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Comparison of Five Methods for Estimating Leaf Area Index of Open-Grown Deciduous Trees

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Abstract

We compared the accuracy of five methods used to estimate leaf area index (LAI) of eight open-grown deciduous trees including six white mulberries (*Morus alba* L.) and two black cherries *(Prunus serotina* var. *rufula* Ehrh.*)*. The methods included the use of four instruments (AccuPAR Ceptometer, CI-100 Plant Canopy Analyzer, Image Processing with the AgVision System, LICOR LAI-2000 Plant Canopy Analyzer) and the application of a logarithmic regression equation. The Image Processing Method demonstrated the highest probability of accurately estimating LAI (P = 0.99). However, all methods showed bias toward returning LAI estimates which did not increase as actual LAI increased when the mulberry tree data was examined separately from the cherry data. Additional research is necessary to determine whether this bias is real or merely a function of the limited sample size.

Introduction

Leaf area is a key parameter for studying many physiological processes associated with urban and

rural trees. Leaf area index (LAI, leaf area per unit ground area) is highly correlated with photosynthesis, transpiration, evapotranspiration, productivity and yield rates (Botkin, 1986; Pierce and Running, 1988; Gholz and others, 1991) . Modeling growth rates, atmospheric deposition, biogenic volatile emissions, climate change, and energy exchange associated with open-grown trees in cities requires accurate estimates of LAI (McPherson, 1992; Nowak, 1994; Winer and others, 1995). However, the majority of research on destructive and non-destructive methods of estimating leaf area has been conducted on forest canopies, orchards and agricultural row crops (Lang and Yuequin, 1986; Norman and Welles, 1983; Norman and Campbell, 1989; Lang and McMurtrie, 1992; Martens and others, 1993; Nel and Wessman, 1993).

Indirect methods for determining LAI include the use of allometric equations (Whittaker and Woodwell, 1968; Marshall and Waring, 1986; Martens and others, 1993; Nowak, 1996). Nowak developed allometric equations to predict leaf area and leaf biomass for open-grown deciduous urban trees based on stem diameter and crown parameters. Other indirect methods, including hemispheric photographs (Bonhomme and Chartier, 1972; Neumann and others, 1989; Martens and others, 1993) and gap fraction analysis, have been applied almost exclusively to forest and agricultural canopies (Norman and Welles, 1983; Lang and Yuequin, 1986; Norman and Campbell, 1989; Martens and others, 1993; Nel and Wessman, 1993). The exception to this is Lang and McMurtrie's use of the DEMON instrument to estimate leaf areas of single *Eucalyptus grandis* trees (Lang and McMurtrie, 1992). Film and video image processing is the only method most commonly tested on open-grown and containerized deciduous trees (Wagar and Heisler, 1986; Gardner and Sydnor, 1987; Wilkinson, 1991; Lindsey and Bassuk, 1992).

The objective of this pilot study was to test a variety of instruments and data analysis methods, initiating a first step toward finding a single, accurate and efficient technique for non-destructively determining leaf area over the wide variety of tree species present in the urban landscape. Nowhere is it more difficult to obtain accurate LAI measurements than in urban settings where few residents are willing to proffer their yard and street trees to destructive sampling by urban forest researchers. Pedestrian and vehicular traffic limit the placement and amount of mensuration equipment that can be setup and utilized safely. Also, buildings, signs, and other objects often shade parts of tree crowns at various times of the day. Therefore, the primary objective of this study was to identify the most accurate and efficient method(s) that can be utilized in a variety of urban settings throughout the course of a day.

Methods

We tested four equipment systems and a logarithmic regression formula on six to eight open-grown trees (sample size depended upon method employed). The systems were hemispheric sensors (LI-COR LAI-2000 Plant Canopy Analyzer, CID CI-100 Computer Canopy Analyzer), linear array of PAR sensors (Decagon Devices AccuPAR Ceptometer), and a photographic system (Decagon Devices AgVision System used in conjunction with Lindsey and Bassuk's (1992) photo image analysis method). Photosynthetically active radiation (PAR) data from the LAI-2000 were processed using three methods. Data from the AccuPAR were analyzed as it came from the instrument and also by removing measurements recording no differences between above and below crown PAR. Image files from the CI-100 were processed using original software that came with the instrument and an updated software program currently being researched and developed. Lastly, we compared results from the application of Nowak's logarithmic regression equation for predicting leaf area to the actual leaf area of six trees sampled in the study.

Study site

Measurements and complete destructive sampling of eight open-grown trees were begun in July, 1995 and completed in early October, 1995 at the Solano Urban Forest Research Area (SUFRA) at Solano Community College near Fairfield in Northern California. The climate at the facility is under a maritime influence and temperatures typically range from 24EC to 35EC (75 to 95EF) during summer months. Typically, summer days are sunny and cloudless. Winds are ever present and may gust to 1.34 $m \cdot s^{-1}$ (30 m.p.h.) by late afternoon. A residential community borders two sides of the site.

The study trees included six white mulberries (*Morus alba* L.) planted at the site from 22- liter (5-gallon) containers in 1985. Their trunk diameters at breast height (d.b.h.) ranged from 12.9 to 19.4 cm (5 to 7.6-in.). Total tree height and crown width ranged from 4.4 to 8.1 m (14.4 to 16.6-ft) and 6.1 to 8.25 m (20 to 27-ft), respectively. Tree shape was ellipsoidal, however. The prevailing southwest winds in the area had produced crowns that were wider on the northeast sides of the trees than on the southwest. The trees tended to have long, leggy upper branches with many gaps.

Two black cherries (*Prunus serotina* var. *rufula* Ehrh.) included in the study were planted in 1986. Their crowns exhibited no shaping effects from the wind and were vertically ellipsoidal with trunk diameters of 20.4 and 20.9 cm (8.03 and 8.22-in.) at breast height. Tree heights were 7.5 and 7.7 m (24.6 and 25.26-ft) and crown widths were both 4.6 m (15-ft). Both species received regular pruning in the first several years of planting to remove low-growing branches and epicormics. The cherries were further pruned to increase crown density and improve form. The six mulberries and two cherries were randomly selected from extremely limited populations of twelve and five trees, respectively. However, for the purpose of this pilot study the assumption is the selection of these trees is as good as if chosen at random from larger populations.

General data collection

Before applying any of the techniques under evaluation, the following crown dimensions were measured for each tree: (1) d.b.h.; (2) tree height; (3) bole height; (4) crown height; (5) crown diameter in two perpendicular directions; (6) crown shape -- paraboloid or vertical ellipsoid; (7) crown vigor based on (a) measurements of last three years' twig elongation, 12 branches per tree; (b) percent crown die back, and (c) foliage discoloration, as per methods described in the Forest Health Monitoring Field Methods Guide (Burkman and others, 1993). Lastly, eight pairs of x, y coordinates that defined the outermost limits of the crown were measured for later use in adjusting the LAI-2000 path lengths.

Random distances along x, y, z coordinates from the tree base were selected to determine leaf sampling locations within each tree crown. Using a break-apart frame made from PVC pipe (0.016 m^3 or 0.565-ft^3), 20 samples of foliage were collected in two stages. After each set of ten quadrat samples were harvested measurements of the crown were repeated for all methods. The use of pruning ladders enabled collection without disturbing the tree crown. Each sample was weighed fresh and all leaves measured for leaf area using leaf area image analysis (Decagon Devices, Inc., Pullman, WA). Samples were then dried (65EC or 149EF for 24 hours) and weighed. Subsample fresh:dry weight and dry weight: leaf area ratios were calculated for each of the 20 samples. Mean values and standard deviations were estimated for each tree's sample.

After quadrat sampling and instrument measurements were completed, all remaining leaves were removed from the crown for a 100 percent destructive sample. These leaves were dried and weighed

to obtain total dry weight of foliage for each tree. Mean leaf area:dry weight ratios were multiplied by the weight of the 100 percent destructive sample to calculate total leaf area per tree (control). Leaf area index for the control was calculated by dividing total leaf area by crown projection. The experiment was established as a randomized block design, with three repeated measurements. Each block consisted of a single tree and LAI measurements were repeated three times per tree, once with the tree in full crown, then after removing leaves from ten randomly selected 0.016 m^3 (0.565-ft^3) quadrats, and again after removing leaves from an additional ten quadrats. Analyses of variance were conducted on the differences between actual and estimated LAI for each method to estimate standard errors. There were two variance components, one due to random effect block (tree) and the other due to variability within the block. Paired t-tests were run on resulting sample means:

t = || ÷ SE()

where || is the absolute value of the sample mean (Mori, personal communication). The alpha-level was set to 0.05 and the critical point, t_{df}, was read from tables with the t-distribution at 5, 6 and 7 degrees of freedom, depending on the number of sample trees included in the analysis.

Instrument sampling and analytical methods

For repeated measurements to be taken with the LAI-2000, CI-100, and AccuPAR from the exact same locations beneath the tree crown, four stakes were driven into the earth, one in each cardinal direction, 20 cm (7.87-in.) from the base of the bole, 15 cm (5.91-in) above ground level, and approximately 0.9 to 1.3 m (2.95 to 4.27-ft) below the bottom of each crown. Each instrument's probe was then leveled while resting on top of the stake and a single measurement taken in each cardinal direction for a full tree crown, then again when the crown was reduced by ten 0.016 m^3 (0.565-ft^3) samples of leaves, and lastly after a total of twenty 0.016 m^3 (0.565-ft^3) samples were removed. Instrument photos and measurements for the image analysis method (Lindsey and Bassuk, 1992) were taken in sequence starting with photographs of the tree crown in two perpendicular directions, then following in order with the LAI-2000, AccuPAR, and CI-100. Photographs and measurements for each tree took approximately 45 minutes to complete.

Since one of the parameters of this study was to duplicate the conditions under which LAI measurements will be taken in urban settings, all instrument readings were taken under clear sky conditions at easily accessible locations at the base of each tree bole, at a range of times between 08:00 and 17:00 (PST).

AccuPAR PAR Ceptometer

This instrument is a battery-operated linear PAR ceptometer used to measure photosynthetically active radiation in the 400 to 700 nm waveband. It consists of an integral, programmable data logger and 80 independent sensors located at 1 cm^2 (0.39-in^2) intervals along the length of the attached probe (Decagon Devices, Inc., Pullman, WA). Most analytical methods for determining LAI assume that canopy elements are randomly dispersed in space. In reality, canopies exhibit some degree of clumping and the assumption of randomness results in a large source of error (Norman and Campbell, 1989). The sensors along the AccuPAR probe may be partitioned into groups to mimic the clumping effects of a canopy. Because of the near constant presence of wind at SUFRA, partitioning to mimic clumping was not feasible; the clumps and distribution of foliage changing from moment to moment. As a result, the probe was divided into five groupings containing 16 sensors each. The instrument then collected data on each group of sensors and the software program averaged the

readings from the sensors to produce the LAI. Latitude, longitude, international date and standard local time for the site also were programmed into the data logger for automatic calculation of zenith angle. The programmed leaf distribution parameter was 1.0. Fractional beam data (the amount of diffuse and direct beam radiation reaching the canopy) was measured for each set of above and below measurements. Although the instrument prompts the operator to measure fractional beam, it does not automatically record the information for later use, but simply uses it in calculating the LAI using an ellipsoidal inversion formula. A single sensor was used to record above and below crown measurements. Above canopy data were taken by walking into an open field adjacent to the study trees. For below canopy measurements, the instrument was placed on the top of the stakes. Gap fraction and LAI were computed by the instrument for each direction using Campbell and Norman's method (1988). here $A = 0.283 + 0.785a - 0.159a^2$ and a is the leaf absorptivity in the PAR band (AccuPAR assumes 0.9 in LAI sampling routines). T is the transmission coefficient and K is the extinction coefficient for the canopy. Average LAI also was calculated for the four directions.Gap measurements producing gap fractions $1 were noted and recorded during field work.

CI-100 Plant Canopy Analyzer

Figure 1. Original photographic image of mulberry captured by the CI-100.

The CI-100 (CID, Inc., Vancouver, WA) uses a digital camera with a fish-eye (150E) lens positioned at the end of a 0.8 m (2.62-ft) probe to scan plant canopies. Up to 32 measurements can be taken in the field before downloading high resolution images to a PC compatible computer. Use of a laptop computer while taking measurements allows the researcher to see the crown or canopy being measured and adjust the image if necessary. The instrument can be used during sunny, cloudy, or partly cloudy sky conditions.

During image analysis, the CI-100 software first divides the image into a user-defined number of zenith and azimuthal divisions, then analyzes the fraction of sky (solar beam transmission coefficient) visible in each sector by tallying the light (monochrome monitor) or blue colored (color monitor) pixels in that sector. After all sectors have been analyzed, average solar beam transmission coefficients for each zenith division are computed. Estimates of leaf area index, leaf distribution, mean foliage inclination, transmission coefficients for diffuse and radiation penetration, and extinction coefficient are produced. The software, PC compatible only, also allows for later downloading of the images and further image adjustments including the masking of areas on the screen, threshold adjustment, and the selection of individual zenith angle for use in LAI calculations.An image adjustment option is available to verify that the center of the image on the laptop computer screen is also the physical center of the fish-eye lens. No adjustments were necessary during this study. Five zenith and four azimuthal divisions were selected and threshold was placed on automatic. Four images for each crown reduction level (full crown, -10, -20 quadrat samples) were captured for each tree by placing the fisheye lens at the end of the probe on top of the stakes at the base of the tree bole (see Fig. 1). Whole-tree LAI was calculated from the average of the four software-processed images. The software uses an ellipsoidal inversion modification of the Beer-Lambert method for LAI computations:

where n_i is the *i*th solar elevation angle division (*n* is the number of divisions selected), *T* is the transmission coefficient and *K* is the extinction coefficient of the canopy:

where $A = x + 1.774(x + 1.182)G^{0.733}$ and *x* represents leaf angle distribution (Norman and Campbell, 1989).

Image analysis method with AgVision Pseudo-color System

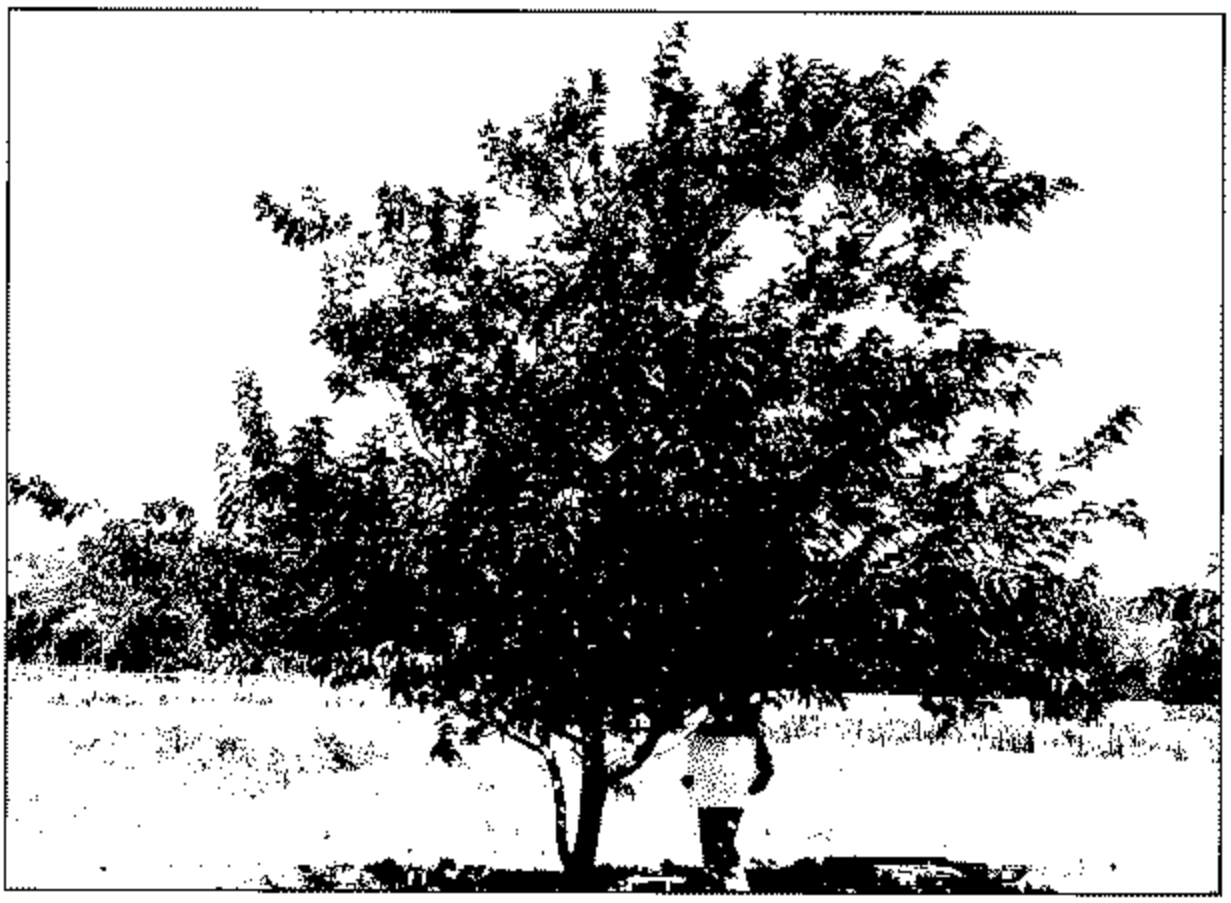

Figure 2. Profile view of mulberry (same tree as in Figure 1) before the original 35-mm photograph was video scanned into the AgVision System.

This method converts a two-dimensional photograph into an estimate of leaf area index using a unitless quantification of tree crown density called silohuette area (SA) as follows:

where PFA is actual photograph's scaled frame area, CPA is the crown projection area of the tree. The SA is the percent of the total viewing field on the monitor that is composed of tree canopy (Lindsey and Bassuk, 1992):

SA= Crown Area/Frame Area

The term SA evolved from an understanding that, in a three-dimensional canopy, certain portions of leaf area remain "unseen" due to leaf overlap, resulting in an underestimation of actual leaf surface area, while inclusion of the stem results in an overestimation. It has been found that when an image processing system is set in area mode, the resulting SA is highly correlated with more conventional methods of

indirectly estimating needle surface area (Lindsey and Bassuk, 1992).

For this study, two perpendicular photographs (90E angles) were taken of each tree in full crown, then again after ten and twenty 0.016m^3 (quadrat leaf samples were removed for a total of six photographs per tree (Fig. 2). A hand held 35-mm Nikon FE with a 55-mm 2.8 lens was used. Shutter speed was adjusted to maintain an f-stop of no less than 8.0 for good depth of field. Kodak Tri-X Pan, 400 ASA black-and-white negative film was selected for its speed and fine grain. A 0.25m^2 (2.69-ft^2) poster board was held next to the bole of each tree as a scale. The three pairs of photographs were taken at the same bearings, but not necessarily the same distances. Film was processed using manufacturer's recommended development and printing techniques, chemicals and paper. Each negative was enlarged so that the crown and bole of the tree filled the largest area possible of a 19.0 x 24.5-cm (7.5 x 9.6-in.)frame. Kodak Polycontrast III Resin Coated paper and a 2.5 polycontrast filter were used. Prints were processed using Kodak Dektol Developer.

The next step was to use the AgVision Pseudo-color System to analyze the images. This system consists of a 386 IBM-AT compatible 40 MHz computer, a CCD video camera, VGA computer monitor, 14-inch color video monitor, camera stand assembly, and software. Photographs of the tree crowns were placed individually in an adjustable print easel on the camera/light stand. The photograph was then viewed via the video camera on the color video monitor. The system processed the image into numerical information with a digitizer and microcomputer and displayed it on the computer monitor for processing.

To calculate LAI, the system was calibrated to the 0.25 m^2 (2.69-ft^2) poster board scale in each photograph. Using paint and erase tools, all non-tree crown components of the image were removed. Once the tree crown was isolated and highlighted, the software calculated total tree crown area (CA). Subsequently, the entire frame (the video screen area) was highlighted and frame area (FA) calculated. The unitless surface area value called silohuette area (SA) was then obtained by dividing the crown area by the frame area.

Conversion of this SA number into estimated leaf area index required five additional steps including 1) scaling from the negative; 2) obtaining frame dimensions from print; 3) scaling from the negative to the print; 4) total leaf area calculation and 5) conversion to leaf area index (Lindsey and Bassuk, 1992). First, the scale of the negative taken with a 55-mm lens was calculated as the representative fraction:

Numerator and denominator were each divided by 5.5 cm to yield the negative scale (1 cm on the negative = *x* cm in reality).

Second, the arms on the print easel holding the photograph on the light stand were adjusted so that the square frame captured all of the tree crown. The photo's frame dimensions were recorded. Third, an object of known size (poster board) on the negative was compared to the poster board on the print to determine an enlargement ratio. Fourth, the frame dimensions were divided by this enlargement ratio and then multiplied by the negative scale in Step 1 to obtain the final adjusted photo frame area (PFA). Estimated leaf surface area for the tree was calculated by multiplying PFA by the mean percent SA. Dividing this product by the crown projection area of the sample tree produced the leaf area index. The average estimated total leaf area obtained from the two photos taken of each tree was used to calculate leaf area index for the eight trees in our sample.

LI-COR LAI-2000 Plant Canopy Analyzer

The LAI-2000 (Licor Inc., Lincoln, NE) sensor head projects a nearly hemispheric view onto five

concentric silicon ring detectors. A dedicated data logger is connected to the optical sensor and it records ring detector readings of above and below canopy light conditions at five zenith angles. Built in software and additional utilities software enable extended analysis of the data files.

The ideal conditions for taking readings with the LAI-2000 call for uniformly overcast skies. An alternative to this is to take measurements at sunset or sunrise to preclude underestimation of LAI (Welles and Norman, 1991). Because our measurements were taken during daylight on sunny days, shading of the lens and a 90E view cap were used to restrict direct sunlight from striking the optical sensor. Four pairs of above and below canopy readings were taken, one pair in each cardinal direction. As with the AccuPAR, above canopy data were taken by walking into an open field adjacent to the study trees. The below readings (again with 90E view cap) were taken 90E apart. The mean of these values was stored in the instrument. Records were maintained noting measurements where sunlight directly struck the probe (resulting in transmittance >1) so that these could be verified when using software to remove records with >1 transmittance. Leaf area index was computed by instrument software using the following formula:

where K_i is the contact frequency, equivalent to the average number of contacts per unit length of travel that a probe would make passing through the canopy at zenith angle *2*, and the values of W_i are computed by breaking the interval 0 to 90E into five uneven intervals based on the center angles assigned to each detector ring. When normalized to sum to 1.0, the values of W_i are 0.034, 0.104, 0.160, 0.218, and 0.494, respectively, for angles 7, 23, 38, 53, and 68E. Subsequently, the instrument's default values for the five distance vectors were adjusted for each tree's canopy. Leaf area index was then computed using Lang's method (1987):

LAI = 2 (S + I)

where S and I are the slope and intercept of the mean contact number (the average number of contacts per unit length of travel that a probe would make passing through the canopy at zenith angle *2*) plotted against zenith angle *2* (in radians).

Lastly, leaf area index was recomputed using the ellipsoidal inversion model discussed previously (Campbell, 1986; Norman and Campbell, 1989). Since the LAI-2000 measures transmittance at five solar zenith angles simultaneously, this model is applicable. All methods used to compute LAI are integrated into the LAI-2000 software program and easily applied to the PAR data collected in the field.

Logarithmic regression equation for leaf area

Nowak (1996) developed a logarithmic regression equation to predict leaf area of open grown deciduous urban trees based on crown parameters. The equation is of the form:

$$\ln Y = b_0 + b_1 H + b_2 D + b_3 S + b_4 C + error$$

where Y is leaf area (m^2), H is crown height (m), D is average crown diameter (m), S is percent light intensity intercepted by foliated tree crowns (average shading factors), C is BD(H+D)/2, based on the outer surface area of the tree crown, and the error is the correction factor discussed below. The regression coefficients and their values are b_0= -4.3309, b_1 = 0.2942, b_2 = 0.7312, b_3 = 5.7217, b_4 = -0.0148. These were derived by Nowak from a study of 54 healthy trees representing five species for application to all open-grown species. A mean square error (MSE) of 0.2317 is also provided. A 0.78

shading factor for mulberry was used (McPherson and others, unpublished data). Because we were unable to find a shading factor for black cherries in the literature, only the mulberry data are compared in this study. To correct for logarithmic bias, a correction factor of $e^{MSE/2}$ (MSE estimated variance of the error from the above regression equation) was added to the untransformed estimates. The estimated leaf areas were divided by tree crown projections to produce leaf area index estimates.

Results and Discussion

For analysis purposes it was assumed that the change in tree foliage area, due to the two harvest of ten quadrat samples each, was negligible. Actual LAI measurements after total destructive harvests confirmed this, revealing a total maximum reduction in LAI of 0.03 for any one tree after harvests were completed (see Table 1). Although Table 1 presents the data ranges from highest to lowest actual and estimated LAIs, all instrument and photographic methods routinely returned estimates after crown reduction that were higher than their full crown estimates. None of the estimation methods were sensitive enough to capture these small levels of crown reduction. Replication of measurements after crown reductions were used for estimating the within tree variability.

TREE	ACTUAL	ACCUPAR	CI-100	IMAGE	LAI-2000	LOGARITHM
Mulberry 01	3.15 - 3.12	2.16 - 1.48	2.92 - 2.65	3.06 - 2.72	4.25 - 2.86	3.32
Mulberry 02	2.26 - 2.25	1.12 - 0.37	3.38 - 3.31	2.65 - 2.14	4.16 - 1.65	3.73
Mulberry 03	3.89 - 3.86	1.30 - 0.92	3.65 - 2.70	2.80 - 2.29	3.51 - 2.05	3.13
Mulberry 04	3.58 - 3.57	1.61 - 0.42	4.07 - 2.66	3.55 - 3.21	2.98 - 2.52	4.08
Mulberry 05	3.24 - 3.22	1.59 - 1.35	3.91 - 3.43	2.72 - 2.53	2.84 - 2.46	3.18
Mulberry 06	2.35 - 2.34	<0.00	n/a	3.35 - 3.00	3.23 - 0.83	2.86
Cherry 01	6.29 - 6.26	1.92 - 0.99	3.30 - 2.37	6.05 - 5.89	7.57 - 4.17	n/a
Cherry 02	4.89 - 4.86	2.48 - 0.49	4.12 - 3.29	7.24 - 6.35	4.61 - 2.73	n/a

Table 1. The range of measurements, from highest to lowest, taken for each tree for actual leaf area index and estimates. Three measurer were taken for each tree at three levels of crown foliation, but decreases in actual leaf area with removal of each ten-quadrat sample of lea were not reflected by the estimation methods; estimates made at reduced crown levels were often higher than full crown estimates. Only tl actual measurements decreased with leaf removal.

The sample for the AccuPAR, Image Processing Method, and LAI-2000 included eight blocks (1 block = 1 tree) anc

repeated measurements (" = 0.05, t_7 = 2.365). The CI-100 sample included seven trees and three repeated measurements (" = 0.05, t_6 = 2.447) and the Regression Equation method included six trees with no repeated measurements (" = 0.05, t_5 = 2.57). Tests initially run on data as they came from each instrument (Table 2) without prior processing showed no significant difference (% = 0.05) between the actual mean leaf area index of 3.69 and tl Image Processing estimated mean LAI of 3.70 (t = 0.017). The tail probability of statistic t was large (P -value = 0.99 t-test results reveal potential for using the Image Processing method to estimate leaf area indices. Plotting these estimates against the actual leaf area (Fig. 3c) initially seems to support this finding. The method appears to be fair precise, as indicated by the small amount of spread between estimated LAI measurements for each tree. For exam the three measurements of mulberry 02, representing the tree in full crown, then after 10 and 20 quadrat sample cr reductions, show an LAI spread of 2.14 to 2.65 compared to an actual spread of 2.25 to 2.26 (Table 1 and Fig. 3c).

The sample for the Logarithmic Regression Equation Method included the six mulberry trees. Paired t-tests run on t actual and regression equation data resulted in no significant difference. The P -value was high (P = 0.36 for % = 0. and estimated mean LAI was 3.38 compared to actual LAI 3.08.

There were significant differences (P-value < 0.01) between actual and estimated leaf area indices for the AccuPAF 100, and LAI-2000 (t = 6.280, 6.599, and 5.722, respectively) revealing that the instruments, with resultant data pro as stated herein, did not adequately estimate leaf area. As a result, we re-processed data from the instruments usir additional methods described below.

AccuPAR

Measurements producing gap fractions $1, the result of early morning and late afternoon low solar zenith angles or missing portions of the tree crown, were removed from the data and LAI recomputed. The t -tests continued to reve significant difference between actual and AccuPAR leaf area indices (3.69 and 1.11, respectively; t = 6.177, P-valu < .01).

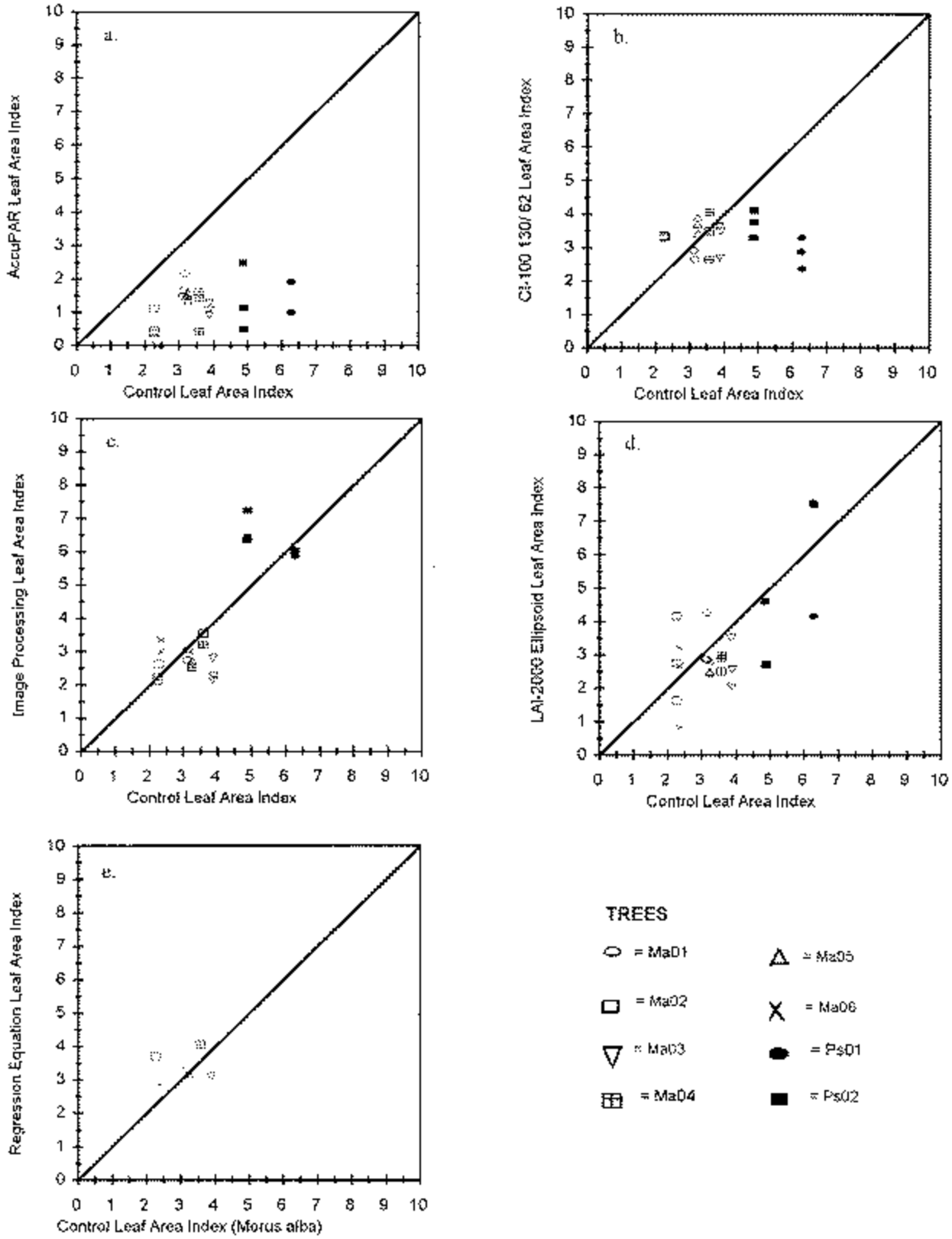
a.
AccuPAR Leaf Area Index
Control Leaf Area Index
b.
CI-100 130/ 62 Leaf Area Index
Control Leaf Area Index
c.
Image Processing Leaf Area Index
Control Leaf Area Index
d.
LAI-2000 Ellipsoid Leaf Area Index
Control Leaf Area Index
e.
Regression Equation Leaf Area Index
Control Leaf Area Index (Morus alba)
TREES
= MaD1
= Ma02
= Ma03
= Ma04
= Ma05
= Ma06
= PsD1
= Ps02

Figure 3. Comparison of estimated leaf area indices with actual leaf area index for five methods including a) AccuP. Ceptometer after removal of measurements resulting in gap fractions $1.0; b) CI-100 processed at 130E view and 6 threshold; c) 35 mm photograph

image processed with AgVision System; d) LAI-2000 processed with ellipsoidal inversion; e) Logarithmic Regressi Equation. The 3 points for each tree represent replications at full crown, -10 and -20 quadrat leaf sample levels. Replication estimates after crown reduction were commonly higher than before reduction. The Logarithmic Regress Equation was applied to mulberries only, with no replications.

CI-100

Initially, LAI was severely underestimated by the instrument. The original program software did not allow viewing of actual fisheye image, only the processed image. Upon examining the latter, it appeared that the automatic threshol feature had stopped working correctly, varying radically when measurements were repeatedly taken at 30-second intervals from the same location. The original image files were imported into a shareware program allowing the viev non-processed camera images. The processed image was then overlaid on the photo image and its threshold adjus match the photo image from the camera. Original thresholds had ranged from 90 to 150 on a scale of 0-255.

The instrument is a new product of CID, Inc., the one we used being the fifteenth the company produced up until Ma 1995. Upon contacting their engineers to discuss the thresholding problem, we were informed that they were develo new software (Yan, personal communication) to adjust for the thresholding problem. A research and development v of this new software was obtained and the original images were loaded and rerun at a zenith angle of 150E and mix threshold levels ranging from 58 to 63 on a new threshold scale of 0-100 (see CI-100 150/mix in Table 2). In this ins thresholds were again adjusted by overlaying the original photo image with the processed image. Next, a mean thre level of 62 was calculated from the software-calculated threshold levels of the 28 images and they were rerun using mean threshold. Lastly, we re-processed the images using mixed and mean thresholds and a zenith angle of 130E, removing the outermost ring since there was little if any foliar matter present at that zenith angle. Processing the im at a mean threshold level, whether at 130 or 150E, appeared to increase the possibility of accurately predicting LAI 2), with the 130E view producing the best results (estimated LAI = 3.30 where actual LAI = 3.89).

Method	Processing	Mean Estimated LAI	Sample Mean Difference ()	SE ()	n	df	t	P value	t Critical " = 0.05 (two-tail)
Actual	100% destructive harvest	3.694 3.887 3.076	n/a n/a n/a	.261* .273 .266	24 21 6	7 6 5			
AccuPAR	None	0.947	2.747	.403	24	7	6.280	<.01	2.365†
	$1								

	Transmissions removed	1.107	2.587	.419	24	7	6.177	<.01	2.36†
CI-100	None	0.354	3.533	.535	21	6	6.599	<.01	2.447†
	130E w/ 62 threshold	3.304	.583	.547	21	6	1.065	.33	2.447
	130E w/ mixed thresholds	2.871	1.016	.486	21	6	2.089	.08	2.447
	150E w/ 62 threshold	3.102	.785	.541	21	6	1.450	.20	2.447
	150E w/ mixed thresholds	2.949	.938	.467	21	6	2.009	.09	2.447
Image Processing	None	3.700	-0.006	.345	24	7	.017	.99	2.365
LAI-2000	None	1.107	2.588	.452	24	7	5.722	<.01	2.365†
	Lang method	3.099	.467	.235	24	7	1.988	.09	2.365
	Ellipsoidal Inversion	3.287	.407	.260	24	7	1.565	.16	2.365
Logarithmic Regression	None	3.383	-0.307	.181	6	5	-1.017	.36	2.015

* Standard error for mean actual † Indicates sample mean significants different from zero.

Table 2. Paired t-tests results for original leaf area index data (no processing) and data processed using the methods listed. Analyses of variance were conducted prior to t-tests for all methods to estimate the standard errors with the exception of Logarithm Regression. Methods produced LAI estimates significantly different from actual LAI at 0.05-level if t > t-critical.

LAI-2000

Data was reprocessed to incorporate the x, y coordinates for individual crowns and to use linearly interpolatec above crown readings. Two processing methods were then used: a) Lang's (1986) method and b) Campbell's (1986) ellipsoidal inversion. Both processing methods improved individual LAI estimates. The t-test results on mean LAI for the two methods were t = 1.988 and 1.565, respectively, with ellipsoidal inversion appearing the better of the two (P-value = 0.09 and 0.16, respectively).

However, the LAI-2000 produced the least precise individual estimates for each tree of all instruments tested, as shown in Figure 3d. An examination of the times at which LAI-2000 measurements were taken does not help to explain the imprecision. For example, two of the measurements of mulberry 02 were taken 14 minutes

apart, producing indices of 2.77 and 4.16 (Fig. 3d). Similarly, two measurements of mulberry 01 taken 2 minutes apart at 11:34 and 11:36 a.m. have LAIs of 2.86 and 4.25, while the third measurement taken 2-1/2 hours later at 1:59 p.m. also produced an LAI of 2.86. Because of this variability and the fact that bad reading (those in which the instrument lens could not be shaded from direct sunlight) were removed before data processing for analysis, it seems unlikely that LAI underestimation is a function of the lens capturing too much light at particular times of the day.

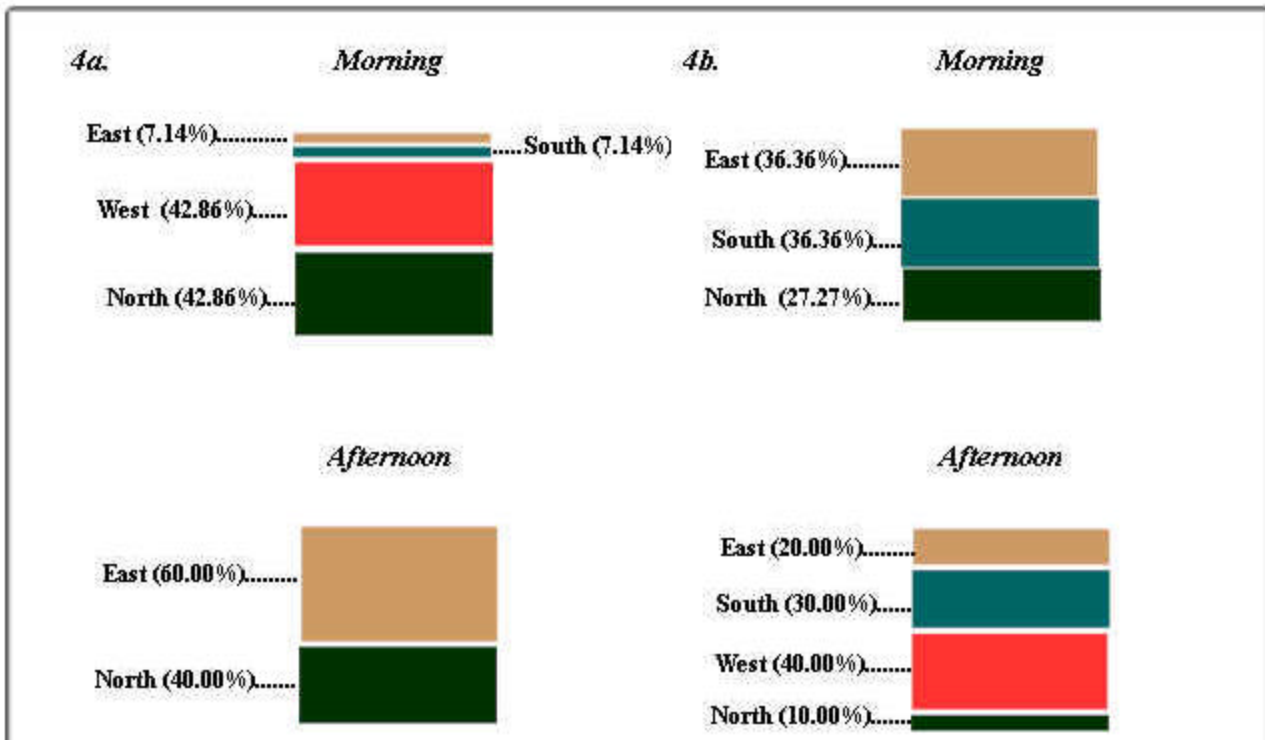

Figure 4. Percent of measurements taken in each cardinal direction for two instruments, a) AccuPAR, b) CI-100, that produced more accurate LAI estimates. Fourteen sets of measurements were made in the morning and ten sets in the afternoon (n = 14 in morning and n = 10 in afternoon).

The Image Processing method appears to have better precision across the range of times when measurements were taken (Fig. 3c). It also initially appears to be less biased than other instruments when data for both tree species are plotted against actual LAI. As actual LAI increases, so does estimated LAI. The LAI-2000 Ellipsoidal Inversion method also shows less bias in comparison to the AccuPAR, (which consistently underestimates LAI at all measurement points) and CI-100 instruments. The consistent underestimation by the AccuPAR (Fig. 3a) may be a function of the distance it was placed from the bottom of the isolated tree crown and the times of day when most measurements were taken. The instrument is designed for the probe to be inserted into tree canopies rather than held beneath a single tree crown. Holding it beneath the crown places it in a position where it is more likely to receive sun beams directly, before they pass through the crown, leading to underestimates of LAI. Field data records support this, revealing that below crown measurements taken with this instrument before 10:00 a.m. (PST) and after 1:00 p.m. registered high transmission coefficients from sunlight directly striking the probe without first passing through the tree crown, resulting in consistent underestimation of LAI. Examining the highest LAI estimates (those closest to actual) produced by the instrument provide further support for this hypothesis (Fig. 4a). Approximately 86 percent (12 of 14) high LAIs measured before 12:00 noon were taken from north and west cardinal directions, where the probe was partially shaded by the tree crown as the sun rose in the east. During the afternoon as the sun set to the west, 100 percent of the high LAI measurements were from beneath the north and east sides of the

crown. Placing the instrument in the canopy may have resulted in more accurate measurements from all cardinal points.

The CI-100 instrument bias (Fig. 3b), although not as great as the AccuPAR shows a trend toward returning a mean LAI of approximately 3.3 (range = 2.37 to 4.12) across the actual LAI range of 2.25 to 6.29 for the eight trees included in the study. Although this instrument takes a hemispherical photograph to estimate LAI, there may be a bias in the software program's conversion of the photograph into the high contrast image from which pixels are counted to determine LAI. The most accurate (approximately 73 percent) estimated by the instrument during morning hours were captured from south and east cardinal measuring points beneath the crown (Fig. 4b). Seventy percent of the most accurate estimates captured in the afternoon were produced from south and west points, suggesting that the instrument may produce better estimates when placed beneath those sides of urban trees nearest the direct beam of the sun, just the opposite of the AccuPAR. It should be stressed again, however, that a larger sample size is needed to determine whether this is true, particularly since the CI-100 registered several accurate measurements at other cardinal points.

Although graphs of the data for Image Processing, LAI-2000 Ellipsoidal and Regression Equation methods display an increase in estimated LAI as actual LAI increases, they also raise a question. Does the estimated LAI actually increase, or is the apparent increase a function of plotting the data for both species? For example when the cherry tree data are eliminated and the mulberry tree data are examined separately, *none* of the methods return mean LAI estimates that increase in proportion to actual indices (Fig. 3). The inclusion of the cherries, with their high actual LAI, may unduly influence the overall results. A larger sample size for each of the two species is necessary to determine whether this is the case.

Of those methods appearing to have the best potential for estimating the LAI of open-grown trees in urban settings, the Image Processing, CI-100, and Regression Equation methods are also easiest to apply in the field. The latter produces the most rapid estimates, but only if shading coefficients are pre-determined for the species being measured. The first two methods provide field technicians with the ability to view the actual tree crown being measured, enabling the operator to adjust camera positioning for the best view of the crown. Since both are essentially photographic methods, they can be used in a variety of sky conditions and do not require above crown measurements like the AccuPAR and LAI-2000. Obtaining those above crown measurements poses a problem in urban settings where the nearest open space may not provide an environment simialr to above-crown light conditions. Similarly, buildings in urban core areas may partially or totally shade tree crowns, eliminating the light necessary for below crown measurements.

Conclusions

None of the methods used as described in this study produced satisfactory or unambiguous measurements of LAI of individual trees. Although t-test results indicate a potential for using the Image Processing method to estimate leaf area index across species of open-grown trees in urban settings, graphs of the data reveal a bias for this and all methods when the two species measured are examined separately. The source of the bias toward returning LAI estimates which do not increase as actual LAI increases, must be determined through additional studies incorporating a larger sample size from a variety of species of different ages and crown architecture. Converting theories on light interception by isolated plants into working software might also allow for the reprocessing of primary data in a way that accounts for discontinuity in canopies.

There are preliminary indications that instrument placement beneath each tree crown could improve LAI estimations since the best AccuPAR estimates came from locations that were partially shaded in the morning (north and west sides) and afternoon (north and east sides), and CI-100 best estimates came from locations that were sunlit (south and east sides in the morning, south and west sides in the afternoon).

As a result of analyses, the CI-100, Image Processing, LAI-2000 and Logarithmic Regression Equation methods will be tested further. Any method used to estimate leaf area index in urban trees must have the flexibility to be used in the wide variety of conditions existing within cities including the presence of homes, buildings, and signs adjacent to the tree, occlusion of direct sunlight by nearby buildings, and traffic and weather-associated winds. Although the LAI-2000 may have limited application within cities, only the AccuPA will be eliminated because of consistent LAI underestimation during all times of day that the instrument was used under clear sky conditions.

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