603 912

For submission to HortScience revised 8/2/02

Indirect Field Measurement of Wine-Grape Vineyard Canopy Leaf Area Index

Lee F. Johnson[1]
California State University, Monterey Bay, 100 Campus Center, Seaside, CA 93955
NASA Ames Research Center, MS242-4, Moffett Field, CA 94035

Lars L. Pierce[2]
Institute for Earth Systems Science and Policy
California State University, Monterey Bay, 100 Campus Center, Seaside, CA 93955

Additional index words: LAI, vineyard, remote sensing, plant canopy analyzer

Abstract. **Leaf area index (LAI) indirect measurements were made at 12 study plots in California's Napa Valley commercial wine-grape vineyards with a LI-COR LI-2000 Plant Canopy Analyzer (PCA). The plots encompassed different trellis systems, biological varieties, and planting densities. LAI ranged from 0.5-2.25 m^2 leaf area m^{-2} ground area according to direct (defoliation) measurements. Indirect LAI reported by the PCA was significantly related to direct LAI (r^2=0.78, p<.001). However, the PCA tended to underestimate direct LAI by about a factor of two. Narrowing the instrument's conical field of view from 148° to 56° served to increase readings by approximately 30%. The PCA offers a convenient way to discern relative differences in vineyard canopy density. Calibration by direct measurement (defoliation) is recommended in cases where absolute LAI is desired. Calibration equations provided herein may be inverted to retrieve actual vineyard LAI from PCA readings.**

A number of key viticultural factors are related to the amount of leaf area. For instance, vineyard leaf area affects fruit ripening rate (Winkler, 1958), disease incidence (English et al., 1989), water status (Smart and Coombe, 1983), and fruit composition and wine quality (Smart, 1985; Jackson and Lombard, 1993; Petrie et al., 2000). Direct measurement of leaf area index (LAI) (m^2 leaf area m^{-2} ground area) can be performed by physically removing leaves from the vine and measuring their cumulative area with an area meter. While accurate, this approach is destructive and labor intensive. Leaf area

---

[1] Senior Research Scientist, Adjunct Faculty Member. E-mail: ljohnson@mail.arc.nasa.gov
[2] Associate Professor.

can be assessed on the basis of pruning weights (mass of prior season woody production) taken during the dormant season. These data give a retrospective view of relative vineyard canopy density among sample locations during the prior growing season, and are useful for making viticultural management decisions to be implemented during the dormant period and ensuing growing season. Optical instruments such as LI-COR's LI-2000 Plant Canopy Analyzer (PCA) offer a means to take relatively quick, *non-destructive, within-season* measurements of canopy density at point locations.

Remote sensing offers a means to greatly increase sampling density with respect to that achievable by ground-based methods alone. Use of airborne imagery has been used to map *relative* differences in canopy density within individual vineyard fields (Wildman et al., 1983; Johnson et al., 1996, 2001; Hall et al., 2002). Commercial wine-grape growers in California's North Coast viticultural region (Napa, Sonoma, Lake, and Mendocino Counties) are using imagery for various purposes such as harvest preparation, vineyard re-development, and identification of problems related to irrigation, nutrient status, disease and pest infestation (Penn, 1999; Carothers, 2000; Aho, 2002). More recently, multispectral satellite imagery has been used to map LAI and leaf area per vine in *absolute* terms (Johnson et al., 2002). For greatest accuracy, such maps require collection of supporting, ground-based LAI data.

This study served to evaluate use of the PCA for LAI estimation in commercial wine-grape vineyards of California's mild-climate North Coast. The PCA is designed for use in a variety of agricultural and natural vegetation canopies, ranging from short grasses to forests. Relatively few PCA studies have been reported for vineyards. In these vineyard studies, LAI differences were evoked at localized sites by irrigation amount (Grantz and Williams, 1993), phenological progression and pruning (Sommer and Lang, 1994; Patakas and Noitsakis, 1999). The current study tested the ability of the PCA to measure diverse plots where LAI variability was driven by such factors as planting density, trellis system and biological variety.

Methods

Study sites. Study areas were the Tokalon and Huchica commercial vineyard properties of the Robert Mondavi Winery (Oakville, CA). The ~500 ha Tokalon vineyard is located in California's Napa Valley at approximately 38°25'N/122°25'W, growing mainly red grape varieties on sandy clay loam soils. Huchica vineyard is located 22 km S-SE of Tokalon in the cooler Carneros region (approx. 38°14'N/122°22'W). Huchica grows red and white grape varieties on clay soils with variable topography. Both properties are subdivided into many fields that can differ from one another in planting density, trellis structure, vine biological variety and age. At both study sites, full canopy expansion (maximum LAI) is attained by late July and generally persists through harvest, which typically occurs in mid- to late September.

Indirect LAI measurement. The PCA was used to indirectly (non-destructively) measure vineyard LAI. This instrument calculates LAI from radiation measurements made with a "fish-eye" optical sensor as fully described in LI-COR, Inc. (1992). Briefly, the instrument has a 148°conical total field-of-view. Incoming energy is measured by five concentric detector rings associated with the following incidence angles: 0-13°, 16-28°, 32-43°, 47-58°, and 61-74°. Upward-looking measurements are made above and below canopy to determine the interception of photosynthetically active radiation. LAI is then derived from light interception by a radiative transfer model of vegetative canopies.

Twelve study plots were established: six each in Tokalon and Huchica (Table 1). Each plot was located within a separate vineyard field. The plots were trained onto the three main trellis types employed in the North Coast (vertical, split and sprawl) and thus represented a variety of canopy architectures. Vertical systems have an "I" cross section and essentially render vertical "walls" of leaves, split systems have a "Y" cross-section and sprawl systems involve minimal training. Differences in planting density, vine biological variety and age were also represented. Plot centers were situated at least 15 m from the nearest field edge, in order to minimize contamination by light scattered laterally into the sensor field of view from outside the canopy.

A procedure was followed for measurement of heterogeneous row-crop canopy, as described in LI-COR (1992). First, a measurement of ambient light was made with the sensor extended upward at arm's length. Four canopy readings were then made along a diagonal transect between rows. The first reading was taken on the row centerline. The next three readings were taken 1/4, 1/2 and 3/4 of the distance to the adjoining row centerline. Each measurement was offset in the along-row direction by approximately one meter. This procedure was repeated on a total of four adjoining rows (Fig. 1). Mean plot LAI and associated standard error was computed and reported by the PCA, based then on a total of 16 canopy and four associated ambient readings.

All canopy measurements were made with the instrument positioned near the ground and at approximately the same vertical distance with respect to the drip line. A field of view delimiter (45° open, facing away from operator) was used throughout. The view direction associated with each transect alternated between along-row and across-row. Care was taken to minimize inclusion of massive, distant objects (such as trees or mountains) in the field of view. A built-in bubble indicator was used to level the instrument prior to each observation. All measurements were made under diffuse light conditions, either with the sun just below the horizon or obscured by fog. This sampling approach required approximately five minutes per plot to complete. Measurements were made at Huchica on 20-Sept-01, and at Tokalon on 27-Sept-01. At this time of year, vineyard LAI was still near the annual maximum.

Direct LAI measurement. Direct (destructive) measurements of leaf area were made immediately upon completion of the indirect measurements (*i.e.*, 20-Sept-01 at Huchica and 27-Sept-01 at Tokalon). Three vines were selected per plot: the plot center vine and vines immediately abreast of the center vine in rows adjoining to either side. Leaves were removed at the petiole from a known and recorded proportion of each sample vine. All leaves were removed from vines at two plots (#1, #7), due to their relatively small size. For the split canopy site (#10), all leaves were removed from one of the four main cordons, for a total of 25% of the vine. At the other plots, all leaves were removed from either the right or left side of vine, for a total of 50% per vine.

All excised leaves per sample vine were immediately weighed. A random subsample was extracted per vine, placed in a sealed bag, weighed and stored in a refrigerator. Within 24 hr, subsample area was measured on an electronic area meter (Model LI-3000, LI-COR, Inc.). Total area per sample vine was calculated as

$$LA_v = W_t * SLA * P^{-1},$$

where LA_v is leaf area (m^2) per sample vine, W_t is total weight (g) of all leaves removed from vine, SLA is specific leaf area ($m^2\ g^{-1}$) of the subsample and P is proportion of all leaves (0.25, 0.50, or 1.0) removed from the vine. Sample vine LAI was then LA_v/(vine_spacing* row_spacing). Plot mean LAI and associated standard error were then derived from the LAI of the three replicate sample vines.

Results and Discussion

Mean plot LAI ranged from 0.5-2.25 by direct measurement. Indirect LAI understated direct measurements by about a factor of two, ranging from 0.26-1.24. (Table 2, Fig. 2). This underestimation, particularly when across-row observations are made as here, was previously noted (Grantz and Williams, 1993; Sommer and Lang, 1994; Patakas and Noitsakis, 1999) and has been attributed to failure of the vineyard canopy, due to row structure and trellising, to fully conform to PCA radiative transfer model assumptions. Specifically, non-random leaf distribution can cause an overestimation of gap fraction, and underestimation of LAI. Distance from the 1:1 line (expressed as RMS error) was 0.61 for the combined dataset, 0.50 for Tokalon only and 0.70 for Huchica only. These results suggest that underestimation is greater in vertically trained canopies, possibly as a result of more pervasive foliage clumping.

Direct and indirect LAI measurements were significantly related at both study areas (Table 3). At Huchica, with all vines planted on vertically shoot positioned trellis with similar planting density, r^2 of 0.90 was observed. Goodness of fit was lower among the more diverse Tokalon plots ($r^2 = 0.74$). Combined r^2 was 0.78 for both vineyards, with the best-fit linear relationship $LAI_{indirect} = 0.58*LAI_{direct}-0.02$.

By excluding data from PCA sensor rings 3-5 (those measuring at greater incidence angles), Grantz and Williams (1993) retrieved indirect readings in good agreement with direct LAI. That approach was tested here as well. The six Huchica plots were post-processed with the MASK function of the LI-COR 2000-90 support software. This correction did increase $LAI_{indirect}$, however by only about 30% (Table 2), and also resulted in a decline in RMS error from 0.70 to 0.51. These improvements were accompanied by decreased goodness-of-fit, with r^2 declining from 0.90 to 0.81 (Table 3).

Conclusions

The LI-COR LI-2000 Plant Canopy Analyzer was used to measure LAI at 12 diverse study plots established in commercial wine-grape vineyards. A significant linear relationship (r^2=0.78) was observed between PCA readings and direct LAI among plots. A stronger relationship (r^2=0.90) was observed among plots of identical trellis and similar planting density.

Mean LAI readings from the PCA, however, tended to underestimate directly measured means by about a factor of two, with greatest underestimation occurring in vertically trained canopies. This error was somewhat relieved by performing a post-processing step to effectively narrow the sensor's field of view. This correction served to decrease RMS error, but overall results were less satisfactory than those reported earlier (Grantz and Williams, 1993).

The PCA is effective for discriminating relative differences in vineyard canopy density. If retrieval of absolute LAI is desired, PCA readings should be calibrated with direct measurements. Such an exercise was performed in this study and the resulting equations are presented. Provided that canopies of interest are reasonably represented by the study plots examined here, and the same PCA data acquisition method is followed, the equations of this report may be inverted to convert PCA readings to actual LAI at least to first approximation.

Leaf area information provides decision support for various vineyard management aspects such as irrigation, pruning, hedging, cover crop cultivation, application of soil and crop amendments, and planning for vineyard redevelopment. Toward this end, PCA data can be valuable when used in standalone fashion, and also may facilitate conversion of remotely sensed imagery into essentially continuous maps of leaf area.

Acknowledgments

The study was sponsored by NASA's Office of Earth Science, through grants NAG13-99020 to LJ and NAG5-6529 to LP. Cooperation of the Robert Mondavi Vineyards (Oakville, CA), particularly vineyard manager Daniel Bosch, is gratefully acknowledged. Use of trade names is for informational use only.

Literature Cited

Aho, J.E. 2002. NASA providing new perspectives on vineyard management. Vineyard and Winery Management, March/April.

Carothers, J. 2000. Imagery technology meets vineyard management. Practical Winery and Vineyard, May/June.

English, J.T., C.S. Thomas, J.J. Marois, W.D. Gubler. 1989. Microclimates of grapevine canopies associated with leaf removal and control of Botrytis bunch rot. Phytopathology 79:395-401.

Grantz, D.A. and L.E. Williams. 1993. An empirical protocol for indirect measurement of leaf area index in Grape. HortScience 28:777-779.

Hall, A., D.W. Lamb, B. Holzapfel, J. Louis. 2002. Optical remote sensing applications in viticulture – a review. Australian Journal of Grape and Wine Research 8:36-47.

Jackson, D.I., and P.B. Lombard. 1993. Environmental and management practices affecting grape composition and wine quality: A review. American Journal of Enology and Viticulture 44:409-430.

Johnson, L.F., D.E. Roczen, S.K. Youkhana, R.R. Nemani, and D.F. Bosch. 2002. Mapping vineyard leaf area with multispectral satellite imagery. Computers and Electronics in Agriculture (accepted).

Johnson, L.F., D.F. Bosch, D.C. Williams, and B.M. Lobitz. 2001. Remote sensing of vineyard management zones: implications for wine quality. Applied Engineering in Agriculture 17:557-560.

Johnson, L.F., B.M. Lobitz, R.A. Armstrong, R.W. Baldy, E.A. Weber, J.A. DeBenedictis, and D.F. Bosch. 1996. Airborne imaging aids vineyard canopy evaluation. California Agriculture 50(4):14-18.

LI-COR, Inc., 1992. LAI-2000 plant canopy analyzer operating manual. LI-COR, Inc., Lincoln, NE.

Patakas, A., B. Noitsakis 1999. An indirect method of estimating leaf area index in cordon trained spur pruned grapevines. Scientia Horticulturae 80:299-305.

Penn, C. 1999. Grape growers gravitating toward space age technologies. Wine Business Monthly 6(2), 53-56.

Petrie, R.P., M.C.T. Trought, G.S. Howell. 2000. Fruit composition and ripening of Pinot Noir (*Vitis vinifera L.*) in relation to leaf area. Australian Journal of Grape and

Wine Research 6:40-45.

Smart, R.E. 1985. Principles of grapevine canopy microclimate manipulation with implications for yield and quality. American Journal of Enology and Viticulture 36:230-239.

Smart, R.E., and B.G. Coombe. 1983. Water relations of grapevines. In Water Deficits and Plant Growth, T. Kozlowski, Ed., Academic Press, New York, 2:137-196.

Sommer, K.J., A.R.G. Lang. 1994. Comparative analysis of two indirect methods of measuring leaf area index as applied to minimal and spur pruned grape vines. Australian Journal of Plant Physiology 21:197-206.

Wildman, W., R. Nagaoka, L. Lider. 1983. Monitoring spread of grape phylloxera by color infrared aerial photography and ground investigation. American Journal of Enology and Viticulture 34:83-94.

Winkler, A.J. 1958. The relation of leaf area and climate to vine performance and grape quality. American Journal of Enology and Viticulture 9:10-23.

Table 1. Study plot description.

Plot	Trellis	Variety	Age (yr)	Vine Space (m)	Row Space (m)
Huchica:					
1	V	PN	11	1.5	2.4
2	V	Ch	6	1.2	1.2
3	V	Ch	11	1.5	2.1
4	V	Ch	11	1.5	2.4
5	V	Ch	10	1.5	2.4
6	V	PN	11	1.5	2.4
Tokalon:					
7	S	CS	28	1.8	3.7
8	S	CF	11	1.5	2.7
9	S	CF	21	2.4	3.7
10	Y	CS	10	1.8	3.0
11	V	CS	10	3.0	1.8
12	S	SB	2	1.5	1.8

Trellis type: V = vertical, S = sprawl, Y = split. Variety: PN = Pinot Noir, Ch = Chardonnay, CS = Cabernet Sauvignon, CF = Cabernet Franc, SB = Sauvignon Blanc.

Table 2. Mean leaf area index for study plots. Direct LAI by vine defoliation. Indirect LAI by PCA sensor. Indirect LAI results shown for unmasked (148° conical field of view) and masked (56° conical field of view) instrument configuration. Final column compares masked and unmasked readings.

Plot	LAI direct	LAI indirect, unmasked	LAI indirect, masked	Difference, masked vs. unmasked
1	0.66	0.31	0.38	+22.6%
2	2.25	1.24	1.41	+13.7%
3	1.66	0.93	1.26	+35.5%
4	1.50	0.66	0.82	+24.2%
5	1.26	0.82	1.11	+35.4%
6	1.11	0.48	0.77	+60.4%
7	0.50	0.26		
8	0.95	0.81		
9	0.96	0.52		
10	1.72	1.12		
11	1.59	1.05		
12	1.26	0.48		

Table 3. Summary statistics for relationship between direct and indirect LAI. Instrument conical field of view (FOV) as indicated. Regression results of the form $LAI_{indirect}=b*LAI_{direct}+a$. Superscripts indicate significant difference from zero. Sample size (n), RMS error and r^2 also shown.

Site	FOV	*b*	*a*	r^2	RMS	n
Combined	148°	$0.58^{.001}$	-0.02^{ns}	0.78	0.61	12
Huchica	148°	$0.58^{.01}$	-0.08^{ns}	0.90	0.70	6
Tokalon	148°	$0.65^{.05}$	-0.05^{ns}	0.74	0.50	6
Huchica, masked	56°	$0.63^{.05}$	0.08^{ns}	0.81	0.51	6

FIGURE CAPTIONS

Fig. 1. PCA sampling strategy, redrawn from heterogeneous canopy guidelines of LI-COR (1992). Large white arrows represent above-canopy measurement of ambient light. Smaller black arrows represent below-canopy observations. In all cases, a physical cap was used to restrict the view to 45°, pointed away from the operator, looking alternately along-row and cross-row.

Fig. 2. Unmasked, indirect LAI (m^2 leaf area m^{-2} ground area), measured by the LI-COR Plant Canopy Analyzer, vs. direct measurement by defoliation. Mean and standard error for 12 study plots.

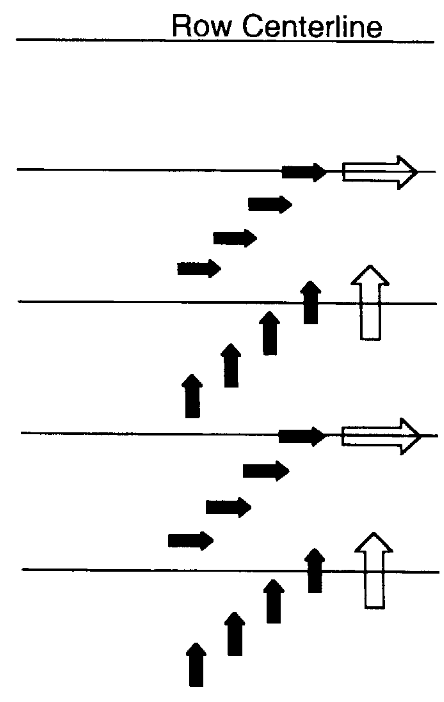
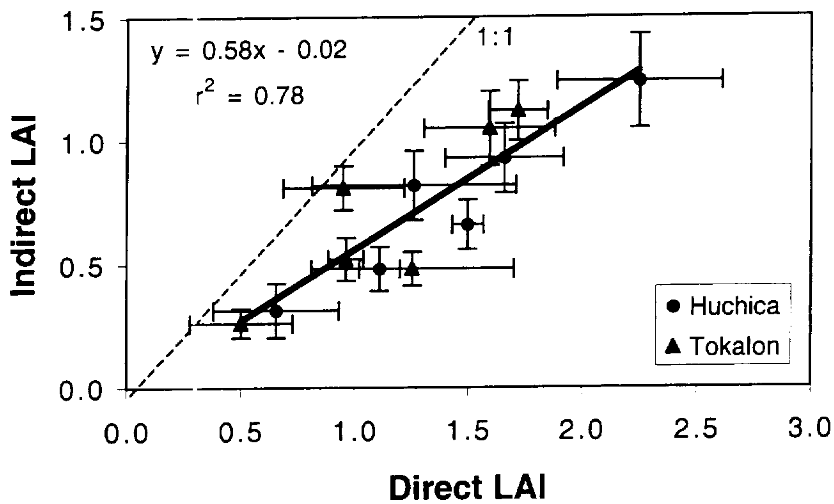

Row Centerline

Fig 2



y = 0.58x - 0.02
r^2 = 0.78
1:1
Huchica
Tokalon
Indirect LAI
Direct LAI
0.0
0.5
1.0
1.5
2.0
2.5
3.0