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Estimating the contribution of canopy components to direct light interception of apple trees using a laser-assisted scanning device

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Abstract

To estimate the amount of direct sunlight intercepted by any part of an apple tree canopy, a modified point quadrat method was developed. The relative direct light interception by different components within apple tree canopies was estimated by a laser scanning method, based on moving a laser beam above the canopy in set patterns. The percent of contacts of the laser-simulated 'sunbeam' on leaves on different shoot types or other parts of the canopy was determined in several different tree forms. The laser was positioned by two different methods: a two-axis laser positioner and a solar arc positioning device. The two-axis laser positioner allowed an above-canopy laser to be rotated accurately in both vertical and horizontal planes to provide a grid of positions surrounding the canopy surface. The solar arc positioning device was designed to move the pole-mounted laser along an artificial solar track to simulate the movement of the sun throughout a day. Various sampling schemes were examined to develop efficient sampling procedures for evaluating the proportion of relative direct light interception by different components of the tree canopy. No particular patterns of light interception by different shoot types were found in three tree forms. From these analyses, to overcome the natural variations in tree canopy characteristics, general recommendations are to use a solar are positioning device to provide an angular range over which measurements can be taken, to use 75–100 laser samples per tree and to distribute the sampling points over the whole canopy with 3–4 are heights per tree. © 1997 Elsevier Science B.V.

Keywords: Crop efficiency; Light utilization; *Malus domestica*; Point quadrat method

1. Introduction

Estimates of total light interception have been widely used as predictors for the potential productivity of apple orchards [4, 5, 8, 9]. Several different techniques for estimating total light interception in orchard systems were described by Wünsche et al. [15]. However, it has been proposed that the actual productivity of healthy, well maintained apple orchards is related primarily to the total light interception by the spur canopy [14]. Therefore, to test this hypothesis, techniques were required which could discriminate between total light interception by spurs versus other shoot types such as extension shoots and lateral short shoots*.

*'Spurs' refer to the short shoot complex that typically bears the flower cluster, fruit and lateral bourse shoot. 'Extension shoots' refer to single vegetative long first year shoots. 'Lateral short shoots' refer to single vegetative shoots from lateral buds on previous season's growth that reach less than 5 cm in length.

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Warren–Wilson [12, 13] measured light penetration and exposed foliage area by using the method of inclined grids of point quadrats. The point quadrat method originally involved the insertion of thin needles at appropriate angles into a plant canopy and the location and the type of each contact of the needle point with foliage was recorded [3, 11].

Vanderbilt et al. [10] proposed a modification of the classical point quadrat method, in which the point quadrat needle was substituted by a laser with a very small beam size. The 'laser technique' provided information about the direct solar irradiance distribution as a function of time and depth of canopy and facilitated calculations of the energy budgets of solar radiation intercepted by the various components in a wheat canopy. A limitation of the laser method is the difficulty of recognizing laser contacts with vegetative parts, and it was mounted on a tripod at one position only.

A modification of the point quadrat method and the laser technique was utilized to develop and test a suitable method for estimating the interception of direct light by different shoot types within apple tree canopies.

2. Materials and methods

Measuring the proportion of relative direct light interception by various shoot types within apple tree canopies was accomplished by using a laser-assisted canopy scanning device. The proposed method is based on aiming a laser beam as a simulated 'sunbeam' in a set grid pattern into the tree canopy and recording the part of the canopy contacted by the beam. The proportion of contacts by a tree canopy component (i.e., spur leaf, extension shoot leaf, fruit, or limb) to total tree contacts was used as an estimate of relative direct light intercepted by this canopy component. As an example, average percent light interception by the spur canopy was estimated by whole canopy percent light interception, obtained e.g. via fisheye photography or the use of lightmeters, and multiplied by the fraction of percent relative direct light interception by the spur canopy, obtained via laser scanning:

Total light interception by spur canopy

= Total light interception per tree or hectare (via fisheye or lightmeter)

* Fractionn of rel. direct light interception by spur canopy (via laserbeam)

Since the direct and diffuse component of total solar radiation is roughly the same throughout the growing season in Geneva, New York (latitude 43°), and the interception of direct light is rather similar to that of diffuse light for north–south oriented hedgerows at that latitude ([6, 7]; Lakso and Wünsche, unpublished data), it seems valid to use a direct beam method for estimating the relative direct light interception by a canopy component and, by applying it to total tree light interception, to calculate the total amount of light intercepted by this canopy component.

A 5 mW laser (Model LAS-200-670-5, Laser-Max, Inc., Rochester, NY) was found to have sufficient power to project the laser spot in the canopy. For easier observation of the laser spot within the tree canopy, the laser beam was initially located with a white cardboard disc held just above the foliage. This proved to be very helpful on bright, sunny days when it was more difficult and time consuming to locate the 200-micron spot inside the canopy. Two laser positioning methods were used: two-axis laser positioning and simulated solar arc positioning.

2.1. Two-axis laser positioner

This method was characterized by attaching the laser to a positioner with two micrometer adjusting screws for vertical (A) and horizontal (B) laser movement (Figure 1). The laser positioner was mounted on the basket of a mechanical lift to elevate it and the operator above an apple orchard with north-south oriented tree rows. The laser positioner was set up on the south side of the test trees and the measurements were taken at a solar position approximately 3 hr before solar noon and at solar

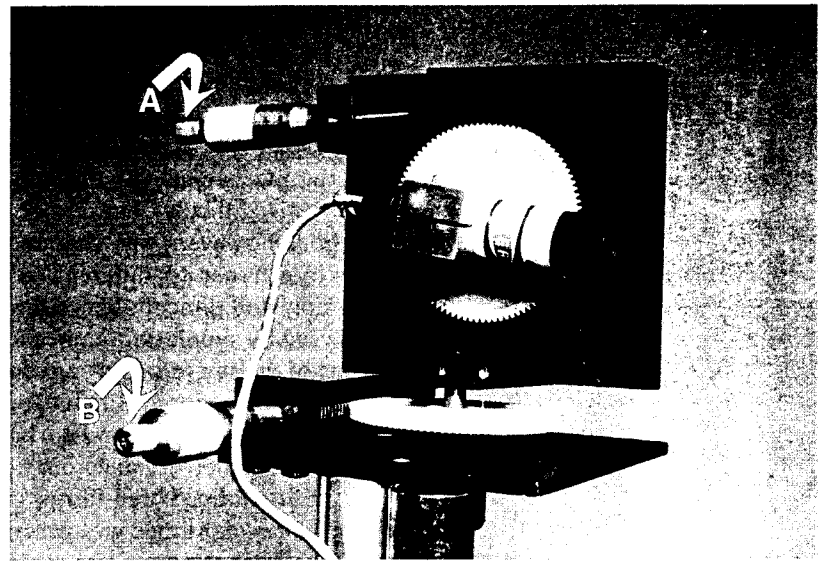


Fig. 1. Laser positioner for measuring the relative interception of direct light by various shoot types within apple tree canopies. Micrometer adjusting screws for (*A*) vertical and (*B*) horizontal laser movement across the tree canopy in a set point grid pattern.

noon. The laser beams were 'shot' into a representative portion of the whole tree canopy by using an 8 point × 8 point square grid, covering at least 75% of the canopy surface.

2.2. Solar arc positioning device

The solar arc positioning device was characterized by the following components: (1) a semicircular steel arc, (2) a wooden supporting structure (3) a 3.5 m long metal pole that rotates from a universal joint and (4) a laser positioned on the pole (Figure 2). By raising the arc to the angle of the latitude (a), the arc was aligned parallel to the earth's axis and this parallel axis projects from the universal joint through the center of the steel arc. For laser scanning of apple tree canopies, the device was positioned about 1.5 m from the trunk on the south side of the test tree with the axis aligned to north and the laser on the pole was adjusted to be pointing from the center-position of the arc towards the tree canopy at the solar elevation angle (b) at noon for the specific day of sampling (Figure 2). Then, with the pole being attached to the universal joint and moved along the 0–180° solar arc, corresponding to the 0–180° azimuth range, the elevation of the laser followed the solar elevation on the natural solar track. Hence, the series of simulated solar positions mimics a series of specific configurations of solar elevation angles (angle of the laser beam above the horizontal ground surface) and azimuth angles (horizontal projection of the laser beam measured east/west from south) for that sampling day and at that latitude. When measurements were taken the pole was moved clockwise from due east in 5° azimuth increments along the arc to simulate a daily solar track. For laser scans of the whole tree canopy, the laser was positioned at three different heights (varied with tree height) on the metal pole and thus the readings were taken in the upper, middle and lower part of the tree canopy.

3. Discussion of the technique

Measurements of the relative interception of direct light by various shoot types within apple tree canopies were obtained by using two methods for laser positioning. The use of the two-axis laser positioner was designed to simulate, with acceptable errors, the array of parallel sunbeams incident on a canopy. Since providing a laser array to match the complete sunbeam array on a large tree canopy is

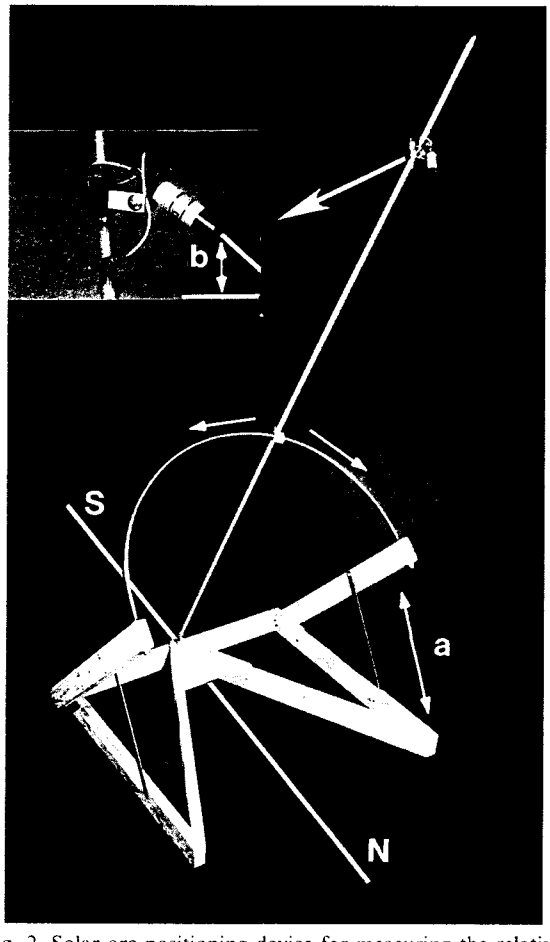


Fig. 2. Solar arc positioning device for measuring the relative interception of direct light by various shoot types within apple tree canopies. The laser, mounted on a metal pole at an angle equal to the solar elevation (*b*) at noon for the specific day of sampling, follows an semi-circular arc which is rotated upward at the latitude angle (*a*) of the user. The supporting structure is aligned in north–south direction.

very difficult, only two locations were used for laser positioning and the laser was rotated in two directions to provide a grid of points. Since the laser itself was not moved laterally in the two directions, the beams were not truly parallel. However, the further the laser was located from the canopy, the smaller the error as fewer micrometer screw adjustments (reduced angles) were needed to produce the grid of required size. For example, if the laser was positioned 5 m from the canopy surface, the external beams of a 1.5 m grid were at approximately 10–11° deflection from the central beam angle. This was felt to be an acceptable compromise.

There were some marked disadvantages with this device. Positioning the mechanical lift and the two-axis laser positioner was time-consuming, and driving the mechanical lift through the narrow alleyways was difficult. The major drawback of this method, however, was that moving the two-axis laser positioner to different solar track locations was slow and difficult, hence the tree canopies were analyzed by simulating sunbeams for only two positions of the sun (data not presented). Although for natural tree canopies the use of a single position, near 57°, has been found to be useful for assessments of solar irradiance distribution [10, 11, 12, 13], with confined tree forms such as trellises the use of one solar angle was generally not suitable.

Since discontinuous tree canopies intercept light from different angles over a day, the different parts of the canopy may intercept varying amounts of sunlight during a day depending on canopy shape and tree spacing. Thus, a method was developed for laser-assisted direct light analysis of tree canopies; a method in which the laser follows an artificial solar arc and thus simulates the path of the sun throughout a day. The solar arc positioning device was comprised of four key components: (1) a semi-circular arc that represents the natural track in which the sun moves, (2) a supporting structure that aligns and positions the arc properly so that the arc was parallel to the sun's natural arc, (3) a pole that rotates from a universal joint and projects the arc above the device, and (4) a laser positioned on the pole. To match closely the movement of the laser on the pole with the sun's natural arc, three main considerations were taken into account: (1) positioning of the solar arc device with the axis aligned to north, (2) elevating the arc upward at an angle equal to the latitude of the location, and (3) adjusting the laser angle to be equal to the solar elevation at noon for the specific day of sampling at that latitude.

Although there were many advantages due to flexibility and ease of use with the solar arc positioner, there was a potential error that had to be considered when estimating relative direct light interception by canopy components. As the laser was moved around the tree canopy along the arc,

the laser beams were close-to-radial (i.e. there was a focal point that generally was located within the canopy, usually near or behind the trunk). However, as the laser was moved to different heights on the pole for multiple arcs, the laser beam at any particular azimuth angle along the solar arc will be parallel with the beam from the same angle in the other heights. Thus, although all the laser beams used were parallel with sunbeams, the total array of beams impinging on the canopy did not represent all sunbeams (the sunbeams that pass only through the edge of the canopy were under-represented). Since a disproportionately higher percentage of the beams passed through the center of the canopy, a potential error may occur if some of the canopy components of interest are located primarily near the trunk. However, since the various arcs were parallel to each other and the canopy shoot types were not distinctly separated in the canopies we measured, we felt that this practical error in our studies was small.

4. Sampling schemes

4.1. Various sampling patterns

The effects of various sampling patterns on estimates of the relative direct light interception by different shoot types within apple tree canopies were examined, using the solar arc positioning device, on six standard pyramidal-shaped tree canopies trained as slender spindles. Laser scanning of the tree canopy was accomplished by: (1) attaching the laser at six different heights (20 cm apart, respectively) on the metal pole and (2) at each height, passing the pole clockwise from due east along the 180° solar arc in 5° azimuth increments. The six arc heights corresponded to different heights within the tree; position 1 represented the lower part of the tree canopy, whereas position 6 represented the upper part of the tree canopy. Thus, a sampling grid was arranged to represent the surface of the complete tree canopy. For each tree the maximum number of observations ($N=222$, 6 heights times 37 azimuth angles) was sampled and the number of contacts with various parts of the tree canopy or ground was recorded. Seven sampling components were distinguished: primary spur leaf, bourse shoot leaf, lateral short shoot leaf, extension shoot leaf, fruit, wood, and ground. For this analysis non-shoot types like fruit, wood and ground contacts were grouped into a single 'other' category. For evaluating the various sampling schemes the data from the six slender spindle trees were pooled.

4.2. Various tree forms

Is it necessary to use the solar arc positioning device that mimics a series of different solar elevation/azimuth angles for the specific day of sampling or is one angle sufficient to analyze apple tree canopies of varying forms and training? This was addressed by analyzing six mature 'Empire'/M.9 trees for each of three forms (slender spindle, Y-trellis and thin 5-wire vertical palmette trellis), respectively. Six arc heights per tree were performed to give 222 observations total per tree, and 1332 observations total per tree form (same sampling procedure as described above). For each tree form, the data were pooled for all trees and were combined into 10° increments, giving 72 points per azimuth angle that were analyzed for the proportion of laser hits by various shoot types.

5. Analysis of sampling

5.1. Homogeneity of distribution

The relative direct light interception by various canopy components of apple trees can be modeled as a series of N independent trials (sampling schemes) in which each of the five mutually exclusive events (spur, bourse shoot, short shoot, extension shoot, other) can occur and in which the probability of occurrence of the ith event is π_i. This constitutes a multinomial distribution, with probabilities π_i and index N. The probability of observing the configuration $(n_1, n_2, \ldots n_5)$ where n_i is the number of contacts with component i, is then:

$$Pr(n_1,n_2,\ldots n_k)=N!\prod_{i=1}^{k}\left(\frac{\pi_i^{n_i}}{n_i!}\right)$$

Various sampling schemes were analyzed for the six slender spindle trees, evaluating the use of the direct

beam technique for estimating the contribution of canopy components to direct light interception:

1. Maximum sampling observation quantity at $N=222$ by using 5° intervals over the 0°–180° azimuth range.
2. How important is sampling frequency? Increasing sampling intervals over the 0°–180° azimuth range to 10°, 20°, 30° and 60°.
3. How important is whole-arc sampling? Decreasing the 0–180° azimuth range to 15°–165°, 30°–150°, 45°–135°, 60°–120° and 75°–105°.
4. How important is arc height? Individual arc heights through the canopy (1, 2, 3, 4, 5, 6) were considered.
5. Combination of are heights through the canopy (1–5, 1–4, 1–3, or 1–2, 3–4, 5–6) were considered.
6. How important is time of day? Comparison of 0°–90° (am) vs. 90°–180° (pm) and 45°–90° (am) vs. 90°–135° (pm).

Whether or not a given sampling scheme favors some components over others was investigated by testing for homogeneity of distribution from the different sampling schemes. Weighted least square analysis of the multinomial data [2] revealed no changes in the proportion of the various components (Table 1) when:

1. azimuth increment between the measurements was increased $\{\chi^2(\mathrm{df}=16)=10.3,\ P>0.85\}$;
2. azimuth range over which readings were taken was decreased $\{\chi^2(\mathrm{df}=20)=9.6,\ P>0.97\}$;
3. individual arc heights through the canopy were combined $\{\chi^2(\mathrm{df}=36)=36.0,\ P>0.45\}$;
4. whole-arc (0°–180°) vs. reduced-arc (45°–135°) was compared $\{\chi^2(\mathrm{df}=4)=3.4,\ P>0.50\}$.

However, there were changes in the proportion of contacts by various canopy components (Table 1) when:

1. individual arc heights were considered as separate samples $\{\chi^2(\mathrm{df}=20)=41.0,\ P<0.004$;
2. 0°–90° (am) vs. 90°–180°(pm) $\{\chi^2\ (\mathrm{df}=4)=14.5,\ P<0.006\}$, and 45°–90° (am) vs. 90°–135°(pm) $\{\chi^2(\mathrm{df}=4)=8.1,\ P<0.09\}$ were compared.

For clarity only the effects of various sampling schemes and consequently of various sampling quantities on the proportion of contacts by different shoot types (primary spur, bourse shoot, short shoot and extension shoot) were included in Table 1.

5.2. Confidence limits for π_i

Since the various sampling schemes were homogeneous with respect to the proportions of contacts (except by comparison among individual arc positions and between morning and afternoon), a single set of confidence limits can be calculated for various sample sizes.

The effect of sample size on estimation of proportion of contacts can be seen by calculating confidence limits for π_i. Simultaneous confidence intervals are given by Goodman [1]:

$$\frac{\chi^2_{1,1-\alpha/k}+2n_i\pm\sqrt{[\chi^2_{1,1-\alpha/k}\{\chi^2_{1,1-\alpha/k}+4n_iN^{-1}(N-n_i)\}]}}{2(N+\chi^2_{1,1-\alpha/k})}$$

where α is the chosen confidence percentage (as example 5% or 10%), and k is the number of elements in π (here 5).

Limits for the actual number of contacts can be obtained by multiplying limits for π_i by N. Therefore, for a specified π_i the effect of sample size, N, can be illustrated (Figure 3). For example, if 30% of laser contacts are actually with spurs, and a sample size of 75 is used, then the 90% confidence limits of spur contacts will be (14, 33) with 18 as the width of the confidence interval. By increasing the sample size to 150, the 90% confidence limits will be (32, 59) with 27 as the width of the confidence interval.

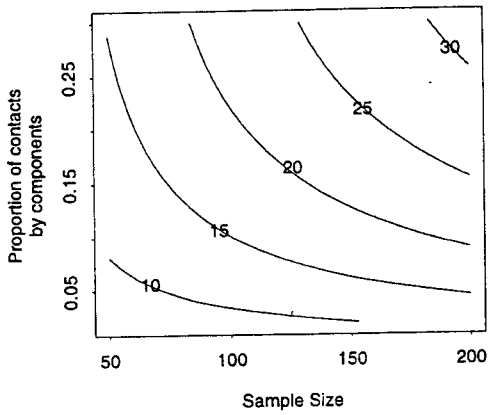
5.3. Various tree forms

There was highly significant variation with simulated solar angle in the proportion of laser hits by the different shoot types in all three tree forms (slender spindle: $\chi^2(72)<0.004$; Y-trellis: $\chi^2(72)<0.001$; vertical palmette trellis: $\chi^2(72)<0.001$). However, no clear trends with laser position angle (i.e. solar elevation/azimuth angle) were seen in the data (Figure 4). Therefore, the analysis suggests that laser sampling should be done at several angles to account for the relatively high natural variability in apple tree canopies.

Table 1
The effect of various sampling schemes on the proportion of contacts by various shoot types within apple tree canopies. Values are means of 6 replicate slender spindle trees.

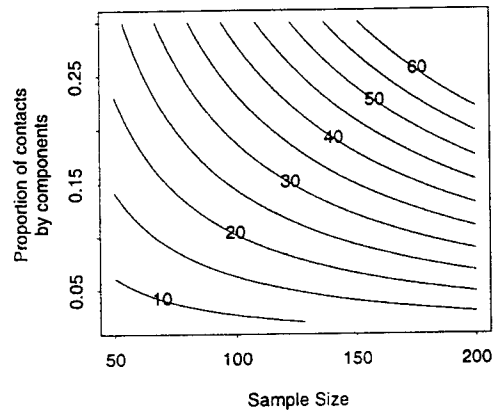
Sampling scheme	Sampling Quantity/tree	Proportion by			
		Spur primary	Shoot		
			Bourse	Short	Extension
Maximum sampling quantity					
0°–180°, 5°	222	0.31	0.22	0.06	0.13
Increasing sampling intervals over the 0–180° *azimuth range*					
10°	114	0.30	0.23	0.06	0.13
20°	60	0.30	0.24	0.05	0.13
30°	42	0.30	0.20	0.10	0.12
60°	24	0.26	O.19	0.08	0.11
Decreasing the 0–180° *azimuth range*; 5° *sampling intervals*					
15°–165°	186	0.32	0.23	0.05	0.14
30°–150°	150	0.33	0.22	0.05	0.14
45°–135°	114	0.32	0.23	0.05	0.15
60°–120°	78	0.31	0.23	0.06	0.16
75°–105°	42	0.32	0.24	0.04	0.16
Arc heights					
1	37	0.33	0.27	0.04	0.08
2	37	0.32	0.21	0.08	0.12
3	37	0.34	0.21	0.05	0.08
4	37	0.25	0.18	0.07	0.21
5	37	0.27	0.24	0.07	0.15
6	37	0.33	0.24	0.05	0.14
Combining arc heights					
1–5	185	0.30	0.22	0.06	0.13
1–4	148	0.31	0.22	0.06	0.12
1–3	111	0.33	0.23	0.06	0.09
1–2	74	0.33	0.24	0.06	0.10
3–4	74	0.30	0.20	0.06	0.14
5–6	74	0.30	0.24	0.06	0.15
Time of day					
0°–90°	114	0.32	0.20	0.07	0.15
90°–180°	114	0.29	0.25	0.04	0.12
45°–90°	57	0.30	0.21	0.07	0.18
90°–135°	57	0.32	0.24	0.04	0.14

A limitation of the laser scanning method is, that the interception of incoming radiation by neighbouring trees at low solar elevation angles could not be considered due to technical difficulties. The interference of adjacent trees can lead to a slight over-estimation of direct beam interception at lower solar elevation angles. However, since low solar angles play only a minor role for whole canopy radiation interception and the used planting system was of low tree densities (less tree interference), the experimental error was felt to be acceptable.



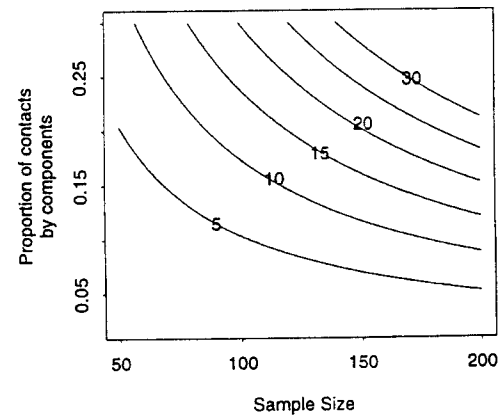
A

Width of Confidence Intervals for varying Sample Sizes



B

Upper Confidence Limits for varying Sample Sizes



C

Lower Confidence Limits for varying Sample Sizes

Fig. 3. The effect of sample size on 90% confidence limits for percentage of contacts by shoot types or other tree components for varying sample sizes: (*A*) width of confidence intervals, (*B*) upper confidence limits, and (*C*) lower confidence limits.

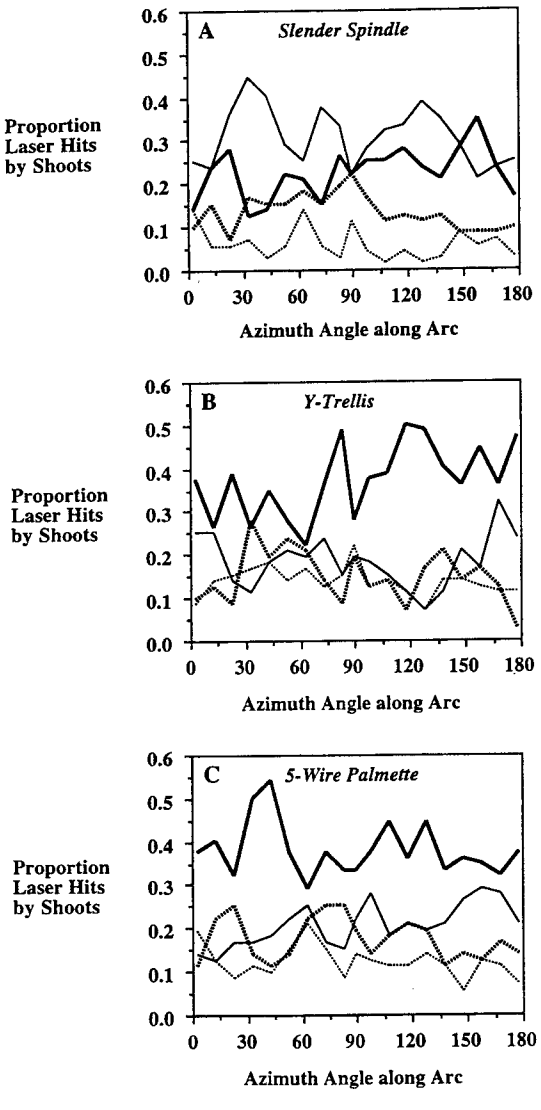


Fig. 4. Variation in proportion of laser hits over the 0–180° azimuth range along the artificial solar arc by leaves on four different shoot types {*bourse shoot* (———), *spur* (———), *short shoot* (· · ·), and *extension shoot* (· · ·)} on mature slender spindle (A). Y-trellis (B) and 5-wire vertical palmette-trained (C) 'Empire' apple trees. The values are the means of six trees of each form.

6. Conclusions

A modified laser point quadrat method has been found to be useful to evaluate the relative importance of canopy parts to direct light interception by apple trees. Analyses of different choices of sampling procedures and the authors' experiences with the method has led to the following general recommendations for use of this method.

1. The solar arc positioning device should be used to overcome the variations in canopy characteristics.
2. At least two, but preferably three arc heights (top, middle and lower part of the canopy) should be used.
3. The use of 5° intervals over the 30–150° azimuth range (25 observations per arc height) is recommended.
4. Three arcs of 25 observations (75 observations per tree) are a generally acceptable compromise of sampling numbers and time required per tree for analysis.

Of course, these recommendations may need to be modified depending on the questions examined and if greater or lesser confidence intervals are required. The analyses given will allow the reader to modify the sampling patterns appropriately for their purposes.

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