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URBAN FORESTRY & URBAN GREENING

# Evaluation of four methods for estimating leaf area of isolated trees*

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**Abstract:** The accurate modeling of the physiological and functional processes of urban forests requires information on the leaf area of urban tree species. Several non-destructive, indirect leaf area sampling methods have shown good performance for homogenous canopies. These methods have not been evaluated for use in urban settings where trees are typically isolated and measurement may be complicated by proximity to residential areas, buildings, signs, and other infrastructure elements. We evaluated the accuracy, precision, efficiency and other practical considerations associated with four methods of estimating the leaf area of open-grown deciduous trees in urban forests. The methods included color digital image processing (CD), the LAI-2000 Plant Canopy Analyzer, the CI-100 Digital Plant Canopy Imager, and a logarithmic regression equation. Regression coefficients, adjusted $R^2$, and confidence intervals were used to determine the best method when using true leaf area of 25 *Platanus x acerifolia* Willd. and 25 *Platanus racemosa* Nutt. as an independent variable. Practical considerations included ease of data collection and processing and costs associated with each method. The CD method and LAI-2000 estimates showed good correlation with true leaf area ($R^2 > 0.71$); however, only the CD method produced estimates within 25 percent of mean true leaf area and met additional requirements for accuracy, precision, and efficient use in urban settings.

**Key words:** digital images, digital photography, hemispheric photography, plant canopy analyzer, urban forest

## Introduction

Metropolitan areas have expanded from 8.5 percent to nearly 25 percent of the land area of the contiguous United States over the past 50 years. Nearly one-quarter of the nation's tree canopy cover – approximately 74.4 billion trees – exists within these areas (Dwyer et al. 2000). Interest in determining the role urban forests have in removing air pollutants, mitigating heat island effects, cooling buildings (reducing energy consumption), and sequestering carbon dioxide has increased with the continued urban expansion (Akbari et al. 1992; Simpson 1998). The influence urban forests and individual tree species have on chemical emissions and the formation of greenhouse gasses is also under study (Benjamin & Winer 1998). The ability to measure or estimate leaf area is fundamental to accurately modeling these physiological and functional processes. For



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example, urban biogenic hydrocarbon inventories increasingly use leaf area-to-foliar biomass conversions to derive whole tree and forest foliar biomass estimators (Winer et al. 1998). Leaf area is used to estimate the effect urban trees have on air quality by measuring pollutant interception and emission rates for individual tree species (Nowak 1994). Total leaf area and stem area also influence rainfall storage capacities for different tree species and their effect on reducing storm water runoff (Rutter et al. 1971; Xiao et al. 2000). Furthermore, the economics of urban trees – the benefits and costs associated with their function in the urban landscape – are typically calculated and reported as dollars per square meter of leaf area or canopy cover (Gacka-Grzesikiewicz 1980; McPherson 1992).

As important as leaf area is to defining the function of urban forests, the majority of the research studying destructive and non-destructive leaf area estimation methods relates to rural forest canopies, orchards and agricultural row crops, not to the open-grown trees typical of urban forests. Integrating radiometers, plant canopy analyzers, hemispheric photographs, and ceptometers utilizing the relationship between light transmittance through the crown and various methods of gap fraction analysis represent the majority of the methods tested for agricultural and forest application (Norman & Welles 1983; Lang & Yuequin 1986; Lang 1987; Norman & Campbell 1989; Martens et al. 1993; Nel & Wessman 1993).

In urban settings research has been limited to geometric surface techniques seeking a relationship between leaf area and outer crown area that is based on crown height, width and shape (Gacka-Grzesikiewicz 1980), leaf mass per unit crown volume relationships based on the crown sampling of trees in Riverside, California (Miller & Winer 1984), and image processing techniques requiring the digitalization of black and white photographs of small, containerized tree seedlings and saplings (Lindsey & Bassuk 1992). In conjunction with a study on Chicago's urban forest, Nowak (1996) has also developed an equation to predict leaf area of open-grown deciduous urban trees, based on combined data from Chicago and Warsaw, Poland (Gacka-Grzesikiewicz 1980).

Our pilot study testing a combination of the methods usually applied to forest canopies and individual trees produced inconclusive results. Although the LAI-2000 Plant Canopy Analyzer and an adaptation of Lindsey and Bassuk's image processing method demonstrated the highest probability of accurately estimating LAI (Peper & McPherson 1998), the sample size of eight trees from two species (six *Morus alba* L. and two *Prunus serotina* J.F. Ehrh.) was too small to establish a definitive correlation between estimation methods and true leaf area.

This article reports the results of the second phase of research, using a statistically appropriate larger sample of 50 six-year-old trees, to evaluate which of four methods best estimated the leaf area of open-grown trees in urban settings. The methods included the CI-100 Computer Canopy Analyzer, a new color digital image processing (CD method), the LAI-2000 Plant Canopy Analyzer, and a logarithmic regression equation from the literature (Nowak 1996). Along with evaluating method accuracy and precision, we were interested in assessing each method's general adaptability to use in urban settings. Was there a method that would produce mean estimates for each species efficiently and accurately (within 30% of true leaf area), without necessitating calibration on a species by species basis regardless of the time of day the method was applied? If so, could the method be efficiently used to collect leaf area data during regular urban forest inventories?

## Methods

To begin our evaluation, we measured and conducted a complete destructive harvest of 25 *Platanus x acerifolia* Willd. and 25 *Platanus racemosa* Nutt. at the Solano Urban Forest Research Area. This was a park-like site at Solano Community College near Fairfield in northern California. Field work began in early July and extended through mid-September, 1998. The study trees were six years old at time of harvest with crowns that had been shaped by constant southwestern winds (gusts to 1.34 $m \cdot s^{-1}$ by mid-afternoon daily) so branches and foliage grew predominantly on the north and east sides of the bole. A residential community bordered two sides of the site, providing a photographic background similar to a suburban neighborhood. All measurements were taken during the sunny, cloudless days typical of California summers.

### Instrumentation and measurement

*Color digital image processing method (CD)*

The CD method was adapted to current digital imagery technology from the black and white print method applied by Peper and McPherson (1998). It converts a two-dimensional photograph into an estimate of leaf area using a unitless quantification of tree crown density called silhouette area (SA) as follows:

$$LA = SA \times CFA \quad (1)$$

where CFA is a framed area of the crown in the image scaled to actual size (in reality). The SA is the percentage of the total image on the monitor that is composed of tree canopy:

$$SA = Crown\ Area/Photo\ Frame\ Area \quad (2)$$

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 leaf surface area, while inclusion of the stem results in an overestimation. When an image processing system is set in area mode, the resulting SA is highly correlated with more conventional methods of indirectly estimating leaf surface area (Lindsey & Bassuk 1992).

We used a Kodak DC50 equipped with a zoom lens equivalent to a 37 to 111 mm lens on a 35-mm camera. Two photographic points were established, perpendicular to one another, at 8.5 m from each tree bole to capture the tree crowns most fully in the viewfinder. All measurements were repeated three times for each tree at approximately 9:00 a.m., 12:00 noon, and 2:00 p.m. to mimic the range of times data might be collected during an urban forest inventory. In urban settings, nearby buildings, signs and other objects often shade parts of tree crowns at various times of day, so we made no attempt to isolate trees from nearby objects or backgrounds (e.g., vehicles, people, homes).

Captured images were downloaded and processed on a personal computer using the camera manufacturer's software to isolate the tree crowns. The crowns were rapidly isolated using "magic wand" features to delete non-crown elements and the isolated images were then loaded into SigmaScan Pro Image Measurement Software (ver. 4.01.003) for calibration and measurement. Since all of the images were taken at the same 8.5 m distance, we were able to calibrate SigmaScan using a single image of a 0.25 $m^2$ poster board, placed 8.5 m from the camera. To obtain SA, we loaded each image, used the software's color intensity thresholding feature to impose a color layer on all crown elements, and then calculated the total two-dimensional area of that layer. The Photo Frame Area (PFA) was obtained by setting the threshold feature at its maximum value to color every pixel within the borders of the image, then measuring its area. This PFA was the same for every image because all images were taken at the same 8.5m distance. Only crown area changed due to differences in tree crown size.

Obtaining the CFA required three additional steps including 1) scaling from the "negative", 2) obtaining frame dimensions from the "print", and 3) scaling from the negative to the print. The scale of the negative (all images taken with the telephoto lens set at 37 mm) was calculated as the representative fraction:

$$\frac{CameraFocalLength\ (3.7\ cm)}{Distance\ from\ Camera\ to\ Tree\ (850\ cm)} \qquad (3)$$

Numerator and denominator were each divided by 3.7 cm to yield the negative scale (1 cm on the negative = 229.73 cm in reality).

Second, the entire tree crown was framed using drawing tools. Maximum height and width of the frame were measured in pixels and converted to centimeters (for these images 1 cm = 56.69 pixels) to obtain the dimensions of the crown in the image. The third step in the original Lindsey & Bassuk method required an object of known size (posterboard) on a negative to be compared to the same object on a print to determine an enlargement ratio. Default image size for the Kodak digital camera was 504 × 756 pixels or 8.89 cm × 13.335 cm. Using this default size as the "print" size, one dimension of the posterboard was measured. The "print" was then reduced to 2.413 cm × 3.63 cm, the size of a 35-mm negative, and the same dimension measured again. Dividing the "negative" dimension by the "print" dimension produced the enlargement ratio. To obtain the final adjusted crown frame area, the frame dimensions were divided by the enlargement ratio and then multiplied by the negative scale calculated in Step 1.

### *CI-100 Digital Plant Canopy Imager*

Designed for use in either sunny or cloudy weather, the CI-100 (CID, Inc. Vancouver, WA) consisted of a digital capture unit with a fisheye lens positioned at the end of a 0.8 m probe, canopy analysis software (v. 2.04), and a laptop computer. The manual stated that it produced LAI estimates from a single, below-crown hemispheric image that the built-in software converted into two colors by imposing a grid over it (Fig. 1). Depending on zenith and azimuth grid coordinates, each square of the grid had a pre-assigned weighting factor to account for the hemispheric projection. The software counted the pixels in each square of the grid, applied the weighting factor, then calculated gaps versus no gaps. The threshold function in the software increased or decreased the range of pixels selected on the grayscale. For example, increasing the threshold would result in the selection of a wider range of grays to be included in the analysis. The gap-fraction inversion procedure (Norman & Campbell 1989) converted these counts into an LAI estimate.

After extensive side-by-side comparison of images like those shown in Fig. 1, we determined that a threshold level of 50 (mid-point) provided the most descriptive two-color interpretation of the original JPEG images.

### *LAI-2000 Plant Canopy Analyzer*

The LAI-2000 (LI-COR, Inc., Lincoln, NE) sensor head projects a 148° nearly hemispheric view onto five concentric silicon ring detectors. A dedicated data logger is connected to the optical sensor to record ring detector readings of above- and below-canopy light conditions at five zenith angles. Measurements made above and below the canopy are used to determine canopy light interception at 5 angles, from which LAI is computed using a radiative transfer model. Built-in software and additional utilities software enable extended analysis of the data files.

As with the CI-100, we used Norman and Campbell's (1989) ellipsoidal inversion model to calculate LAI and entered six pair of x,y coordinates that describe the outline of the tree crown and provide path lengths for each zenith angle required to determine leaf area density (Miller 1967). Leaf area density (LAD) is related to LAI by canopy height ($z$)

$$LAI = LADz \tag{4}$$

and the path lengths are related to the zenith angle by

$$S(\theta) = z/\cos(\theta) \tag{5}$$

with the solution for LAD.

$$LAD = -2\int_0^{\pi/2} \frac{\ln T(\theta)}{S(\theta)} \sin \theta d\theta \tag{6}$$

Therefore, LAI may be calculated as

$$LAI = -2\int_0^{\pi/2} \ln T(\theta) \sin \theta \cos\theta d\theta. \tag{7}$$

Lang (1987) suggested a linear relationship between $\theta$ and contact number ($K(\theta)$) defined as $-\cos \theta \ln[T(\theta)]$. Thus, Eq. (6) can be simplified to

$$LAD = 2(A + B) \tag{8}$$

where A and B are the intercept and slope of the linear equation relating $K(\theta)$ and $\theta$. Since path lengths cannot be calculated in non-homogenous canopies using Eq. (5), direct measurements of path lengths were required for each zenith angle to determine LAD using Eq. (6).

The ideal conditions for taking readings with the LAI-2000 call for uniformly overcast skies, a rare event during California summers. As a result, we followed the manufacturer's recommended use of view caps to restrict direct sunlight from striking the optical sensor. We used a 90° view cap when taking the two pairs of above- and below-canopy readings, one pair each at north and east cardinal direction. The above-canopy data were taken in an open field west of the study trees.

For LAI-2000 and CI-100 measurements from identical locations, two tripods were placed beneath two sides of the tree crown, halfway between the bole and drip line. The distance between probe and tree crown base was adjusted to approximately 30 cm (as recommended in the LICOR LAI-2000 manual). Due to the wind effects, there was no foliage to place intruments beneath on the south and west sides of the tree boles. Initial readings at these locations resulted in estimates of zero leaf area; thus, measurements were limited to the north and east sides of the trees where the majority of foliage grew. For each instrument, averaged north and east LAI estimates were multiplied by crown projection measurements ($0.78539d^2$ where d = average tree crown diameter) to obtain the estimate of whole tree leaf area.

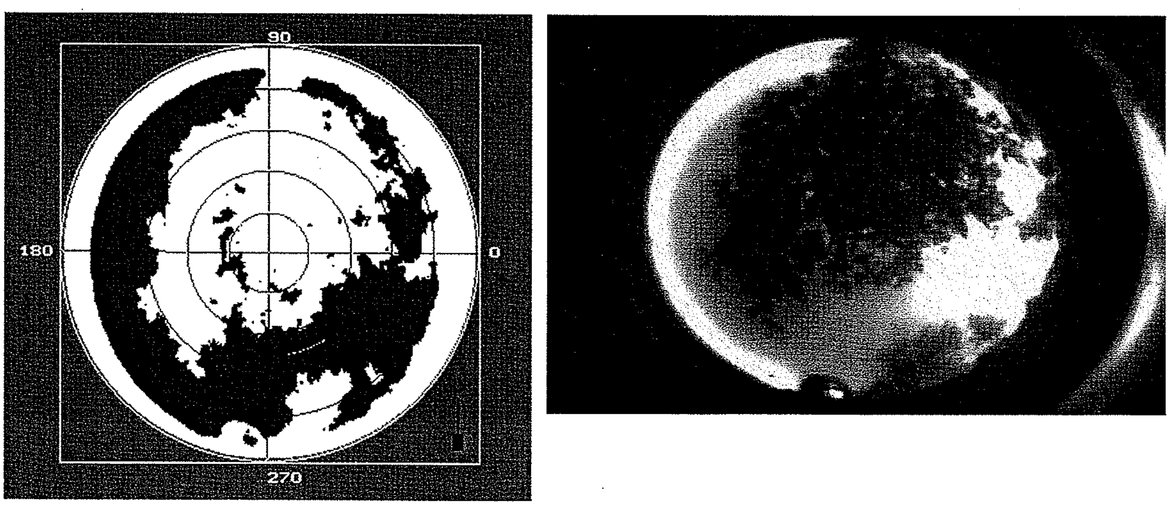


**Fig. 1.** Tree crown JPEG image captured by the CI-100 (right) and software-translated version at mid-point threshold (left). Note the surrounding trees and head of instrument operator along outer edge of photo. After thresholding, nearly the entire outer ring appears to have been translated into leaf area by the instrument (white area).

*Logarithmic regression equation for leaf area*

The following regression equation to predict leaf area of open-grown deciduous urban trees based on crown parameters was used:

$$\ln Y = -4.3309 + 0.2942H + 0.7312D + 5.7217S + -0.0148C + error \quad (9)$$

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 $\pi D(H+D)/2$, based on the outer surface area of the tree crown. The back-transformed estimated response, $\hat{Y}$, is multiplied by $e^{MSE/2}$ to correct for the bias due to the logarithmic transformation. The correction factor is added to the untransformed estimates (Nowak 1996). We measured the crown dimensions for each tree and applied shading factors of 0.89 and 0.91 for *P. acerifolia* and *P. racemosa*, respectively (McPherson 1984).

*General data collection and analysis*

Tree height, trunk caliper (measured 15 and 30 cm above ground per American Nursery and Landscape Association Standards), crown height and maximum crown diameter (*mcd*) in two perpendicular directions were measured for each sample tree. After taking measurements and digital images, all leaves were removed, bagged, and taken to the lab where we ran them through a LI-3100 Leaf Area Meter to determine total true leaf surface area for each tree.

Linear regression analysis (SAS 1988 mixed model procedures) was used to determine which method worked best to estimate leaf area when true leaf area was used as an independent variable. The regression model was:

$$Y_{ij} = a_i + b_i X_j + Tree_j + error_{ij} \quad (10)$$

where $Y$ = estimated leaf area by a method, $X$ = true leaf area, Tree = error term due to tree effect, i = method number, and j = number of trees.

## Results and Discussion

*Sample trees*

For the sample of 50 trees, trunk caliper ranged from 2.8 cm to 11.1 cm with total tree height and crown width ranging from 3.25 m to 7.2 m and 1.75 m to 5.3 m, respectively. Actual *P. acerifolia* leaf area ranged from 4.72 to 74.38 m$^2$ (mean = 20.94 ± 1.64) and from 5.23 to 33.26 m$^2$ (mean = 16.08 ± 0.88) for *P. racemosa*. The wider range for *P. acerifolia* was due to a single, unusually large specimen (compared to the other 6 year old trees). Without that tree, the maximum true leaf area was 34.53 m$^2$, similar to the *P. racemosa*.

Generally, the tree crowns in this study violated the assumption of random disbursement of canopy elements (e.g., leaves, fruits) required by the CI-100 and LAI-2000 instruments. Not only were leaves clumped within tree crowns, but an individual tree crown essentially represented a clump@ in an otherwise clear sky. Our attempts to compensate for the violation of canopy assumptions were unsuccessful. Despite the use of a 90° view cap (LAI-2000) or a solar disk (CI-100) to block sunlight from directly striking the hemispheric lenses. The subsequent underestimation of leaf area suggested that diffuse radiation or sunlit foliage influenced the readings. Taking measurements close to the crown base apparently did not compensate for the large gap of blue sky surrounding the individual tree crowns captured by the CI-100 (Fig. 1) or the LAI-2000.

*Method precision and accuracy*

The descriptive statistics for the sample trees and the four methods are presented in Table 1. Regression intercepts, slopes, confidence intervals and adjusted $R^2$ values for the four methods are presented with the plotted estimates for each method in Figs. 2 and 3. A 1:1 reference line is presented in each graph to allow comparison with the regression response line.

*Color digital image processing method (CD)*

The CD method slopes were closer to one for *P. acerifolia* (0.91) and *P. racemosa* (0.96) than for all other methods (Figs. 2 and 3). *P. acerifolia* estimates produced from images captured during morning hours were slightly higher than noon and afternoon estimates (Fig. 4); noon-captured *P. racemosa* estimates, however, were higher than morning or afternoon. All mean estimates, regardless of time of day images were taken,

**Table 1.** Descriptive statistics of leaf area for the true measurements and the four methods (n = 75 for all, except Log. Equation, n = 25)

| | Mean | SE | Min. | Max. |
|---|---|---|---|---|
| *P. acerifolia:* | | | | |
| True LA | 20.94 | 1.64 | 4.72 | 74.38 |
| CD | 18.00 | 1.64 | 2.30 | 65.29 |
| CI-100 | 6.65 | 0.69 | 0.92 | 27.10 |
| LAI-2000 | 4.70 | 0.46 | 0.67 | 23.38 |
| Log. Eqtn. | 24.44 | 1.01 | 7.39 | 29.38 |
| *P. racemosa:* | | | | |
| True LA | 16.08 | 0.88 | 5.23 | 33.26 |
| CD | 12.02 | 0.98 | 0.95 | 29.50 |
| CI-100 | 8.35 | 0.65 | 0.66 | 25.08 |
| LAI-2000 | 4.90 | 0.33 | 0.35 | 10.31 |
| Log. Eqtn. | 22.20 | 1.48 | 7.54 | 31.48 |

were within 16 and 23 percent of true *P. acerifolia* and *P. racemosa* leaf area, respectively.

### *CI-100 Digital Plant Canopy Imager*

Mean sample estimates were 32 and 52 percent of true *P. acerifolia* and *P. racemosa* leaf area, respectively. Estimates were inaccurate (slopes = 0.25 and 0.42) and imprecise ($R^2$ = 0.34 and 0.32). Morning measurements produced estimates that were 36 and 26 percent higher than noon and afternoon estimates for *P. acerifolia* and *P. racemosa* (Fig. 4). A re-examination of the JPEG files did not provide an explanation for this inconsistency. Although measurements captured on the north side of trees tended to be higher than those taken on the east, leaf area was underestimated for 145 of 150 total measurements taken.

Attempts to improve the accuracy of CI-100 estimates by eliminating azimuth divisions and zenith angles from measurements or adjusting threshold levels were unsuccessful. The ability to block out segments from inclusion in LAI calculation was limited to removal of zenith angles or contiguous azimuthal wedges@. In many images, vegetation, people, and cars adjacent to the sample tree were visible in the outermost ring of the captured JPEGs and the software appeared to interpret all objects,

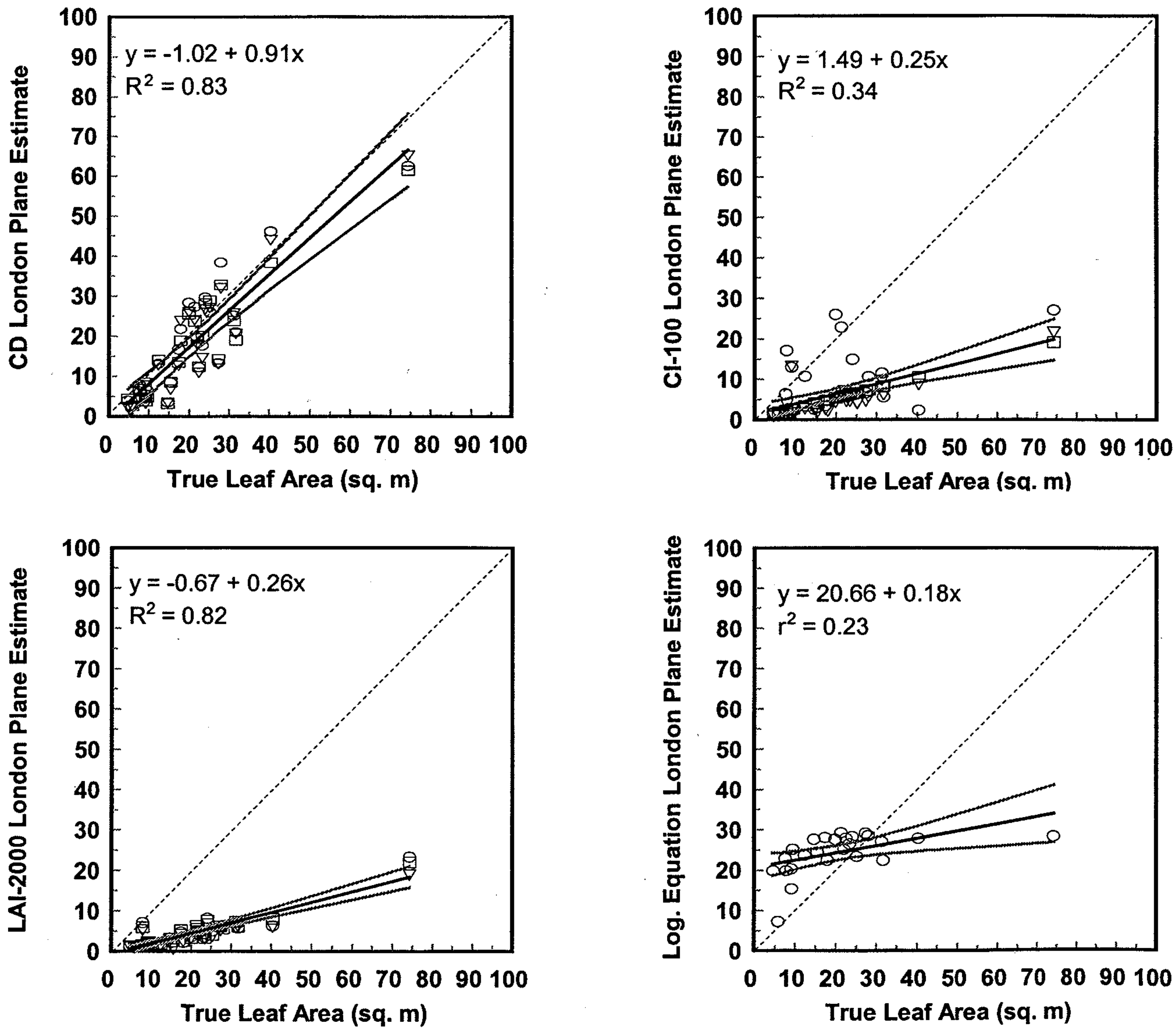


**Fig. 2.** Leaf area estimates (m²) and regressions with confidence intervals (∝ = 0.95) for *P. acerifolia* for the four methods; ○ = Morning, □ = Noon, ▽ = Afternoon.

including much of the sky, as leaf area (see Fig. 1). Removal of the outer ring actually increased estimated leaf area. Removing all but the two center zenith rings increased slopes for *P. acerifolia* to 0.50 and *P. racemosa* to 0.56, but reduced correlation ($R^2 = 0.33$ and 0.14 for *P. acerifolia* and *P. racemosa*) and nearly doubled the MSE (from 4.85 and 4.66 to 9.8 and 9.2 for *P. acerifolia* and *P. racemosa*, respectively).

*LAI-2000 Plant Canopy Analyzer*

The LAI-2000 also underestimated leaf area (*P. acerifolia* slope = 0.26 and *P. racemosa* slope = 0.32) but did so with precision and consistency ($R^2 = 0.82$ and 0.71 for *P. acerifolia* and *P. racemosa*, respectively). Mean leaf area estimates for *P. acerifolia* and *P. racemosa* were less than one-third of mean true leaf area (4.70 $m^2$ and 4.90 $m^2$, respectively). Morning and noon estimates were slightly higher than afternoon. Using the LAI-2000, Villalobos et al. (1995) were able to obtain accurate estimates of isolated olive tree LAD and found that reducing the number of rings caused a reduction in the intercept and an increase in the slope, suggesting that reducing the number of rings would lead to underestimation of leaf area for small trees and overestimation for larger trees. We found the opposite

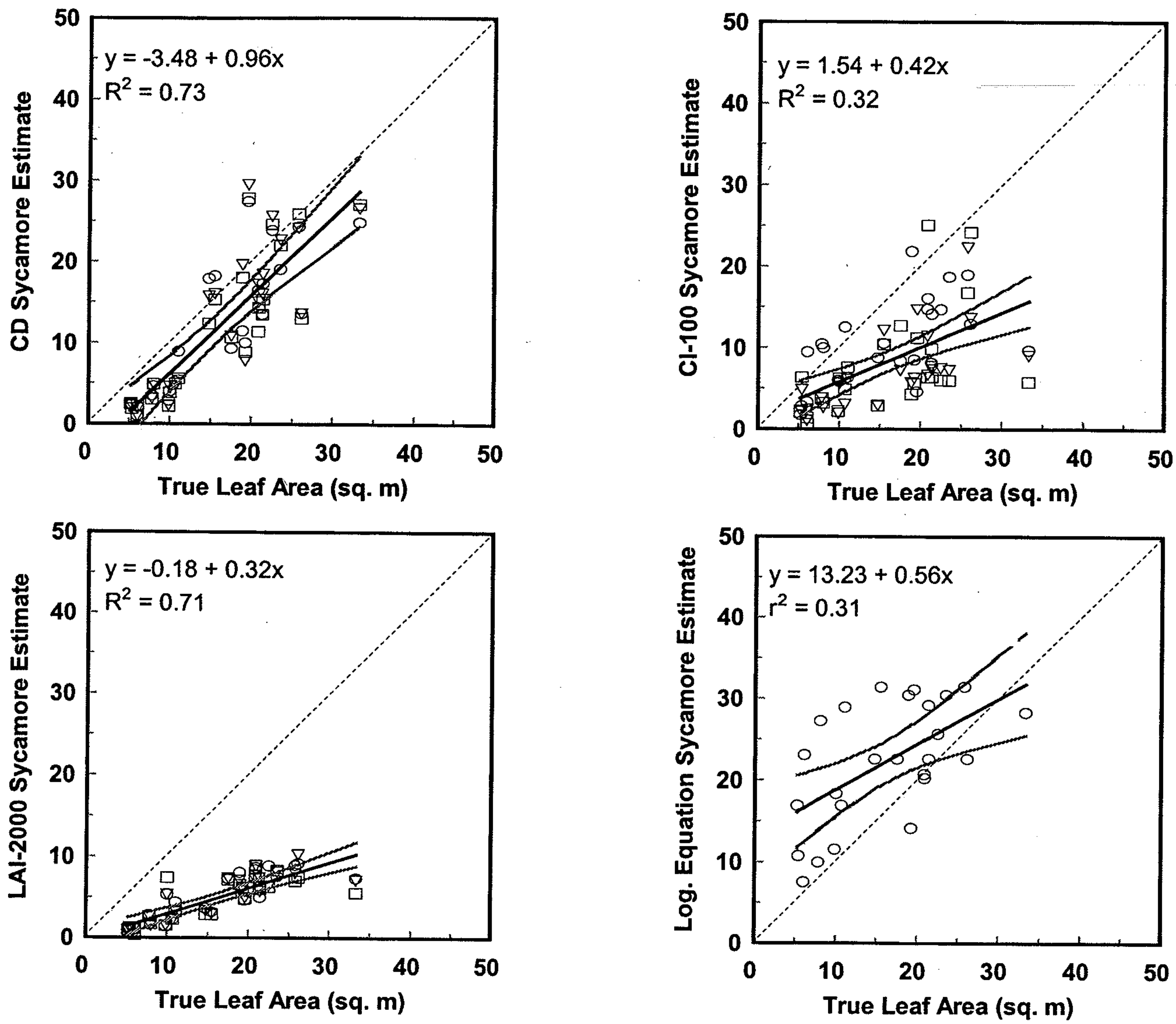


**Fig. 3.** Leaf area estimates ($m^2$) and regressions with confidence intervals ($\propto = 0.95$) for *P. racemosa* for the four methods; ○ = Morning, □ = Noon, ▽ = Afternoon.

to be true. Isolating measurements to only the center ring reduced the number of sunlit gaps being measured and increased mean estimates. Slopes increased to 1.11 and 1.09 and intercepts decreased to –0.63 and –5.75 and slopes increased (1.11 and 1.09) for *P. racemosa* and *P. acerifolia*, respectively. However, as with the CI-100, the change was accomplished at the cost of estimate precision; the standard error of the estimate (SEE) more than tripled to 6.63 and 6.52 for *P. racemosa* and *P. acerifolia.*

*Logarithmic regression equation for leaf area*

The logarithmic regression model was the only method that generally overestimated leaf area. Twenty of twenty-five estimates for each species were greater than true leaf area. Intercepts were 20.66 for *P. acerifolia* and 13.23 for *P. racemosa* with slopes of 0.18 and 0.56, respectively. Low correlation indicated that little relationship existed between true leaf area and estimates for either species. For example, estimates for *P. acerifolia* remained between 20 to 30 $m^2$ although true leaf area ranged from 4.72 to 74.38 $m^2$.

The shading coefficients we used (McPherson 1984) were from older trees, probably having fewer crown gaps than the young trees in this study. Incorrect shading coefficients may have contributed to inaccurate estimations, but the equation itself is logarithmic, not linear, and based on a total of 17 tree species (88 trees), none of which were *Platanus* species.

*Practical considerations*

Equipment costs, method adaptability to uses other than leaf area calculation, and whether the methods are easily and efficiently applied are issues that may be as important to potential users as method accuracy and precision. Table 2 presents a synopsis of these and other practical considerations we assessed.

*CD method*

Digital photographs were a simple and efficient method for capturing leaf area data in the field, requiring the ability to point and shoot a camera. Taking two photos of each tree took less than one minute, usually from 15 to 30 seconds per image. The digital format of the CD method eliminated the photo processing requirements and costs associated with the original black and white photo print method described by Peper & McPherson (1998). The crown isolation process was also simplified; pixels were removed through the selection and removal of contiguous and non-contiguous color ranges, not by the more subjective paint and erase process.

Since collecting field data only requires the ability to "point and shoot" a camera, this method could be applied easily during regular urban forest inventories to collect leaf area data.

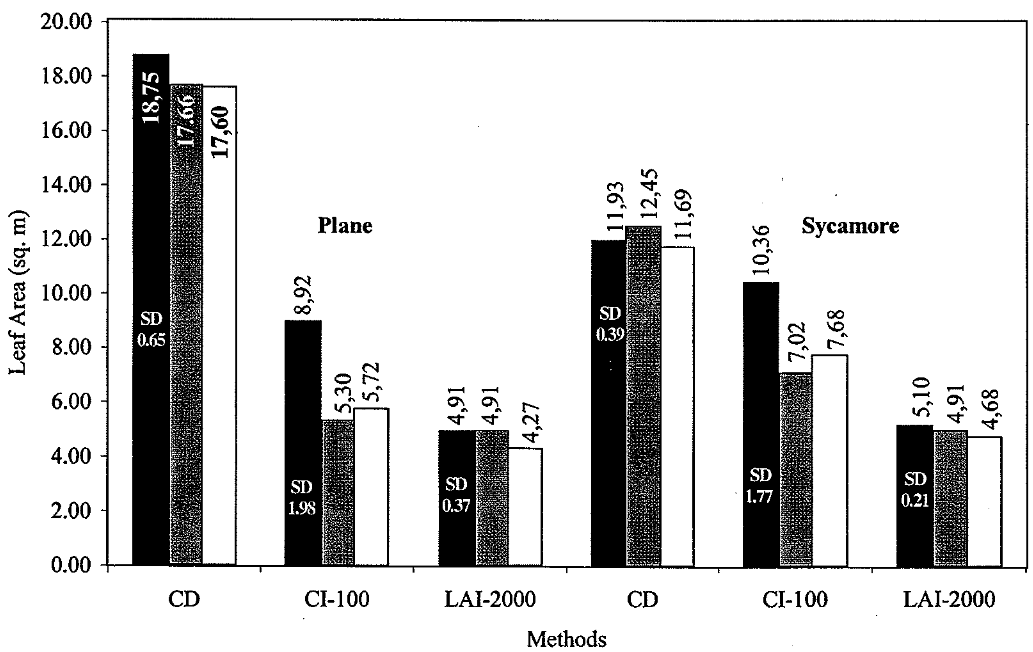


**Fig. 4.** Morning, noon and afternoon mean leaf area estimates for *P. acerifolia* and *P. racemosa* trees showing the standard deviation (SD) for each set of three measurements. True leaf area for *P. acerifolia* and *P. racemosa* was 20.94 and 16.08, respectively ■ = a.m., ▒ = noon, □ = p.m.

**Table 2.** Practical considerations for the five methods used to estimate leaf area

| | Color Digital | CI-100 | LAI-2000 | Log. Regression |
|---|---|---|---|---|
| *Instrument* | | | | |
| Cost (approx.) | $ 900 – camera<br>$ 1100 image software with measurement features | $ 6000 including laptop computer<br>($ 4650 without computer) | $ 5020 | $ 0 |
| Other uses | Camera and software have multiple applications | Gap fraction | Gap fraction | None |
| *Field Sampling* | | | | |
| Sky conditions required | Clear or cloudy | Cloudy/diffuse sky, sun at or below horizon | Cloudy/diffuse sky, sun at or below horizon. | N/A |
| Setup | Measure distance from trunk bole to camera | Beneath crown setup and leveling required, computer viewing and adjustment, lens shading | Above, beneath crown setup and leveling required, instrument calibration, x,y coordinates, lens shading | None |
| Reference readings | Photo scale | None | Above crown readings | Shading coefficients, crown height and diameter |
| Ease of use | Easy - Point and shoot camera | Moderate - training necessary, solar flare protection | Moderate-training necessary for users | Easy - if shading coefficients are available |
| Time required | <1 minute | ~5 minutes | ~20 minutes | ~5 minutes* |
| *Data Processing* | | | | |
| Obtaining LA | Downloading, crown isolation, image measurement, spreadsheet calculated LA | Downloading, image to threshold image adjustment, software calculated LAI | Downloading, user calculates using supplied software and entering x,y pairs | Calculation |
| Time | 5–7 minutes | 3 minutes | 3 minutes | < 1 minute |

* if shading coefficient is available in literature and does not need to be measured for each tree

### *LAI-2000*

The average 15 minutes per tree required to measure x,y coordinate pairs describing the shape of the crown and the necessity for above-crown and below-crown measurements made the LAI-2000 the least efficient method to apply, a problem that might be resolved by using scaled photographs, rather than field measurements, to measure the coordinate pairs. More difficult to resolve is the method's requirement for above-crown measurements. In many cases this would necessitate the additional expense and time of using a boom truck or other equipment. Nearby buildings, signs and other objects may also influence with below-crown measurements.

### *CI-100*

When we were researching instruments to use in this study, the key feature that differentiated the CI-100 from the LAI-2000 was the ability to see the hemispheric image of a tree's crown before capturing it. Although our laptop computer met the manufacturer's minimum system requirements, we were unable to open or preview the images before we captured them. Also, the CI-100's nickel-cadmium batteries were quickly drained by downloading images to the computer. This necessitated image capture without preview and we lost the purported preview advantage.

Manufacturer modifications to the instrument since the pilot study included a lens change from 150° to nearly 180°. Unlike the previous model, the newer, wider-angled lens was prone to solar flare. For our field measurements we made a "solar disk", a 15 cm diameter cardboard circle attached to a piece of flexible copper tubing, to shade the lens and reduce the glare that otherwise rendered images unusable. Held beneath the tree crown, the disk was seldom discernable from the leaves in the images (see Fig. 1).

In the lab, the CI-100 software did not allow viewing of the original grayscale images (.jpg files); we had to use another image processing software to open and print hard copies to compare with the processed two-color image (Fig. 1). Basing threshold adjustment and azimuthal division elimination on comparison of two images reduced efficiency and introduced a level of subjectivity that would be eliminated by modifying the software to allow the user to directly impose color threshold, azimuth and zenith changes to an original image.

### *Logarithmic regression equation*

The logarithmic regression method had the potential to be the most efficient method, requiring less than six minutes to produce a leaf area estimate when shading coefficients are readily available. Unfortunately, shading coefficients are not available for the majority of urban tree species and the time required to obtain them negatively influences the cost and efficiency of the method.

## Conclusions

Because the CI-100 and LAI-2000 instruments shared basic assumptions and analytical theory we expected to find they produced similar estimates. This was clearly not the case. Both significantly underestimated leaf area but in very different manners. The LAI-2000 estimates were highly correlated with true leaf area; furthermore, the narrow confidence interval of the regression suggested a potential for calibrating the method to individual species. Conversely, the CI-100 estimates were inconsistent and poorly correlated. Since detailed information about the CI-100's engineering is not available, it is difficult to assess the source of problem; the fisheye lens' susceptibility to solar flare may have contributed or there may be an inaccurate weighting of the hemispheric grid imposed on the images. Regardless of the source, the lack of consistent behavior is troubling.

The Logarithmic Regression Equation estimates appear to have little correlation to true leaf area. Differences in *P. acerifolia* and *P. racemosa* growth patterns or rates compared to any of the 17 species used to develop the equation may account for the lack of correlation. Since Warsaw and Chicago climates are significantly cooler, with fewer growing days, than climates in California's coastal valleys, differences in growth rates are likely.

Of all the methods evaluated, the CD method produced the most accurate and precise responses. Method estimates were more highly correlated to true leaf area for *P. acerifolia* ($R^2 = 0.83$) than all other methods, indicating better precision compared to the others. Correlation was also high ($R^2 = 0.73$) for the *P. racemosa*. Mean leaf area estimates within 25 percent of true leaf area were within the acceptable 30 percent level of accuracy for urban forest research applications. The method was the most efficient to use, requiring the least amount of time for data collection in the field. Because of the ease of collecting the field data, there is potential for photographic data to be collected during regular inventories of urban trees. At $ 2,000 for camera and software, the investment required is relatively small compared to the other methods, plus users can use the digital camera and software for additional purposes. Continuing evaluation of the CD method should assess its transferability to digital cameras having different formats and resolutions. Digital camera design and features have changed extensively since the start of this study. Medium-priced cameras now offer the option of shooting at a range of resolutions and in color or black and white.

Lindsey & Bassuk's 1992 study provided the prototype for the development of the CD method. Their study focused on containerized seedlings and saplings with mean leaf area for all five species never exceeding 47 $cm^2$ compared to the exponentially larger true leaf area of 20.9$m^2$ in this study. The high correlation between photographic image-derived estimates and true leaf area in both studies suggests that image processing methods may be applicable to a broad range of tree sizes and species. Further study is necessary to determine this and to evaluate transferability to conifers, palms and other tree species having a variety of leaf shapes and attachment angles.

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