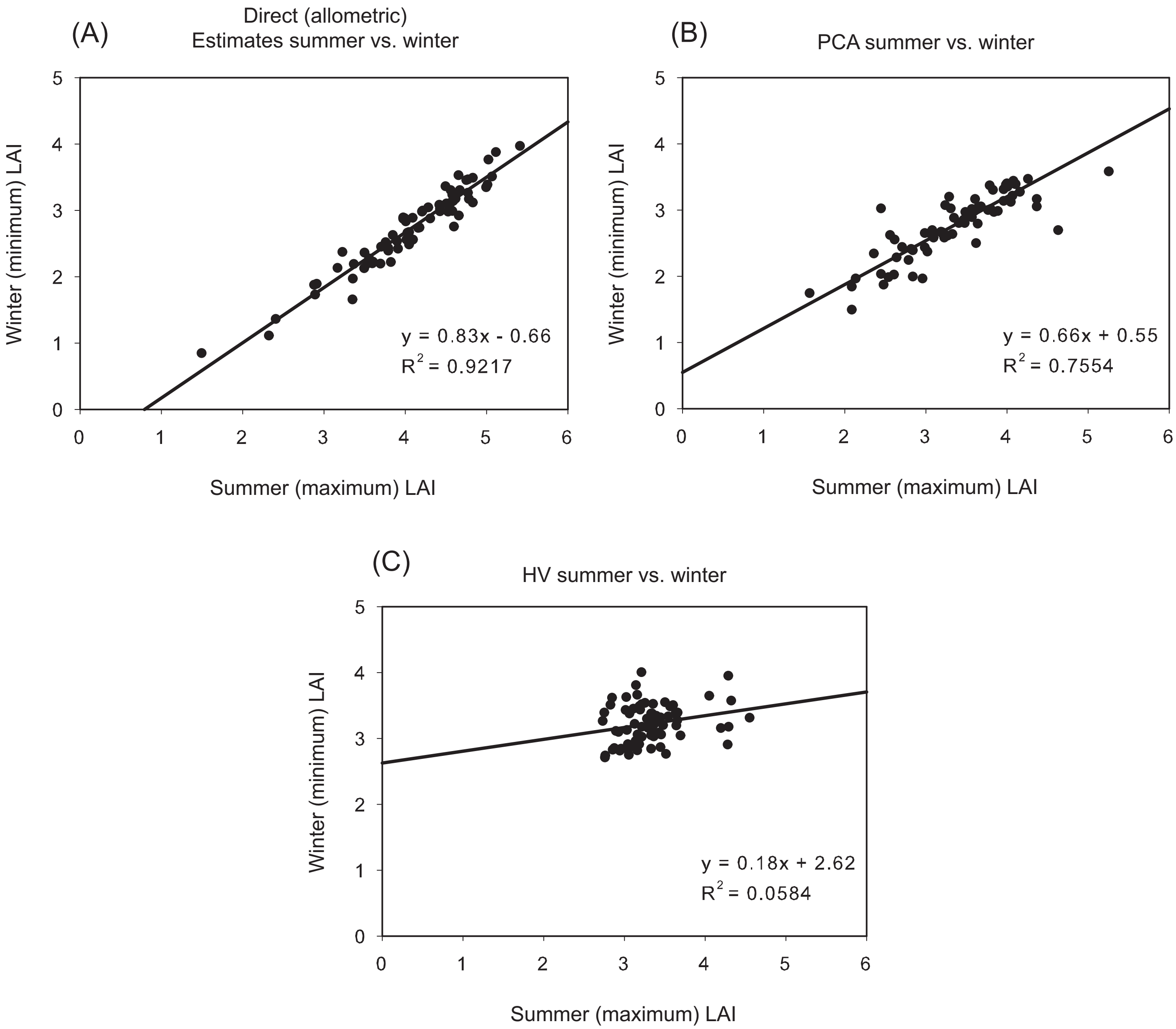

Figure 3—Correlation between estimates of summer and winter LAI (m^2/m^2): (A) Relationship between summer and winter direct measurements, (B) relationship between summer and winter PCA measurements and (C) relationship between summer and winter hemispherical photography measurements.

Of the two indirect estimation approaches examined, the PCA was more sensitive to seasonal changes in LA. The PCA yielded a mean winter LAI of 2.79 as compared to the mean direct winter estimate LAI of 2.73. LAI measurements using the PCA yielded a seasonal change of 18 percent (from 3.39 in summer to 2.79 in winter) as compared to a 33 percent seasonal change yielded by direct methods. Hemispherical photography was not sensitive to seasonal change in LA, greatly overestimating winter LAI. Hemispherical photography yielded a mean winter LAI of 3.22 as compared to the direct estimate value of 2.73. The measured seasonal change was only 4 percent (from 3.33 in summer to 3.22 in winter), as compared with 33 percent from direct methods.

LA of mature, closed-canopy loblolly pine stands in this region may be too high for remote methods of LAI determination to be effective in summer. Following fall needle abscission, the LAI-2000 PCA appeared to be more accurate at measuring winter LAI, suggesting that there is a threshold level of LA above which the LAI-2000 is unreliable. That threshold level appears to lie somewhere between the winter and summer values for loblolly pine stands in north-central Mississippi.

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