Literature Cited

1. Ballinger, W. E., E. P. Maness, and L. J. Kushman. 1970. Anthocyanins in ripe fruit of the highbush blueberry. *J. Amer. Soc. Hort. Sci.* 95:283-285.
2. ———, ———, G. J. Galletta, and L. J. Kushman. 1972. Anthocyanins of ripe fruit of a "pink-fruited" hybrid of highbush blueberries. *J. Amer. Soc. Hort. Sci.* 97:381-384.
3. Camp, W. H. 1945. The North American blueberries with notes on other groups of *Vacciniaceae. Brittonia* 5:203-275.
4. Francis, F. J., J. B. Harborne, and W. G. Barker. 1966. Anthocyanins in the lowbush blueberry, *Vaccinium angustifolium. J. Food Sci.* 31:583-587.
5. Fuleki, T. and F. J. Francis. 1967. The co-occurrence of monoglucosides and monogalactosides of cyanidin and peonidin in the Ameri- 1708.
6. Galletta, G. J. 1975. Blueberries and Cranberries. p. 154-196. *In* J. Janick and J. N. Moore (eds), Advances in fruit breeding, Purdue Univ. Press, West Lafayette, Ind.
7. Harborne, J. B. 1967. *Comparative Biochemistry of the Flavonoids.* Academic Press, New York.
8. Timberlake, C. F. and P. Bridle. 1975. The anthocyanins. Chap. 5 of *The Flavonoids*, ed. by J. B. Harborne, T. J. Mabry, and H. Mabry. Academic Press, New York.
9. Troyan, A. V. and I. F. Borukh. 1968. Biologically active substances of wild-growing berries of the Carpathians. *Tr. Vses. Semin. Biol. Aktiv.* (Lech.). *Veshchestvam Plodov. Yagod.*, 3rd. [*Chem. Abstr.* 73, 119394; 1968.]

*J. Amer. Soc. Hort. Sci.* 104(4):557–560. 1979.

# Penetration of Photosynthetically Active Radiation as a Measurement of Canopy Density of Citrus Trees[1]

Otto L. Jahn[2]
*Agricultural Research, Science and Education Administration, U.S. Department of Agriculture, Orlando, FL 32803*

*Additional index words.* defoliation, leaf area, *Citrus* spp.

*Abstract.* **Citrus trees were defoliated to obtain measurements of radiation penetration at various canopy densities. Tree size measurements were used to calculate the leaf-area index (LAI) and leaf-area to canopy-area ratio (LAC) of trees. Penetration of photosynthetically active radiation (PAR) increased curvilinearly as defoliation increased and LAC decreased. Observed relationships between PAR penetration and LAC were used to estimate LAC values from PAR penetration measurements. Correlations between PAR penetration and LAC were slightly higher than with LAI. LAI and LAC appeared to vary independently from tree size as measured by tree diameter or leaf area.**

Heinicke (3, 4) showed that light penetration in apple trees was nonlinear, with a change in leaf density affecting light penetration more at low than at high leaf densities. More recently, measurements of light penetration have been used to estimate the LAI of apple trees (1). In citrus a dense canopy develops at the outer periphery of the tree, resulting in little penetration of light beyond the first 1 m of canopy depth (2). The density of this canopy is indicated by counts of 24,446 leaves on a 6-year-old tree and 142,728 on a 15-year-old orange tree. These trees had estimated leaf areas of 74 and 296 $m^2$, respectively (Selhime, personal communication). Turrell (9) obtained leaf counts of 16, 37, 93, and 173 thousand on 3-, 6-, 12- and 29-year-old orange trees, respectively. Leaf areas were reported as 34, 59, 146 and 203 $m^2$. Formulas were developed for estimating leaf area from tree age and trunk diam.

In preharvest degreening studies with ethephon, defoliation losses of more than 10% may occur (10). Recent work showed that most of these losses were of older, inside leaves (5). Although losses of over 20% were found, no consistent effect on PAR penetration was shown and there was no reduction in yield the following year. These observations prompted further studies on methods of measuring canopy density and its relation to PAR penetration with the objective of developing a rapid method of estimating leaf density. Objective

## Materials and Methods

Trees were selected for uniformity of canopy density and for a range in size. A total of 16 trees of 7 cultivars were studied in 1975, 1976, and 1977. Repeated ethephon applications were used to defoliate selected trees. Fallen leaves were collected, air-dried, and weighed at frequent observation dates. Separate samples were counted, measured with an area meter, and dried. Calculated leaf area or number per gram dry weight from these samples was then used to estimate the number and area of leaves for each tree and date of collection. For dry weight determinations, leaves were oven-dried at 70°C. In 1976 and 1977, estimates of defoliation were obtained by counting leaves on 8 to 20 twigs per tree at each observation date.

Radiation penetration measurements were taken on each tree initially and at each leaf collection date. Photosynthetically active radiation (PAR) was measured as $\mu E\ m^{-2} s^{-1}$ on a meter with a quantum sensor (400-700 nm sensitivity). The sensor was held 25 cm above and aimed at the center of a 0.4-$m^2$ reflectance board painted white. In use, the board was placed horizontally at preselected points on the ground around the tree trunk. In 1975, 4 positions per tree were used. In 1976, additional measurements were made on the north side of 3 of the preselected points. In 1977, an additional 4 points were added about 1 m inside the edge of the canopy. Measurements of direct sunlight and unshaded reflected PAR were also recorded.

Light measurement time varied from tree to tree, but measurements for each tree were made at the same time for all observation dates. All trees were measured within an hour of 12 noon. No attempt was made to adjust for the changing sun angle occurring over the 4- to 6-week duration of a test.

[1]Received for publication November 3, 1978.
The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper must therefore be hereby marked *advertisement* solely to indicate this fact.
[2]Research Horticulturist.

Measurements were aver... to provide a single PAR penetration ... For each date ... observation of canopy density on a tree. Data from a few points with unusually high PAR values caused by gaps in the canopy were not used in the calculations.

Tree size measurements included canopy height (tree height minus average height to bottom of canopy) and in-row and cross-row diameter. Canopy surface areas for each tree were then calculated. The ground area (GA) was based on the average diameter. The prolate spheroidal area (PA) (9) was determined as one-half the area calculated by using twice the canopy height for the long axis and the average diameter for the short axis in formulas for fruit surfaces (8). The ratios of total leaf area (LA) to these areas were then calculated as leaf area index (LAI) = LA/GA or as leaf area to canopy area ratio (LAC) = LA/PA.

In 1977, 14 additional trees were used to estimate LAC from PAR penetration measurements. Tree size and initial PAR penetration measurements were made as in the defoliation studies. The canopies were then collected to compare with the calculated leaf density.

## Results

*PAR penetration and defoliation.* Increases in PAR penetration were relatively small at low levels of defoliation (Fig. 1). Penetration increased rapidly above 40 to 50% defoliation. Tree 3, which showed a more direct relationship between PAR penetration and defoliation, was a small tree with a relatively thin canopy. Even with 100% defoliation on this tree, PAR penetration was only about 50% of available radiation because of shading from branches in the trunk area. Plotting the PAR measurements of Fig. 1 on the log scale (not shown) gave a straight-line relationship above about 40% defoliation on the 3 largest trees.

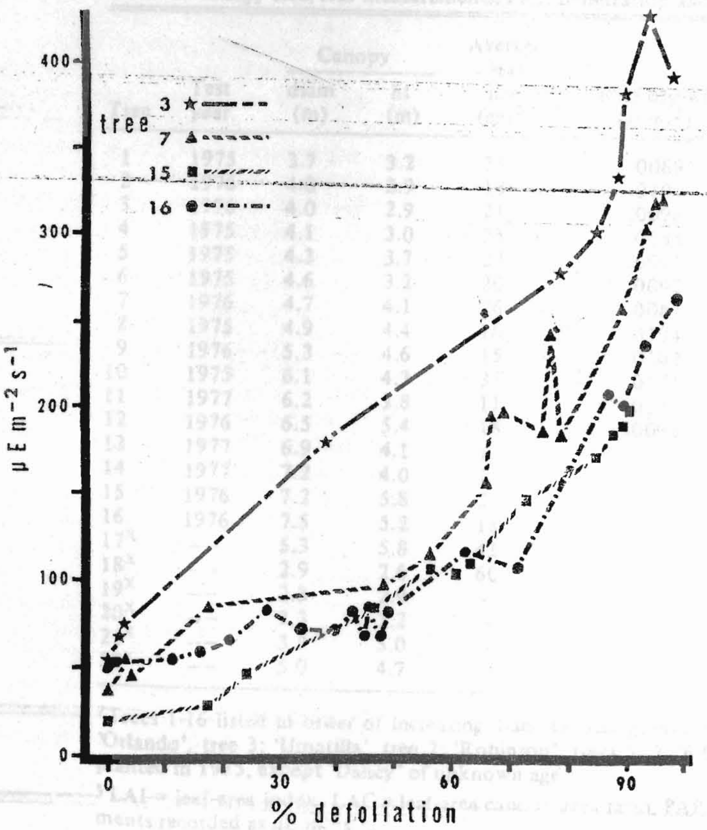


Fig. 1. Relationship of percentage defoliation to photosynthetically active radiation (PAR) penetration $\mu E\ m^{-2}s^{-1}$ in citrus trees.

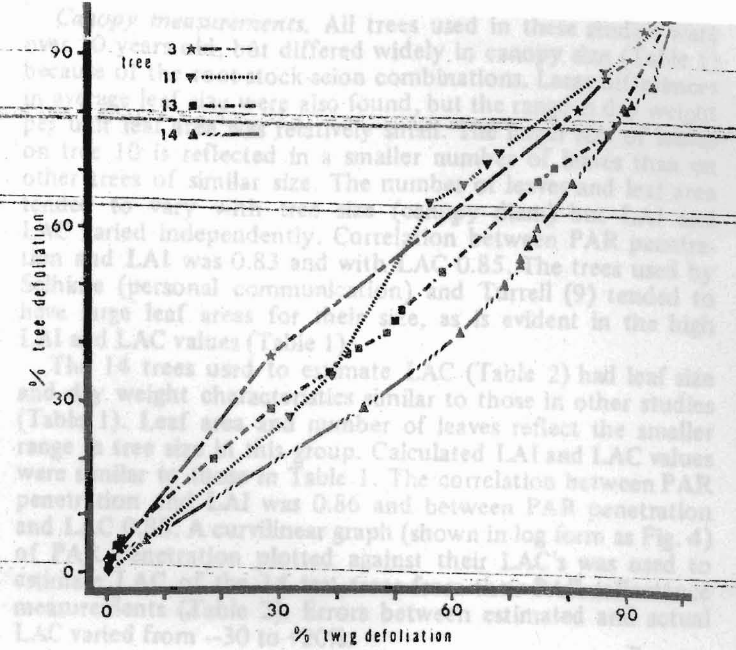


Fig. 2. Relation between defoliation on tagged twigs and defoliation of the entire citrus tree.

Leaf counts on tagged twigs gave useful estimates of defoliation (Fig. 2), although they tended to overestimate defoliation, especially in the range of 40 to 70% defoliation. Twig counts underestimated defoliation of the 2 smallest trees. Counts of 8 twigs (trees 3 and 11) gave as good an estimate of defoliation as counts of 20 twigs/tree (trees 13 and 14).

Graphs of PAR penetration against LAI showed a curvilinear relationship resembling that for percentage defoliation in Fig. 1 but with less difference between trees. Plotting PAR on a log scale showed a linear relationship (Fig. 3) as has been reported

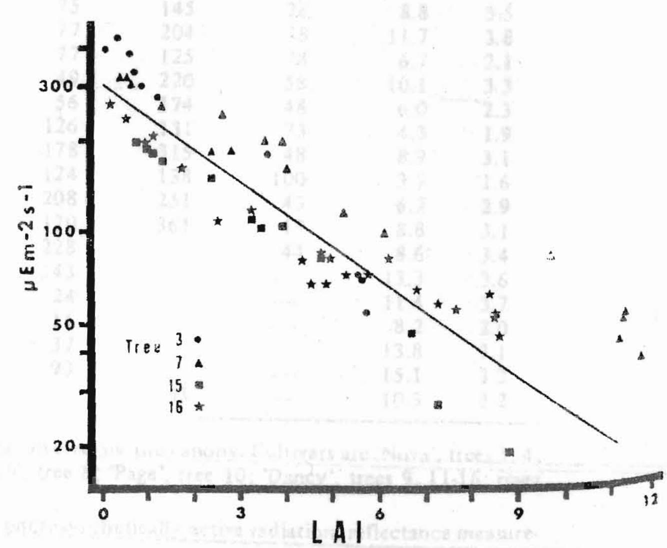


Fig. 3. Relationship of leaf-area index (LAI) to photosynthetically active radiation (PAR) penetration, $\mu E\ m^{-2}s^{-1}$ in citrus trees.

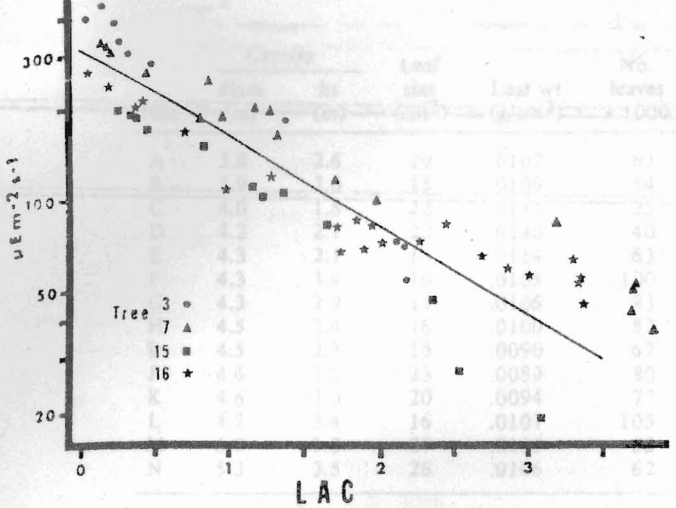


Fig. 4. Relationship of leaf-area to canopy-area ratio (LAC) to photosynthetically active radiation (PAR) penetration, $\mu E\ m^{-2}s^{-1}$ in citrus trees.

for some herbaceous plants (7). Penetration of PAR also showed a linear relationship with LAC when plotted on a log scale (Fig. 4). The large trees (No. 15 and 16) had less PAR penetration at low leaf density than the smaller trees due to greater branch shading in the measurement area. Inconsistencies in PAR

*Canopy measurements.* All trees used in these studies were over 10 years old, but differed widely in canopy size (Table 1) because of the root-stock-scion combinations. Large differences in average leaf size were also found, but the range in dry weight per unit leaf area was relatively small. The larger size of leaves on tree 10 is reflected in a smaller number of leaves than on other trees of similar size. The number of leaves and leaf area tended to vary with tree size (canopy diam) but LAI and LAC varied independently. Correlation between PAR penetration and LAI was 0.83 and with LAC 0.85. The trees used by Selhime (personal communication) and Turrell (9) tended to have large leaf areas for their size, as is evident in the high LAI and LAC values (Table 1).

The 14 trees used to estimate LAC (Table 2) had leaf size and dry weight characteristics similar to those in other studies (Table 1). Leaf area and number of leaves reflect the smaller range in tree size in this group. Calculated LAI and LAC values were similar to those in Table 1. The correlation between PAR penetration and LAI was 0.86 and between PAR penetration and LAC 0.88. A curvilinear graph (shown in log form as Fig. 4) of PAR penetration plotted against their LAC's was used to estimate LAC of the 14 test trees from their PAR reflectance measurements (Table 2). Errors between estimated and actual LAC varied from −30 to +20%.

## Discussion

In these studies, defoliation had less effect on PAR penetration in a dense canopy (under 50% defoliation, Fig. 1) than the same amount of defoliation in a more open canopy. This pattern was also noted by Heinicke (3, 4) in apple, and presumably is due to greater shading within the canopy at higher

Table 1. Canopy size, leaf measurements, PAR penetration and leaf density measurements of citrus trees.[z]

| Tree | Test year | Canopy diam (m) | Canopy ht (m) | Average leaf size ($cm^2$) | Leaf dry wt ($g/cm^2$) | No. leaves × 1000 | Total leaf area ($m^2$) | Original PAR[y] | LAI[y] | LAC[y] |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1975 | 3.7 | 3.2 | 25 | .0089 | 46 | 91 | 28 | 8.7 | 2.8 |
| 2 | 1976 | 4.0 | 2.9 | 18 | .0100 | 45 | 83 | 53 | 6.5 | 2.5 |
| 3 | 1976 | 4.0 | 2.9 | 21 | .0096 | 33 | 71 | 53 | 5.7 | 2.2 |
| 4 | 1975 | 4.1 | 3.0 | 25 | .0088 | 50 | 100 | 77 | 7.5 | 2.8 |
| 5 | 1975 | 4.3 | 3.7 | 22 | .0091 | 66 | 138 | 41 | 9.3 | 3.2 |
| 6 | 1975 | 4.6 | 3.2 | 20 | .0092 | 75 | 145 | 28 | 8.8 | 3.5 |
| 7 | 1976 | 4.7 | 4.1 | 26 | .0087 | 77 | 204 | 38 | 11.7 | 3.8 |
| 8 | 1975 | 4.9 | 4.4 | 16 | .0104 | 77 | 125 | 78 | 6.7 | 2.1 |
| 9 | 1976 | 5.3 | 4.6 | 15 | .0102 | 149 | 220 | 58 | 10.1 | 3.3 |
| 10 | 1975 | 6.1 | 4.3 | 33 | .0101 | 56 | 174 | 48 | 6.0 | 2.3 |
| 11 | 1977 | 6.2 | 3.8 | 11 | .0118 | 126 | 131 | 73 | 4.3 | 1.9 |
| 12 | 1976 | 6.5 | 5.4 | 18 | .0092 | 178 | 315 | 48 | 8.9 | 3.1 |
| 13 | 1977 | 6.9 | 4.1 | 12 | .0118 | 124 | 138 | 100 | 3.7 | 1.6 |
| 14 | 1977 | 7.2 | 4.0 | 13 | .0102 | 208 | 251 | 43 | 6.2 | 2.9 |
| 15 | 1976 | 7.2 | 5.8 | 21 | .0091 | 170 | 361 | 19 | 8.8 | 3.1 |
| 16 | 1976 | 7.5 | 5.2 | 16 | .0100 | 228 | 376 | 44 | 8.6 | 3.4 |
| 17[x] | -- | 5.3 | 5.8 | 41 | -- | 143 | 296 | -- | 13.3 | 3.6 |
| 18[x] | -- | 2.9 | 2.6 | 60 | -- | 24 | 74 | -- | 11.4 | 3.7 |
| 19[x] | -- | 2.3 | 2.9 | – | -- | 16 | 34 | -- | 8.2 | 2.0 |
| 20[x] | -- | 2.3 | 3.2 | – | -- | 37 | 59 | -- | 13.8 | 3.1 |
| 21[x] | -- | 3.5 | 5.0 | – | -- | 93 | 146 | -- | 15.1 | 3.2 |
| 22[x] | -- | 5.0 | 4.7 | – | -- | 173 | 203 | -- | 10.3 | 3.2 |

[z]Trees 1-16 listed in order of increasing diameter and ground area covered by the canopy. Cultivars are 'Nova', trees 1, 4; 'Orlando', tree 3; 'Umatilla', tree 2; 'Robinson', trees 5, 7; '6-9-10', tree 8; 'Page', tree 10; 'Dancy', trees 9, 11-16; trees planted in 1965, except 'Dancy' of unknown age.

[y]LAI = leaf-area index, LAC = leaf-area canopy-area ratio, PAR = photosynthetically active radiation, reflectance measurements recorded as $\mu E\ m^{-2}s^{-1}$.

[x]Data for 'Hamlin' trees 17 and 18 from Selhime (personal communication). Data for 'Valencia' trees 19-22 from Turrell

trees[z]

| Tree | Canopy diam (m) | Canopy ht (m) | Leaf size ($cm^2$) | Leaf wt ($g/cm^2$) | No. leaves x 1000 | Leaf area ($m^2$) | PAR[y] | LAI[y] | LAC[y] Actual | LAC[y] Estimated | LAC[y] Error (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 3.8 | 2.6 | 20 | .0102 | 63 | 134 | 19 | 11.8 | 4.7 | 4.2 | −11 |
| B | 3.9 | 2.0 | 15 | .0109 | 54 | 83 | 60 | 7.0 | 3.4 | 3.6 | + 5 |
| C | 4.0 | 1.8 | 22 | .0114 | 25 | 65 | 78 | 5.1 | 2.7[x] | 2.4 | −10 |
| D | 4.2 | 2.7 | 22 | .0140 | 40 | 104 | 38 | 7.6 | 3.1 | 3.7 | +19 |
| E | 4.3 | 2.1 | 16 | .0114 | 63 | 97 | 30 | 6.6 | 3.3[x] | 4.1 | +22 |
| F | 4.3 | 3.4 | 16 | .0105 | 100 | 155 | 38 | 10.5 | 3.8 | 3.7 | − 3 |
| G | 4.3 | 2.9 | 15 | .0106 | 93 | 144 | 37 | 9.7 | 4.0 | 3.7 | − 5 |
| H | 4.5 | 2.4 | 16 | .0100 | 82 | 128 | 10 | 8.0 | 3.8 | 4.2 | +10 |
| I | 4.5 | 2.3 | 18 | .0090 | 67 | 142 | 56 | 9.0 | 4.4 | 3.0 | −32 |
| J | 4.6 | 3.0 | 23 | .0089 | 80 | 170 | 40 | 10.4 | 4.2 | 3.7 | −13 |
| K | 4.6 | 3.0 | 20 | .0094 | 77 | 163 | 43 | 9.6 | 4.0 | 3.6 | − 8 |
| L | 4.7 | 3.4 | 16 | .0107 | 105 | 163 | 34 | 9.3 | 3.6 | 3.9 | + 7 |
| M | 5.0 | 3.0 | 27 | .0116 | 56 | 144 | 65 | 7.4 | 3.2 | 2.7 | −14 |
| N | 5.3 | 3.5 | 26 | .0106 | 62 | 161 | 73 | 7.4 | 3.0 | 3.6 | +20 |

[z]Trees listed in order of increasing diameter. Cultivars are 'Nova', trees A, I, J, K; 'Robinson', trees B, E-H, L; 'Page', trees C, D, M, N, planted in 1965.

[y]LAI = leaf-area index, LAC = leaf-area canopy-area ratio, PAR = photosynthetically active radiation recorded as $\mu E\ m^{-2}s^{-1}$.

[x]LAC values for trees C and E were calculated as oblate rather than prolate spheroids because canopy diameter was more than twice canopy height.

leaf densities. Similar changes in PAR penetration were found when plotted against LAI, LAC, or percentage defoliation of the larger trees. Locating PAR measurement points in relation to the edge of the canopy instead of around the trunk probably would have reduced the effect of tree size on the percentage defoliation data (Fig. 1). However, percentage of defoliation would not be as satisfactory where greater variation in the initial leaf density occurred.

Leaf counts on twigs can provide an estimate of defoliation for use in field studies (Fig. 2). The errors shown may be due to several factors, including the less vigorous growth of twigs on the side than on the top of the tree and the possibility of greater spray coverage on the lower part of the tree.

Once the slope of the PAR penetration curves are determined (Fig. 4), LAC values for trees are readily determined from PAR penetration measurements (Table 2). Tree size measurements can then be used to estimate total leaf area. Calculated LAC showed large errors for some trees (Table 2). Several sources of error were noted in this test, including the presence of scattered clouds when PAR was measured. The previous season's hedging and the crowding of larger trees may have caused errors in tree size measurements. Also, selection of more typical or a larger number of measurement points may have provided better PAR data.

At low leaf densities, the log of PAR penetration was linear with both LAI and LAC: at high leaf densities, some inconsistencies were shown (Fig. 3, 4). Data for trees 7 and 16 (Fig. 4) are typical of LAC values for most trees studied. This nonlinear relationship at high leaf densities could point to several factors, including possible stray light from around the sides of the canopy and the clustering of leaves, that permits some direct penetration of sunlight. Interference from adjacent trees may have reduced the PAR penetration in tree 15.

The total leaf area per tree increased with tree size as measured by canopy diameter (Table 1, 2). Cultivar and cultural differences, especially nitrogen nutrition (6), probably contributed to the variation shown. Removal of tree diameter differences by calculation of LAI reduced the range in leaf density and this was further reduced when tree height was considered in calculating LAC. For example, in Table 1, the largest tree had 5.3 times the leaf area of the smallest tree. Comparable values were 3.2 for LAI and 2.4 for LAC. This tree-to-tree variation is shown by CV's of 53, 28 and 22%, respectively. Further work is needed to compare LAI and LAC as methods of expressing canopy density. However, estimation of LAC from PAR penetration should be useful for determining the importance of shading on leaf survival and the optimum leaf density for maximum fruit production.

## Literature Cited


1. Cain, J. C. 1973. Foliage canopy development of McIntosh apple hedgerows in relation to mechanical pruning, the interception of solar radiation and fruiting. *J. Amer. Soc. Hort. Sci.* 98:357-360.
2. Green, B. A. and J. F. Gerber. 1967. Radiant energy distribution in citrus trees. *Proc. Amer. Soc. Hort. Sci.* 90:77-85.
3. Heinicke, D. R. 1963. The microclimate of fruit trees. II. Foliage and light distribution patterns in apple trees. *Proc. Amer. Soc. Hort. Sci.* 83:1-11.
4. ________. 1964. The microclimate of fruit trees. III. The effect of tree size on light penetration and leaf area in Red Delicious apple trees. *Proc. Amer. Soc.Hort. Sci.* 85:33-41.
5. Morton, C. C., O. L. Jahn, R. H. Young, and R. H. Biggs. 1978. Ethephon-induced defoliation patterns and subsequent yields in citrus. *J. Amer. Soc. Hort. Sci.* 103:670-673.
6. Smith, P. F. 1969. Nitrogen stress and premature leaf abscission in citrus. *HortScience* 4:326-327.
7. Szeicz, G. 1974. Solar radiation in crop canopies. *J. Applied Ecology* 11:1117-1156.
8. Turrell, F. M. 1946. Tables of surfaces and volumes of spheres and of prolate and oblate spheroids and spheroidal coefficients. Univ. Calif. Press. Berkeley. p. 134.
9. ________. 1961. Growth of the photosynthetic area of citrus. *Bot. Gaz.* 122:285-298.
10. Young, R. H., O. L. Jahn, and J. J. Smoot. 1974. Coloring and loosening of citrus fruits with ethephon. *Fla. State Hort. Soc. Proc.* 87:24-28.